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CULTURE OF SPECTRUM SHARING

Emancipation of the hertz

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To Mimi.

DECLARATION

I declare that this thesis has not been submitted as an exercise for a degree at this or any other university and is entirely my own work.

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SUMMARY

The dissertation provides theoretical and experimental groundwork for dynamic spectrum sharing policy design. It embeds the tool of culture of sharing into a sharing framework and proposes dynamic spectrum sharing as a predominant way of spectrum use, necessary to answer to the future spectrum demands and put spectrum into a cycle of optimal and efficient use. Contemporary challenges to spectrum sharing policy are centered around: (1) the technological enablers of the past two decades which can support shareability of spectrum resource, and (2) the emerging regulatory initiatives which recognise the necessity of sharing the spectrum to serve public interest of today's society. Increase on demands for lower latency, pervasive connectivity, higher throughput, and more capacity has an exponential trend. To meet the demands is to put to use all spectrum resources we have and all of the technology capable of "multiplying" it. This asks for a dynamic, responsive regulation that will set free the inappropriately allocated and underutilised spectrum bands - not by designing a new band plan, but with a continuous, dynamic engagement aimed at optimising spectrum use by sharing it instead. Finally, it asks for the stakeholders' readiness to share and their awareness of spectrum recyclability, inherent to the nature of the resource. The nature of spectrum resource is the one of multidimensional spectrum space, as spectrum varies in time, frequency, and area, but its unique features of instantaneous recyclability, non-depletability and fluidity have not been utilised in the regulatory circles.

This is where the dissertation starts: describing the identified domains of a spectrum sharing ecosystem and seeking for the enablers of sharing within them. The conceptual framework for dynamic spectrum sharing, informed by the phenomenon of a sharing economy, is an initial step in methodology design as it serves to depict the holistic approach needed to answer the main research question of how to build the culture of spectrum sharing and its nine sub-questions answered in each of the chapters. It is termed the NTBRS conceptual framework for dynamic spectrum sharing after the five identified domains: **n**ature, **t**echnology, **b**usiness, **r**egulation, and **s**ociety. It serves to support the thesis, analyse the problems we encounter and interpret their results. After setting the stage with the NTBRS framework, we proceed with building a compact, heterogeneous set of methods tailored for the multidimensional nature of spectrum resource and its sharing ecosystem. It is an interdisciplinary methodology design, needed to account for the interplay of technology, economics, law and politics in spectrum policy. Engineering research methods (e.g., optimisation, modeling and simulation, pattern recognition, geospatial analysis) are coupled with social science research methods (e.g., content analysis based on Krippendorff's framework, historiographic method of policy analysis), theories of regulation (e.g. socioeconomic theory of regulation of Lawrence Lessig), and philosophical methods of interpreta-

tion and exposition (e.g. philosophical and pragmatic nature of context in policy design). For example, geospatial analysis is used simultaneously with historiographic research methods and Lessig's pathetic dot theory while portraying the context in the enstranged form of Socratic dialogues. While representing the foundation of the thesis, the framework and the methods are contributions of their own as they can ground other related research and the regulatory designs.

The initial evidence gives rise to the hypothesis that the culture of sharing is the missing enabler of sharing. To rigorously show it by employing the chosen methods and the framework developed, we conduct a case study of the regulatory design of a spectrum sharing framework in the Citizens Broadband Radio Service (CBRS) 3.5GHz band. This sharing model recently emerged as the response of the US regulator, the Federal Communications Commission (FCC) to the Presidential Council of Advisors on Science and Technology (PCAST) report in 2012 which laid out a vision for a dynamic spectrum sharing model. While historiographic in nature, this case study deals with the present and the future as well, by documenting regulatory developments currently in progress and making future predictions on the sharing enablers in the CBRS band. The findings however, are universal and they extend to spectrum sharing in general. A significant part of the case study is the thorough content analysis of the FCC proceeding on CBRS sharing model, the docket GN. 12-354. The content analysis provides inputs and building blocks for the subsequent parts of the thesis, but also represents a valuable resource on its own, as it presents the CBRS spectrum sharing ecosystem in a coherent and structured manner. The CBRS landscape is painted and it reveals the little known sub-culture of stakeholders, an epistemic community which shapes the policy rules of sharing. The role of the regulator is to resolve the situation of conflicting policy positions coming from different stakeholders driven by their business interests and to reach a middle ground solution. The one policy issue on which the balanced regulatory approach was not applied is the issue around the CBRS licensing framework: adopting the census tract demographic areas as the basic license area units. We have explored the effectiveness of such licensing scheme design for geographic spectrum sharing and proposed a solution for its shortcomings.

The conjectured imbalance of sharing enablers is proven using Lessig's pathetic dot theory of regulation. Our approach extends Lessig's orginal approach in two ways. First we established new interconnections between the forces of regulation (law, market, norms and architecture) to predict the future development of the CBRS band and the sharing behaviour within it. Then we discovered that decomposing the force of architecture into its two components, nature and technology, allows a description of social norm shaping in spectrum sharing. This is where the culture of sharing lives and where Lessig's set of forces transforms into the NTBRS framework. This key result of the thesis is then a major component of SPECTRUMISM, the underlying philosophy for future dynamic spectrum sharing economy. Along the mechanisms for sensible incentivisation and building the culture of spectrum sharing we also discover a new dimension in spectrum space which reveals itself through several types of analysis con-

ducted and that is the data. The nature of spectrum resource is about its uniqueness and shareability, within which we ground our proposal of a dynamic digital license (DDL). The much needed responsiveness of regulations is achieved through machine-enabled spectrum sharing ecosystem, which we present in a future dynamic spectrum sharing scenario. Finally, the culture of spectrum sharing calls for an inclusion of an important, in spectrum policy discourse disregarded stakeholder - the citizen. After summarising the thesis results we provide actionable recommendations and propose future research directions enabled by this work.

PUBLICATIONS

Some ideas and figures have appeared previously in the following dissemination efforts:

1. Avdic, E., Macaluso, I., Marchetti, N. and Doyle, L., 2016, December. Census Tract License Areas: Disincentive for Sharing the 3.5 GHz band?. In Global Communications Conference (GLOBECOM), 2016 IEEE (pp. 1-7).

2. Gomez-Miguelez, I., Avdic, E., Marchetti, N., Macaluso, I. and Doyle, L., 2014, May. Cloud-RAN platform for LSA in 5G networks—Tradeoff within the infrastructure. In Communications, Control and Signal Processing (ISCCSP), 2014 6th International Symposium on (pp. 522-525).

3. Morgado, A., Gomes, A., Frascolla, V., Ntougias, K., Papadias, C., Slock, D., Avdic, E., Marchetti, N., Haziza, N., Anouar, H. and Yang, Y., 2015, June. Dynamic LSA for 5G networks the ADEL perspective. In Networks and Communications (EuCNC), 2015 European Conference on (pp. 190-194).

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5. Comments of Elma Avdic, Irene Macaluso and Linda Doyle, In the Matter of Promoting Investment in the 3550-3700 MHz Band; Petitions for Rulemaking Regarding the Citizens Broadband Radio Service, GN Docket No. 17-258, Before the Federal Communications Commission, Washington, D.C. 20554, Nov 23, 2017. Available at: `https://ecfsapi.fcc.gov/file/1124135896869/Comments_CBRS_EA_IM_LD.pdf`

6. Elma Avdic, Tim Forde and Linda Doyle, CONNECT's Response to Ofcom Consultation on 3.8 GHz to 4.2 GHz band: Opportunities for Innovation, June 6, 2016. Available at: `https://www.ofcom.org.uk/__data/assets/pdf_file/0031/85198/connect_research_centre_for_future_networks_and_communications_trinity.pdf`

7. Elma Avdic and Linda Doyle, CONNECT's Response to Ofcom Consultation on Improving consumer access to mobile services at 3.6 to 3.8 GHz, Dec 15, 2016. Available at: `https://www.ofcom.org.uk/__data/assets/pdf_file/0037/96895/CONNECT.pdf`

8. Research Purge Collaboration with The Department of Ultimology, Trinity College Dublin, – *Spectrum is Dead*, audio-visual presentation, Oct 2017.

9. Panel Session: *Culture of Sharing in the Competitive Digital*, Digital Cultures Conference, Leuphana University Lüneburg, Germany, Sept 2018. Available at: https://digitalculturesconference.org/files/2018/09/KCT18_Program_Abstracts.pdf

10. Talk: *Let the Machines Govern Things*, Radical Networks Conference, Berlin, Germany, Oct 2018. Available at: https://www.youtube.com/watch?v=4DuqGe2RV-U

11. Irish Research Council (IRC) postdoctoral fellowship application, extending the thesis into a book: *AI regulator to liberate the hertz: Culture of spectrum sharing* (submitted Nov 2018).

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ACRONYMS

5G Fifth Generation

ABM Agent Based Modelling

ACT Aggregated Census Tract

AI Artificial Intelligence

AIP Administrative Incentive Pricing

ALP Area Loss Percentage

APA Administrative Procedures Act

API American Petroleum Institute

ASA Authorised Shared Access

CAF Critical Access Facility

CBRS Citizens Broadband Radio Service

CBSD Citizens Broadband radio Service Device

CEA Consumer Electronics Association

CEO Chief Executive Officer

CEPT Conférence européenne des administrations des postes et télécommunications (European Conference of Postal and Telecommunications Administrations)

CDF Cumulative Distribution Function

CDMA Code Division Multiple Access

CFS Correlation-based Feature Subset Selection

CFR Code of Federal Regulation

CII Critical Infrastructure Industry

CMA Cellular Market Area

CPE Consumer Premises Equipment

CR Cognitive Radio

C-RAN Cloud Radio Access Network

CSMAC Commerce Spectrum Management Advisory Committee

CT Census Tract

CTIA Cellular Telecommunications and Internet Association

CTO Chief Technology Officer

DARPA Defense Advanced Research Projects Agency

DDL Digital Dynamic License

DOD Department of Defense

DSA Dynamic Spectrum Access

DSA Dynamic Spectrum Alliance

DYSPAN Dynamic Spectrum Access Networks

EA Economic Area

EBU European Broadcasting Union

EC European Commission

ECC Electronic Communications Committee

EIRP Effective Isotropic Radiated Power

EM Expectation-Maximisation

ESC Environmental Sensing Capability

ETSI European Telecommunications Standards Institute

ETSI-RRS ETSI Technical Committee on Reconfigurable Radio Systems

ETSI-ERM ETSI Technical Committee on Electromagnetic Radio Matters

EU European Union

FCC Federal Communications Commission

FM Frequency Modulation

FNPRM Further Notice on Proposed Rulemaking

FRC Federal Radio Commission

FSS Fixed Satellite Services

FWCC Fixed Wireless Communication Coalition

GAA General Authorized Access

GDP Gross Domestic Product

GIS Geographical Information System

IA Incumbent Access

IIOT Industrial IoT

IOT Internet of Things

IP Internet Protocol

IRAC Interdependent Radio Advisory Committee

ISO/OSI International Organization for Standardization/Open Systems Interconnection

ITI Information Technology Industry

ITU International Telecommunication Union

ITU-R ITU Radiocommunication Sector

ITU-RRR ITU-R Radio Regulations

JRC Joint Research Centre

LC LSA Controller

LR LSA Repository

LSA Licensed Shared Access

LTE Long Term Evolution

M2M Machine to Machine

MIMO Multiple Input Multiple Output

MMIMO-U Massive MIMO Unlicensed

MNO Mobile Network Operator

NCTA National Cable & Telecommunications Association

NEC National Economic Council

NIST National Institute of Standards and Technology

NOI Notice of Inquiry

NPRM Notice of Proposed Rulemaking

NRA National Regulatory Authority

NRECA National Rural Electric Cooperative Association

NSN Nokia Solutions and Networks/Nokia Siemens Networks

NSS National Security Staff

NTBRS Nature, Technology, Business, Regulation, Society

NTIA National Telecommunications and Information Administration

OA&M Operations, Administration and Management

OET Office of Engineering and Technology

OFCOM The Office of Communications

OMB Office of Management and Budget

OSM Office of Spectrum Management

OSPA Office of Strategic Planning and Policy Analysis

OTI/PK Open Technology Institute/Public Knowledge

OTSP Office of Technology, Science and Policy

P2P Peer to Peer

PA Priority Access

PAL Priority Access License

PCAST Presidential Council of Advisors on Science and Technology

PCIA Personal Communications Industry Association

PCS Personal Communications Services

PCTAS Population of Census Tract with Access to Spectrum

PEA Partial Economic Area

PISC Public Interest Spectrum Coalition

PN Public Notice

PPP Public Private Partnership

PSD Power Spectral Density

PU Primary Users

PWC PricewaterhouseCoopers

QOS Quality of Service

RF Radio Frequency

RMS Root Mean Square

R&O Report and Order

RSPG Radio Spectrum Policy Group

SAS Spectrum Access System

SDR Software Defined Radio

SIA Satellite Industry Association

SMR Simultaneous Multiple-Round

SMT Spectrum Management Team

SNR Signal to Noise Ratio

SPTF Spectrum Policy Task Force

SSP Spectrum Sharing Partnership

TAS Time, Area, Spectrum

TIA Telecommunications Industry Association

TVWS TV White Space

UE User Equipment

UHF Ultra High Frequency

UNII Unlicensed National Information Infrastructure

USC United States Code

UTC Utilities Technology Council

UTM Universal Transverse Mercator

UWB Ultra-Wide Band

VHF Very High Frequency

WINNFORUM Wireless Innovation Forum

WISPA Wireless Internet Service Providers Association

WRC World Radiocommunication Conference

WSD White Space Devices

XG neXt Generation

Part I

INTRODUCTION TO THE PROBLEM

1 INTRODUCTION

Over the last decade, the radio spectrum community recognised how crucial the technological enablers and the more progressive designs of regulations are for the support of *dynamic spectrum sharing*. But the *culture of sharing* and *what really motivates users to share spectrum* are left under-explored. The regulations of spectrum sharing are framed through a set of rules that govern the sharing, regulatory frameworks. The thesis sheds light on how the culture of sharing can emerge from the mechanism design of spectrum sharing frameworks, so that sharing schemes become widely implemented so that, ultimately, radio spectrum is used more efficiently.

To tackle the complexity of spectrum policy design, we perform a multi-domain analysis on the emerging example of an innovative spectrum sharing framework through the lenses of culture of sharing and motivations (incentives) to share, exploring what kind of change can happen if sharing frameworks are constructed to encourage sharing and how that has an effect on better utilisation of spectrum. The purpose of this chapter is to unpack the opening statements by: (1) providing preliminary background information for the research context in Section 1.1, (2) describing the overall aim and research objectives in Subsection 1.2.1, (3) introducing key definitions and terms in Subsection 1.2.2, (4) stating the assumptions and providing justifications in Subsection 1.2.3, (5) articulating the contributions in Subsection1.2.4, and (6) mapping the structure of the dissertation in Section1.3.

1.1 THE ROAD TO CULTURE OF SPECTRUM SHARING

The race between technology and regulations, organised and sponsored by economics, was never a fair one, but only because regulations were lagging so much behind. Technological enablers have always been developing at a much faster pace than regulations could ever follow. The missing piece of the puzzle has always been the responsiveness. We define the responsiveness *as an ability of a regulatory framework to dynamically adapt to the real-time changing conditions in the radio surroundings*. This means that the regulatory frameworks have to incorporate contemporary technology and anticipate the one to come. The inertia of regulatory frameworks has kept them back from keeping up with changes and anticipating future solutions, a diverse range of new services and new ways in which we will communicate, that we cannot even see today. What the history of regulations taught us about the future of spectrum is that we solve problems on a service-by-service basis, without long-term thinking. As the thesis will show, the responsiveness of a regulatory framework can emerge with an effort to build the culture of spectrum sharing through the policy design aimed at incentivising users to share spectrum.

For a sustainable future in terms of connectivity, sharing will need to become a dominant way of using spectrum. And for that future spectrum policy to be sustainable, the culture of sharing needs to develop. As a fluid, fast-cleansing natural resource, radio spectrum can be shared dynamically and technologies have evolved to put it in a cycle of optimal, efficient use. Dynamic spectrum sharing is the one of responsive regulation as well, without the rules of sharing the concept cannot sustain in practice.

1.1.1 *Spectrum Sharing Today and Tomorrow Morning*

Short-term planning gets things done but has a blind eye for the context. Without a roadmap in which every step clearly reflects progressive thinking in spectrum sharing, the horizon will always stretch no further than tomorrow morning. Spectrum sharing roadmap based on short-term planning fails to acknowledge the long-term, larger scale dynamics. Contemplating spectrum within a narrow time window will always simply fail to capture market and technological trends.

The evidence is compelling[1]. Regulatory approaches have never been able to anticipate the pace and the scale of technological change or the markets coming out of it. This led to the anxiety about spectrum scarcity. On the other side of the spectrum is the users' hunger for connectivity and gadgets and for unlimited data traffic at maximum speeds to support, e.g., their digital extension, Internet of Self[2]. Demand for spectrum is real and undeniable, but so is the spectrum abundance in time and space. The scarcity is a product of the inefficient use of spectrum, not the lack of spectrum.[3]

Spectrum is a perfectly renewable natural resource. It is vital for wireless communications which just emerged in the last century. It existed always but the sense of spectrum we just got a hundred years ago. Like oil, it has always been there, but we are only using it for the last 100-150 years. Today we are finding the alternatives for oil, which is a non-renewable resource. Spectrum is renewable and doesn't need an alternative source, but perhaps alternative management.

What makes the science of radio spectrum complex is the fact that the hertz is bounded by the information theory and the regulations which govern its use. And yet, physics and philosophy of spectrum are fundamentally different from all other resources. Today spectrum is regulated, controlled and managed in three ways: (1) via administrative rights of the command and control approach (still the dominant approach), (2) as unlicensed where the rights are issued based on technology certification, or (3) as a property, where the users get a license describing their rights of use and emphasising their rights of ownership over the spectrum through the exclusivity. Over the last two decades, spectrum debates focused on asking should the command

[1] *See* chapters 2 and 5

[2] Multitude of personal, portable devices, some of them wearable, all using wireless communication.

[3] Staple, G. and Werbach, K., 2004. The end of spectrum scarcity [spectrum allocation and utilization]. IEEE Spectrum, 41(3), pp.48-52.

and control approach to spectrum policy be abandoned and what are the alternatives. The focus on licensed spectrum is one side of the debate amongst spectrum scholars, unlicensed (license-exempt) spectrum being on the other side. The bipolar world reflects two mutually exclusive options of getting spectrum: either by paying for spectrum licenses or by just entering the band. Both sides of the debate put ownership rights in the centre of the discussion and offer opposite approaches to it, a strictly capitalist and a somewhat anarchist one. This leaves a lot of grey space in between, which could allow a new approach, combining socialist and free market models with the rights to access spectrum and replacing the exclusivity rights on the spectrum bands.

Today, with spectrum license the users get the right to be protected from interference and also the right to exclude others from using that spectrum, even when they are not using it. This is the right exercised by traditional carriers, a group that comprises the majority of players in commercial spectrum markets. They have felt entitled to spectrum bands for a long time, enjoying their preferred options: long-term licenses, renewable licenses, QoS protection guarantees and a blind-eye of the regulator to the monopoly as a potential side-effect. Now the times are changing with new types of players entering the market. The technological trends in wireless communications such as densification and granular small-cell based geographic sharing are bringing out the small-scale operators willing to get a license for a short period of time to provide service according to the real-time demand. The rest of the spectrum ecosystem is occupied by the stakeholders who are database providers, equipment vendors, and user device manufacturers. For each of them, the question of incentives and sharing stimulation must be asked. This thesis argues that it is going to be about the right to access, not the right to own spectrum[4].

A spectrum resource is used by the wireless network operator to produce capacity and serve the forgotten stakeholder in the ecosystem - end user, the citizen. The spectrum footprint of a citizen can be looked at as what is the citizen using out of spectrum resource, directly (Wi-Fi, IoT wearables) and indirectly (subscription to a licensed carrier)[5]. The term spectrum footprint is a reference to the ecological footprint[6] which measures human demand on nature. The quantity of natural spectrum resource needed to support people (and economies!) is a measure of the demand, and its increase is driven by the hunger for communication and connectivity. If all of our footprints were disjoint like the regulator disjoints the spectrum users in the allocation

[4]Others have suggested that the more flexible licenses are more valuable (*See* Calabrese, M., 2003. The Future of Spectrum Policy and the FCC Spectrum Policy Task Force Report.) and that the right to protection, which is the focus of ownership rights over spectrum (discussed in later chapters) should not be given such a priority as it is currently the case (*See* Marshall, P., 2017. Three-Tier Shared Spectrum, Shared Infrastructure, and a Path to 5G. Cambridge University Press.). But this thesis argues that the ownership rights should be replaced by the rights to access spectrum, and aims at bringing the rights to access from the example of sharing economies, as succesful sharing of this century - to spectrum policy.

[5]It is also the factor that determines the price and the value of spectrum for the average user, but that is a research topic on its own.

[6]Rees, W.E., 1992. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environment and urbanization, 4(2), pp.121-130.

chart[7], we would need several universes to satisfy the demand since the universe has a constant amount of spectrum. The fact that the spectrum can be shared, has to be put to use because when we look at the necessarily disjoint ecological footprints of the countries of the world, they are the size of 1.6 planet Earths.[8] This can and has to be avoided in the case of spectrum, by making sharing a predominant way of using it.

Where is the spectrum footprint of a citizen going? The IP traffic generated by a user in 2021 will be three times larger than in 2016[9]. The majority of that traffic will be Wi-Fi and mobile, overtaking wired devices by 25% margin. There is going to be 3.5 times more networked devices than humans in 2021, setting the grounds for the Internet of Self.

The demand for spectrum is worrying service providers and the regulators that we will not have enough spectrum anymore. The regulator “creates” the supply of spectrum, and the users generate the demand. The role in the middle of using the spectrum resource to produce capacity and provide service to the users/consumers in order to satisfy the demand, is given to a service provider. Ideally, supply needs to match the demand and equilibrium is reached through the way in which the middle role is done. What can bring supply and demand into equilibrium for this degree of a connected human is sharing and the spectrum markets which emerge from business models built on sharing. This means that we have to step on each other’s toes in a spectrum footprint of the future and share the spectrum. All the time. And we need to make it modular, make it personal. We are approaching the point where an individual user will have 100 devices, produced by 10 different manufacturers, tuned for several different frequencies, determining their amount of bandwidth and the radio environment around each of these devices. We will need to share on a micro level, for everything to be seamless.

The understanding of spectrum and the ecosystem it forms has been subject to change throughout the better part of the century, ever since it has been recognised as a resource[10]. Spectrum economically defies categorisation, lying on the continuum between a public and private, a collective and commons good. Spectrum’s defiance of categorisation has absurdly led to it being treated as a generic resource. It is a resource like no other, but regulated like every other, thanks to the power of legacy and stretched analogies relating it to other resources. Its uniqueness allows it to be shared across time, space and frequency. The world of spectrum sharing cannot be reduced to dissecting the technological advancements that support dynamic sharing so that they match accordingly dissected spectrum bands, but demands a holistic approach that can only come through using the lens of the culture of sharing, *enculturating* the spectrum bands and emancipating the hertz. Segregated and alienated spectrum

[7]FCC online table of frequency allocations, `https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf`

[8]"Data Sources". Global Footprint Network. `http://data.footprintnetwork.org/`

[9]“The Zettabyte Era—Trends and Analysis,” Cisco Visual Networking Index white paper, 2017

[10]Ryan, P.S., 2003. Application of the Public-Trust Doctrine and Principles of Natural Resource Management to Electromagnetic Spectrum. Mich. Telecomm. & Tech. L. Rev., 10, p.285.

cannot support regulatory designs for multi-service, multi-band, multi-technological manner of spectrum usage.

1.1.2 *Culture of (Spectrum) Sharing*

Spectrum policy prescribes the rules aiming to shape the behaviour of the spectrum users in a spectrum band. Since culture has an immense effect on shaping the behaviour, it is natural to align the policies with the culture - and yet we have not seen that so far. This work aims at opening a dialogue between the culture of sharing and the conflicting policies of sharing by analysing policy making, questioning incentives for sharing and building the context we always needed in order to learn the lessons from the past. But, what do we mean by the culture of sharing?

The culture of sharing has the power to change the mindset of the inhabitants of spectrum ecosystem. Sharing is a type of behavior. And culture, in a broad sense, is behaviour through social learning[11]. Sharing is a cultural thing, an inheritance of civilisation. It exists universally; every communication is sharing[12]. In a network-centric world we live in, where resources are precious it is possible to imagine the future in which we will extremely share every resource on the network. To interact will mean to share. What is socialised behaviour in the spectrum sharing world? It is the stakeholders' attitudes, their policy positions, their level of engagement, their inclination towards spectrum and spectrum sharing, towards cooperation. The world of spectrum sharing discussions is a highly technical one, never using the word culture and not recognising it as the foundation of sharing. But...we live in the world where the notion of sharing is changing; from something that in many areas has not been acceptable to things are the norm.

We will show that there is a lack of norms of sharing in the design of spectrum policy. Furthermore, there is no conversation initiative by the regulator about the incentives to share. There are no educational campaigns to explain the reasoning behind the rules which would aim at building the trust amongst the spectrum sharers. The lack of norms of culture of sharing in spectrum policy implies that the regulator ignores the examples from the past coming from different sharing scenarios in society in which education about sharing has turned the involved parties into sharing advocates because the culture of sharing, as a part of socialised behaviour, is something that can be learned.

We argue in this thesis that the culture of sharing built into the frameworks through the right kind of dialogue is what would make the sharing models sustainable and build trust. This lack of trust is a product of the notion of risk in spectrum sharing world: putting network operations at risk while fearing interference or having rev-

[11]For general scope of the definitions of culture, see: `http://people.tamu.edu/~i-choudhury/culture.html`

Our own definition is provided in corresponding subsection 1.2.2; here we aimed to provide a preliminary bridge between the culture of sharing and the radio spectrum.

[12]*See* Chapter 3, Section 3.2.1

enue reduced due to sharing the resource. Technology has evolved to the point where two adjacent networks can coexist and operate in close proximity while avoiding interference. The coexistence studies and interference measurement reports are always done for the worst case scenarios assuming macrocell deployments. A sharing model promising to tackle these issues and sources of fear has recently emerged and is used as a case study within this thesis.

1.1.3 *Vision of Dynamic Spectrum Sharing*

Traditional spectrum ecosystem exists on an exclusive use licensing model and macro cell deployment. Traditional player in the market is the mobile network operator (MNO) who owns and operates macro towers. This kind of deployment provides wide coverage, serves a large number of users and enables cellular carriers to dominate the deployment sites and form oligopolies. The licenses granting the exclusive rights to use spectrum are granting two types of rights: the right to be protected from interference and the right to exclude other users from the protected spectrum even when it is not used by the license holder. This type of configuration rights, combined with the fact that these exclusive use licenses are traditionally issued on long term basis (10-15 years) and are geographically large (entire country, cities, metropolitan areas, regions) has been a significant barrier to efficient spectrum use. The bands are underutilised and spectrum is effectively bound to the few dominant players in spectrum markets.

In our perspective, the described status quo of spectrum utilisation is not the way for the future. Here we briefly outline a potential future path, through a list of principles orthogonal to the traditional concepts, aimed at putting underutilised spectrum into a cycle of optimal, efficient use. The list is our interpretation of sharing principles which dynamic spectrum sharing model should incorporate. The list of reference points is also a list of unresolved issues in contemporary spectrum policy. Each one of them has a place in the thesis, the first evidence of non-functioning spectrum sharing for each of the features is shown in extensive literature synthesis in Chapter 2 which provides the background information on spectrum domains of nature, business, technology, regulation and society.

A. Observed as a resource in *nature*, radio spectrum has unique properties that call for abandoning generic resource management approach in spectrum regulation. It is shareable, fast-cleansing, fluid, perfectly renewable natural resource which grounds sharing as a natural state of spectrum consumption.

B. Transition of spectrum resource in the domain of *technology* is coming from its 'naturality' as well, the spectrum does not exist until put to use by technology. The level of development of technologies capable of supporting dynamic spectrum sharing and operating even in the presence of interference speaks volumes against regulatory approach to managing spectrum with the interference protection as a priority over sharing it. The fast data-handling enables the technology to match the fast dynamics of spectrum and its almost instant reuse to share it more efficiently. The new dimension of spectrum, the data, can now host more real-time monitoring information, on a fine scale in time, space and frequency. The scarcity and fear of interference cannot remain invariant and ignore the technological efforts.

c. In the domain of *business*, spectrum markets of dynamic spectrum sharing need to offer more modular, smaller units of allocation (in time, frequency, space and data) which would issue spectrum rights to access it and not own it. Innovation in technologies and business models will come as a consequence of choices offered to diverse market players, traditional ones and newcomers. In a competitive spectrum environment with micro-licenses users are stimulated to innovate to preserve their place in bands. Auctioning the smaller units of spectrum allocation via frequent and automated transactions results in revenue gains in long term scale and introduces dynamic spectrum sharing as an opportunity and not the decrease in revenue gains.

d. In the domain of *regulation*, there needs to be an effort to build the trust for a sustainable spectrum sharing. Spectrum bands are underutilised, while spectrum allocation charts are showing overcrowded spectrum. The regulators need to build frameworks for sharing based on controlled interference in the bands without exclusivity rights, and encourage diverse users to participate in dynamic spectrum sharing markets, experiment with their business models. They need to build feedback mechanisms and responsive regulations capable of adapting to unpredictable new situations, use cases, technologies. This should be the basis of the machine regulation of dynamic spectrum sharing. The regulator should link the markets and the nature of the resource through elaborate incentivisation mechanism to encourage sharing and build the culture of spectrum sharing.

Throughout the thesis we contextualise the vision of dynamic spectrum sharing through a multi-domain analysis of its most advanced existing framework, the Citizens Broadband Radio Service (CBRS) sharing model, recently introduced in the US regulations by the Federal Communications Commission (FCC)[13]. It was a regulatory response to the recommendations of a policy paradigm shifting report published in 2012, President's Council of Advisors on Science and Technology (PCAST) Report[14]. The CBRS sharing model is important to the world, it is gaining momentum, and we perform its technical and governance analysis, a historical process analysis, a licensing analysis and a culture of sharing analysis. The CBRS sharing model in its intended, original form satisfies more criteria from the list we devised than any other available sharing model.

[13] Federal Communications Commission, 2012. Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band, Enabling Innovative Small Cell Use In 3.5 GHz Band NPRM & Order. Available at: `https://www.fcc.gov/document/enabling-innovative-small-cell-use-35-ghz-band-nprm-order`

[14] President's Council of Advisors on Science and Technology (PCAST) Report Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth, 2012.
`https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf`

1.2 THE THESIS

The main research focus is on the notion of culture as the missing ingredient of the regulatory force field. The question of why spectrum sharing is not being implemented despite the existing efforts in regulations, technical developments and the academic work is important. This work offers one reason why we do not have a sustainable dynamic spectrum sharing model yet and the way to overcome it. It deals with the problem of creating the norms of culture of sharing in spectrum sharing policy by performing a multi-domain analysis on a case study of CBRS spectrum sharing model. Specifically, through the lens of culture of sharing we are looking at: (1) the policy positions of stakeholders as future hosts of culture of sharing, (2) spectrum licensing as an incentive tool which can motivate sharing, and (3) modalities of regulation that interact with each other to shape the norms.

The thesis hacks into spectrum by going deep into the genesis of one representative of a spectrum sharing model, learning from both the destination and the journey. Once inside the system, we offer a way to implant sharing into the mindsets using the ubiquitous tool of culture. The intensity with which we share spectrum today will not be sufficient to satisfy the growing traffic demand unless the regulators put in place proper motivations to share. The language of incentives needs to become a part of the regulatory language, and the frameworks need to be built on the foundations of a culture of sharing. The approach so far has been addressing technology or policy issues around spectrum sharing in isolation. The modalities through which technology and policy aspects come together are the incentives: spectrum users need to be clear about the potential of a business model by following regulatory rules on technical specifications and specific policies. Unless users are motivated to share, the culture of sharing is unlikely to evolve which in turn is unlikely to lead to successful implementations of spectrum sharing. Therefore, the premises we operated upon are:

- Sharing is not as widely adopted as we would hope by now.
- There is something to be learned by taking a wider perspective on sharing – namely looking at the 'culture' of sharing in all its depth.
- We believe that the sharing frameworks need to be designed to include this wider perspective.
- The methodology and research practice of spectrum sharing has to be aware of the context, policy, and the rules.

1.2.1 *Research Aim and the Objectives*

The overall aim of this research is to answer the question: **How to build the culture of spectrum sharing?** The main rationale is that the policy shapes the rules for spectrum sharing, the culture has an enormous effect on shaping the sharing behaviour and it is natural to align policies and the norms of culture of sharing for spectrum sharing systems but we have not seen that yet. With this goal in mind, we perform multi-domain policy analyses of the CBRS spectrum sharing model. The research objectives are:

- **Objective 1** is to examine and critically review the literature in order to determine the initial conditions for culture of spectrum sharing and provide the wide context of spectrum by telling its multifaceted story.
- **Objective 2** is to identify connections between culture of sharing and dynamic spectrum sharing and to propose a framework for embedding sharing economy ideas to spectrum policy towards its flexible/fluid management.
- **Objective 3** is to suggest a range of methods for forward-looking interdisciplinary approach to spectrum sharing.
- **Objective 4** is to investigate in depth the CBRS model in order to: (1) determine initial conditions for dynamic spectrum sharing, (2) map out the CBRS ecosystem and its stakeholders, (3) evaluate the effectiveness of incentivisation tool (geographic licensing in CBRS), and (4) find modalities of regulation that can shape the norms of culture of sharing.
- **Objective 5** is to provide a roadmap and actionable recommendations for enabling dynamic spectrum sharing in the future.

1.2.2 *Key Definitions and Terms*

1.2.2.1 *Radio Spectrum*

As discussed in Chapter 2, Subsec. 2.1.1, we define spectrum as *the entirety of the degrees of freedom between entities interacting in wireless communication.*

We elaborate in corresponding section on such choice of the definition. The definition is generalised because there is no absolute truth when it comes to spectrum definitions, which breaks the epistemology for that question. Depending on which working definition of spectrum is selected for the analysis, a different sets of conclusions arise, which are also orthogonal. We find this generalistic definition useful, as it ensures that no dimension of spectrum space is left out.

1.2.2.2 *Dynamic Spectrum Sharing*

As announced in the introduction of Chapter 2 based on our vision of dynamic spectrum sharing in Subsec. 1.1.3 we define it as *the freedom of use of radio spectrum at any given time, place and frequency that does not degrade the performance of other users in the spectrum space neighborhood.*

We note that for a general sense of what spectrum sharing is, we follow the taxonomy of Peha[15] in adopting a definition of spectrum sharing for this work. One of the reasons is that spectrum sharing seems to be an umbrella term as well (e.g., horizontal, vertical, con-current, overlay, underlay, spatial, temporal, spectral, dynamic, static, licensed shared, unlicensed shared), depending on engineering, legal, economic or policy perspective taken. As the thesis takes an interdisciplinary perspective on spectrum, we find the classification provided by Peha the most helpful for this task. He classifies sharing based on the main features a system can manifest: (1) cooperation (when users negotiate among themselves and/or agree on common protocol, etiquette) and (2) coexistence (when technology enables sharing). He further classifies it in (3) sharing among equals (e.g. unlicensed bands) and (4) hierarchical sharing among the primary and secondary users (PU, SU) (e.g. mainly licensed bands). As CBRS sharing is our case study, and the PCAST report proposed a hybrid model of dynamic spectrum sharing with PU governmental incumbents and SU consisting of licensed and unlicensed-alike classes of users - this three tier model we see as something that asks for both, coexistence and cooperation, sharing among equals but also hierarchical. This is the perspective we bring to CBRS multi-domain analyses in the thesis.

1.2.2.3 *Spectrum Utilisation Efficiency*

As discussed in Chapter 2, Section 2.2 and in Subsec. 2.1.2, unlike instantaneous, static utilisation efficiency where the spectrum in use is quantified at a particular time instant, we are interested in a dynamic, overall utilisation efficiency: all spectrum, all the time.

In dynamic spectrum sharing perspective, a piece of spectrum should be in use constantly. Spectrum utilisation efficiency in such context means allowing spectrum to be more fully utilised by enabling its shared access use. Therefore we define spectrum sharing utilisation efficiency *as a sum of static utilisation efficiency values over a range of time instances, so that spectrum sharing efficiency is a measure of how much spectrum is in actual use across time, frequency and space.*

Similarly to how spectrum occupancy measurements are comprised in marginal values of all electrospace coordinates, we are also interested in marginal utilisation efficiency (a cumulative one), where these values are summed over a range of coordinates, but with a goal. The goal for efficiency is to be high and slowly varying, i.e. maximising the mean value and minimising the variance of spectrum occupancy measurement. The metrics of spectrum efficiency are a topic on its own and not of this thesis, but the point is that we suggest that spectrum utilisation efficiency should be defined by desire to achieve high average usage with small variations in usage.

[15] Peha, J.M., 2009. Sharing spectrum through spectrum policy reform and cognitive radio. Proceedings of the IEEE, 97(4), pp.708-719.

1.2.2.4 *The Norms and the Culture of Sharing*

As discussed in Chapter 2, Section 2.5, *the norms are collective sets of beliefs held by people engaged in a collective activity that shape their behaviours.* Culture of sharing is a norm that is necessarily linked to a community and the resource being shared. To emerge it needs two conditions: (1) positive perception in a society about the sharing behaviour and (2) its wide adoption. In the context of spectrum policy, *culture of spectrum sharing is a socialised behaviour of the regulator and the stakeholders' community: their attitudes towards sharing, their inclination towards cooperation, collaboration and their attitudes towards innovation.*

1.2.2.5 *Spectrum Sharing Economy*

As discussed in Chapter 3, spectrum sharing economy is a model of the multi-domain perspective of spectrum consumption which uses the *shareable, underutilised resource* in its domain of *nature*, by relying on *advanced networks and feedback mechanisms* in its domain of *technology*, that builds *innovative markets* in its domain of *business* based on *the right to access* the resource enabled by responsive, dynamic rules in its domain of *regulation* which manifests through a community that hosts the *culture of sharing* in its domain of *society*.

1.2.3 *Assumptions and Justifications*

This thesis is built on a set of assumptions, proofs of which constitute material for separate theses and treatises. We list the assumptions here, with brief considerations of each.

1. *Sharing spectrum will lead to abundance*. This assumption has grounds on all sides of the debates: the FCC concedes it in Faulhaber's and Farber's report[16] and pundits like Calabrese insist on it for decades[17]: abundance is already there, but the administration is keeping it locked ("Spectrum is abundant, if only citizens could use it", writes Calabrese).

2. *Sharing means more efficient use*. This is a premise known for a while in the cognitive radio and dynamic spectrum access community, one driving the research in the field[18] and it has been proven in the early days by Peha[19,20]. There is inherent

[16] David J. Farber and Gerald R. Faulhaber, Spectrum Management: Property Rights, Markets, and the Commons, ET Docket No. 02-135, July 18, 2002, at 19 (comment before F.C.C.)

[17] Calabrese, M., The End of Spectrum 'Scarcity': Building on the TV Bands Database to Access Unused Public Airwaves.

[18] Ji, Z. and Liu, K.R., 2007. Cognitive radios for dynamic spectrum access-dynamic spectrum sharing: A game theoretical overview. IEEE Communications Magazine, 45(5), pp.88-94.

[19] Salgado, H., Sirbu, M. and Peha, J., 1995, June. Spectrum sharing through dynamic channel assignment for open access to personal communications services. In Proceedings IEEE International Conference on Communications ICC'95 (Vol. 1, pp. 417-422). IEEE.

[20] Peha, J.M., 1997. Developing equipment and services for shared spectrum: is it a good gamble?. International Engineering Consortium Annual Review of Communications, 50, pp.955-958.

idleness in exclusively assigned spectrum which could be filled by the growing demand of other users, if allowed to.

3. *A responsive regulator follows the ecosystem with a culture of sharing*. The recent practice in sharing economies shows that once everyone is accustomed to their role in a sharing economy, the regulator makes dynamical efforts to keep the economy running[21]. When sharing prevails, the regulator responds[22].

4. *Balance of modalities is a regulatory principle*. In one of the early applications[23] of Lessig's Pathetic Dot theory (PDT)[24], we find the following quotes: (1) on PDT "By demonstrating the functionality, any imbalances on regulation can be found as well. Finding the imbalances will allow you to correct any policy or procedural creating the imbalances." and (2) on Lessig's work: "His model purports to demonstrate an imbalance in the constraints on regulation of the Internet. From this imbalance, he proposes some possible directions for policy development of the code for the further development of the Internet to bring balance back to the code."

5. *There is a reinforcement between knowledge of the resource and its better utilisation*. The relationship between improved policy and knowledge about the nature of the resource is a reinforcing one. Not only does the increase in knowledge lead to policy improvements[25], but the opposite holds as well[26]. When Oran Young[27] and others inspired by him[28] speak of any resource management analysis, they recognise the nature of the resource as a fundamental part of the regime dynamics and insist on including it.

   The solutions arise from the nature, the problems arise from something else: that is one of the claims in Haas's work on oil[29] which reinforces another important point we raise in Chapter 2 and throughout the thesis: the one of scarcity scare used as a political and economical tool of control.

   Saying that institutions should build their existence on the nature of the resource

[21] Cohen, M. and Sundararajan, A., 2015. Self-regulation and innovation in the peer-to-peer sharing economy. U. Chi. L. Rev. Dialogue, 82, p.116.

[22] Rauch, D.E. and Schleicher, D., 2015. Like Uber, but for local government law: the future of local regulation of the sharing economy. Ohio St. LJ, 76, p.901.

[23] Basham, M.J., Stader, D.L. and Bishop, H.N., 2009. How "pathetic" is your hiring process? An application of the Lessig "pathetic dot" model to educational hiring practices. Community College Journal of Research and Practice, 33(3-4), pp.363-385.

[24] Lessig , L. (1999). Code and other laws of cyberspace . Cambridge , MA : Basic Books .

[25] Moxnes, E., 2000. Not only the tragedy of the commons: misperceptions of feedback and policies for sustainable development. System Dynamics Review: The Journal of the System Dynamics Society, 16(4), pp.325-348.

[26] Holt, S.J. and Talbot, L.M., 1978. New principles for the conservation of wild living resources. Wildlife Monographs, (59), pp.3-33.

[27] Young, O.R., 1982. Resource regimes: Natural resources and social institutions (Vol. 7). Univ of California Press.

[28] Miles, E.L., 1992. Future challenges in ocean management: towards integrated national ocean policy. Ocean management in global change, pp.595-620.

[29] Haas, P.M., 2002. Constructing environmental conflicts from resource scarcity. Global Environmental Politics, 2(1), pp.1-11.

is not a new idea: the seminal work of Pfeffer and Salancik[30] revolves around it but the spectrum world successfully avoided indulging in it completely. When Newell and Wheeler[31] say "the nature of a resource, and who has access to it, defines possibilities for justice, redistribution and change", we agree.

6. *A regulatory objective change works in practice.* At different stages of resource exploitation, different priorities are set for the regulation of it. At first, it is anyone's game, but as the time progresses, the competition needs to be regulated, and the resource must be efficiently utilised. An example on a mass scale is China's energy consumption[32] with its major success in increasing energy efficiency after a long period of ignoring efficiency as a metric and stimulating growth by subsidising energy consumption[33]. The result came from a diversified campaign in all segments of the energy market. However, it is noticed how the change did not transform the economic structure, as it was not informed by the market. Another massive policy change example from China is that of land consolidation (the land equivalent of spectrum relocation) fitting into the large reforms of the industry, agriculture and housing, the Three Old Reform[34] liberating new fertile land from the administratively scarce allocation.
   The knowledge of the nature of relations remains instrumental for true change. Iyer[35] writes:
   "If we merely try to improve efficiency in administration and to find institutional or legal answers to political and attitudinal problems, we may indeed have some (limited) successes, and they will be very welcome, but the major concerns will remain unresolved. Water governance and water politics cannot be transformed without transforming water policy (which reflects our understanding of and relation to the resource), and the transformation of water policy can only be brought about by water-wisdom."

1.2.4 *Contributions*

1.2.4.1 *Overview*

The culture of sharing, whether it is sharing our emotions and thoughts, or sharing information and knowledge, or sharing any kind of resource in today's connected world always involves the process of re-thinking the world towards progress and getting

[30]Pfeffer, J. and Salancik, G.R., 2003. The external control of organizations: A resource dependence perspective. Stanford University Press. First printed in 1978.

[31]Newell, P. and Wheeler, J. eds., 2006. Rights, resources and the politics of accountability (Vol. 3). Zed Books.

[32]Yang, M., Hu, Z. and Yuan, J., 2016. The recent history and successes of China's energy efficiency policy. Wiley Interdisciplinary Reviews: Energy and Environment, 5(6), pp.715-730.

[33]Hong, L., Liang, D. and Di, W., 2013. Economic and environmental gains of China's fossil energy subsidies reform: A rebound effect case study with EIMO model. Energy Policy, 54, pp.335-342.

[34]Yan, J., Xia, F. and Bao, H.X., 2015. Strategic planning framework for land consolidation in China: A top-level design based on SWOT analysis. Habitat International, 48, pp.46-54.

[35]Iyer, R.R., 2008. Water Governance, Politics, Policy. Governance of Water: Institutional Alternatives and Political Economy, p.18.

things to become acceptable in society. In the contemporary policy around spectrum sharing, the amount of effort spent on enabling technology for different systems to coexist in spectrum space and designing a set of technical rules to follow in order to share efficiently is way bigger than the effort to actually get users to be willing to share or make sharing an acceptable form of operating wireless networks. Without the enculturation of spectrum bands and without thinking what really motivates the users to share, it becomes difficult to effectively translate the regulatory framework and sharing rules into the real world implementations, which is the current situation with spectrum sharing models. This thesis aims to inspire a multilogue about the culture of sharing in the spectrum context. Interested in the ways culture of sharing and language of incentives can help improve spectrum usage in the bands below 6GHz, we bring the concepts of culture of sharing from the society issues to spectrum sharing world, linking them with the current policies on spectrum sharing.

With this in mind, a unique methodology is devised. The methods used here have either not been used before or not been used in this manner. Research design combines historiographic research method, modelling, simulation, optimisation, geospatial analysis, pathetic dot theory, and a conceptual framework devised from sharing economies. From the social science research toolbox, we utilise the content analysis, case study, historiographic context, timeline/chronology, approach to sources and critical interpretation. A historiographic method element of context which is pragmatic by nature is extended with the philosophical concept of context. It is further augmented with the tool of dialogue, as a scientific form of laying out the counter arguments[36]. The prologue of each chapter is a dialogue, with imaginary characters depicting the notion of conflict in policy; dialogue seeks conflict but also seeks culture. We use this form to exemplify the *deeply coded language* in spectrum space (fear of interference, need to be protected, diversity of users coexisting without the guard bands) and to *enstrange* the multilogue of the regulator and the stakeholders. Behind the scenes of CBRS there is a little known subculture of the stakeholders' community that gives the voice to shaping the policy. We examined this community by learning from the philosophical notions of estrangement, alienation, defamiliarisation[37], political technology[38] and the concept of context as a communicative action[39].

Modelling, simulation, optimisation and geospatial analysis and synthesis are used to explore the effectiveness of CBRS licensing scheme and propose solutions. The pathetic dot theory of Lawrence Lessig[40] gives us a way to approach the modalities of CBRS regulation holistically. We examine the balance of the four forces acting on the CBRS band which are law, market, norms and architecture modalities of regulation.

[36]Hofstader, D.R., Gdel, Escher, Bach: An Eternal Golden Braid. Basic Books. 1979.

[37]Boym, S., 2005. Poetics and politics of estrangement: Victor Shklovsky and Hannah Arendt. Poetics Today, 26(4), pp.581-611.

[38]Foucault, M., 1988. Technologies of the self. In Technologies of the self: A seminar with Michel Foucault.

[39]Wittgenstein, L., In Anscombe, G. E. M., & In Wright, G. H. (1972). On certainty; Wittgenstein, L., Tractatus Logico-Philosophicus.

[40]Lessig, L., 2000. Code and Other Laws of Cyberspace.

The conceptual framework gives us a chance to observe the problem, interpret the results and devise a new philosophy for spectrum sharing, SPECTRUMISM.

The contributions to spectrum sharing policy design outlined here can be mapped to chapters as follows.

1.2.4.2 *Chapter-by-Chapter*

Chapter 2 is a background chapter. The contribution of it is reflected in the approach:

- providing a thorough overview of physics, engineering, regulation, business and social norms of spectrum consumption, coming from the perspective of spectrum policy and the idea of sharing;

Chapter 3 is devoted to linking spectrum sharing and sharing economies. Opening this link leads to two contributions:

- devising a conceptual framework inspired by sharing economies capable of encompassing the complexities of dynamic spectrum sharing;
- detecting the culture of sharing as an essential enabler of sharing (economies) that is lacking in spectrum sharing;

Chapter 4 deals with the research design. Due to the nature of our problem and its generality, its contribution has a wider applicability.

- devising an interdisciplinary methodology for spectrum sharing policy research led by the conceptual framework;

Chapter 5 is a coherent historical and structural introduction to CBRS. It brings a contribution of its own:

- analysis of primary and secondary sources to determine in detail the initial conditions at the time of CBRS inception;

Chapter 6 hosts the content analysis of the CBRS proceeding. Content analysis is an uncommon method in engineering theses, so this chapter has contributions in terms of methodology and analysis results alike:

- applying a rigorous content analysis design for spectrum sharing;
- showing the key differences between the CBRS and traditional bands as seen by the stakeholders;
- converting unstructured expressions of policy positions in CBRS rulemaking proceeding into data re-usable for other analyses;

Chapter 7 focuses on the licensing issue in CBRS. We diagnose the problem, propose a solution and document the related events in the rulemaking proceeding all at the same time. The contributions come in those three aspects:

- showing that different operators occupying the same channel in adjacent census tracts make these channels unusable in urban conditions;
- proposing a continuum of solutions based on census tract aggregation and discussing them in terms of balance with respect to geography and social welfare metrics;
- submitting comments to the regulator and offering a discussion on the development of the CBRS rulemaking situation;

Chapter 8 is the chapter which concludes the case study of CBRS rulemaking by investigating the interconnections between the rules and the modalities of regulation. Here we find the answer to the central question of our research and arrive to other contributions in showing that:

- the culture of sharing should stem from the nature of the spectrum resource - either directly, or through the mechanisms of market force[41];
- the CBRS sharing model is in the state of perpetual imbalance, mainly because of the weak component of norms in the ecosystem[42].
- our conceptual framework generalises Lessig's pathetic dot theory and makes it applicable to the case of spectrum sharing and it goes beyond Lessig framework to propose that modalities do not just act on the regulatee but interact with each other;

Chapter 9 combines the conclusions of the thesis and a manifesto of our new philosophy of spectrum sharing economy, spectrumism. Hence, it has two contributions in:

- defining the directions of future research emanating from this work;
- showing that the principles of spectrumism enable successful spectrum sharing in the future through building the culture of sharing;
- providing actionable recommendations for the vision of dynamic spectrum sharing educated by the findings, a future that asks for a chance;

The results of the case study are readily generalised from the particular case of CBRS to dynamic spectrum sharing model, as the findings were universal.

1.3 CONTENTS

The thesis is divided into four parts dealing with: the introduction of radio spectrum conundrum, description of research design, the case study and the solution, respectively. Another component of the thesis is the radio drama in eight dialogues, *Eight Bits*

[41] This is the culture building mechanism, as a recipe for the missing link forging.
[42] This is the proof of the missing link.

of Frank and Laura. The chapters begin with a quote from the corresponding dialogue and a link to its audio recording[43].

1.3.1 *Part I: Introduction to the Problem*

Part I of the thesis is structured to introduce the problem and provide the reader with background information needed to comprehend the context. In an orthodox approach, it would be brief as possible, but the multifaceted problem encountered asked for a multifaceted interpretation.

In Chapter 1 we give an idea of why should we care about spectrum, spectrum sharing and the culture of spectrum sharing and proceed by reinforcing it in the chapters to come.

In Chapter 2 spectrum is observed as a physical, technical, social, economic and political construct, the reflections of which we find in the domains of its nature, business, technology, regulations and society. In this chapter we face the perception of spectrum as a scarce resource, the first challenge for culture of sharing. It offers a wide context of spectrum, defines concepts and tells the tale of a radio century. From its very beginning it clearly makes it a multi-faceted story and shows the holes left by all the players while attempting to pursue their diverse goals without coordination. It shows the existence and emergence of the major ingredients of a (regulated) market, but also the lack of a genuine, inherent culture.

1.3.2 *Part II: Methodology*

Part II establishes connections between culture of sharing and dynamic spectrum sharing and offers a unique interdisciplinary toolbox of methods.

It starts with introducing sharing economies in Chapter 3 with the objective to devise a conceptual framework for spectrum sharing. There we investigate what are the enablers of sharing, how do they look like in the case of spectrum sharing, what are the origins of culture of sharing and its identity, and what part does the culture of sharing play in the framework.

That is the beginning of the methodology approach which continues with a medley of methods in Chapter 4, where we ask: How to approach the question of culture of sharing in a problem that is a mix of engineering, policy, economics and social aspects? In this chapter, we look for methods capable of tackling the facets of this challenge and make a move from multidisciplinary to interdisciplinary research design.

[43] The dialogues written for the thesis have been enacted and recorded. The audio files are available for listening at: `https://www.youtube.com/playlist?list=PLM7vMjV_-KFTLr0zPbyzWyJEShotRxYrn`

I wish to acknowledge the artists **Jessica Foley** (as Laura Lustig) and **Aidan O'Donovan** (as Franklin Charles Cambridge and Anon Black) for lending their voices to the characters.

1.3.3 *Part III: CBRS Behind the Scenes*

Part III is the case study where we investigate in depth the CBRS framework as the best existing example of a sharing model. This is where we encounter a range of exciting problems in past (Chapter 5), present (Chapter 6) and future (Chapter 7) and tackle it with social science and engineering research methods simultaneously.

In Chapter 5 we start the case study by first investigating how spectrum policy came to the state it is in today, i.e. how did we come to the CBRS spectrum sharing? We examine the processes by which decisions are made in spectrum sharing rulemaking and get acquainted with the diverse community (stakeholders) involved.

This community starts interacting with the rulemaker and the rulemaking process in Chapter 6. To determine how is CBRS spectrum sharing different from approaches in traditional (sharing and non-sharing) bands, we examine the issues they have. Are they led by traditional or progressive values? How do they envision the new spectrum sharing band? What motivates the users to share spectrum?

We then investigate how can an effective licensing model be an incentive to share spectrum in Chapter 7. To determine how to design a licensing scheme for geographic spectrum sharing, we put the effectiveness of the model proposed by the regulator under scrutiny. Are social welfare criteria taken into account as an enabler of culture of sharing? What happened with the licensing framework under the pressure of the community? What could have been an alternative?

1.3.4 *Part IV: Balance of the Forces*

Part IV seeks balance of the four forces (modalities of regulation) acting on CBRS by using Lessig's pathetic dot theory in Chapter 8. We take a step further in Chapter 9 to bring our own balance in spectrum policy and propose a new philosophy for spectrum sharing economy, SPECTRUMISM.

In Chapter 8 we ask are there patterns of incentivised behavior (detectable in the rules of spectrum sharing frameworks), that we could call architectural or juridical, or normative or market-imposed? We question the balance of the CBRS rules - did it exist, does it exist, and will it exist? To determine how to regulate the sharing behaviour in order to build the culture of sharing, we are interested in how the rules are interconnected and how do they guide the evolution of the ecosystem. In particular, we look for the effects on the culture of spectrum sharing.

Chapter 9 allows us to reflect on the CBRS case study and envision a new spectrum sharing school. To propose actionable recommendations, we are guided by the vision of future spectrum sharing policy which we illustrate through a futuristic scenario. How would it be different, what the emphasis would be on? We go back to the core question of the thesis and make suggestions that converge to building of culture of spectrum sharing. With this chapter we conclude the dissertation and describe the infancy of a new area identifying future research directions.

The Coded Language

"And yet your laws were made for 'dumb' receivers.
They are the legacy of long long time ago."

Audio version at: `https://www.youtube.com/watch?v=Re7ITM9cyRA`

2 THE RADIO SPECTRUM

To answer the main research question of how to build the culture of sharing as an enabler of sustainable dynamic spectrum sharing systems, this chapter aims to set the scope of the thesis by introducing the main concepts, reviewing the literature and synthesising information we consider important to build the context of spectrum policy developments and understand what comes later. *Dynamic spectrum sharing, for this work, is the freedom of use of radio spectrum at any given time, place and frequency that does not degrade the performance of other users in the spectrum space neighbourhood.* The goal is to fill the holes in spectrum sharing ecosystem caused by conservative borders. We analyse and synthesise the initial conditions for dynamic spectrum sharing found in the works of the regulator, spectrum scholars, technological developments, and the existing social norms. This chapter also aims to bridge the gap between regulatory designs and the academic work by offering a wider perspective, the one of a spectrum (sharing) ecosystem. Therefore, the background information provided throughout the following sections is the initial step in building the framework for viewing the connections between culture of sharing and dynamic spectrum sharing, which is then fully developed in the next chapter.

Spectrum behind the scenes is the compelling story of telecommunications because of the intense interplay between politics, technology, economics and being the social issue per se, as spectrum is so much used in everyday communication. In this chapter, we will look at the wealth of the resource in the domains of nature, business, technology, regulation and society. Section 2.1 tells the story of spectrum in its domain of *nature*: its questionable existence, proclaimed scarcity and the attached fear of interference, the means of spectrum management and the divided opinions on its future. Section 2.2 tells the story of the economic resource in the domain of *business*, where spectrum markets are. Section 2.3 tells the story of sharing the resource in its domain of *technology*, where the mechanical miners of the abundant resource are. Section 2.4 is focused on the domain of *regulation* and offers an insight into the structure behind spectrum sharing. In Section 2.5 we discuss current norms in spectrum allocation and usage. Section 2.6 wraps up the story of spectrum multitudes which ends the Part I of the thesis.

2.1 NATURE

To answer the question "What is spectrum?" in this section, we take a physical perspective on spectrum resource and its unique nature. Our main points are: (1) spectrum is shareable, natural, recyclable, multi-dimensional unique resource which does not exist until put to use by technology and, (2) sharing is a natural state of spectrum. As a complex resource, spectrum asks for policies that are uniquely tailored to its nature. We unpack the layers of this argument through the discussion of existence and uniqueness of spectrum, its finiteness, multidimensionality, the proclaimed scarcity and the fear of interference.

2.1.1 *What Is Spectrum?*

The debates on this question are based on imperfect definitions, as spectrum is a complex resource hard to define in a mathematically precise way. For example, a discussion and an analysis of five definitions of spectrum is provided in the work of de Vries and Westling[1], showing that in each definition there is at least one attribute which cannot be found in other definitions under certain conditions. This tells us that this question is far from epistemological and instead seems to ask for a wide perspective on spectrum that does not bound the term but is precise enough for understanding the scope of the problems. In our view, spectrum is a multi-dimensional generalisation of the ether, it is a name we give to a communication channel. We define spectrum as *the entirety of the degrees of freedom between entities interacting in wireless communication.*

In other words, the answer to the question of what is spectrum lies in the context of its usage and management. And the answer changed throughout the last 150 years. To observe the evolution of the term spectrum to this day, we will borrow the concepts of existence and uniqueness from mathematical analysis. The goal is not to prove rigorously either of the concepts but to show the evolution of thinking about spectrum in those two terms.

2.1.1.1 *Existence and Uniqueness*

The greatest trick the regulator ever pulled was convincing us the radio spectrum exists[2]. Before we had any use for it, we called it the *ether*. An elusive matter, filling the space and embedding the world in it, ether was the necessary medium for wave propagation for the 19th century scientists. This wave was the light, and only at the end of the century came the lower wavelengths, radio waves. Ether became a convenient misnomer for the medium between the transmitter and a receiver, the apocryphal

[1] De Vries, Jean Pierre and Westling, Jeffrey, Not a Scarce Natural Resource: Alternatives to Spectrum-Think (October 2, 2017). Available at SSRN: `https://ssrn.com/abstract=2943502` or `http://dx.doi.org/10.2139/ssrn.2943502`

[2] Singer, B., Ottman, J., MacQuarrie, C. and MacDonnell, M., 1995. *Usual suspects*. USA/Germany: MGM Home Entertainment.

wireless cat[3]. Even when the existence of ether was finally disproved and the idea of it abandoned, the term remained in use as a palpable wireless communication channel. So, in the early days of radio regulation, the broadcast era, the rights to use the spectrum were referred to as the rights to ether[4]. As soon as few more users started using the ether at different frequencies, a new term entered the discourse. The adopters of the physics term spectrum, which describes the continuum of electromagnetic wave frequencies, were fast to divide the ether into bands, both in use and regulation[5].

Spectrum does not exist until put to use by technology. According to Mueller[6],

> There is no "spectrum," then; there are only transmitters and receivers of electromagnetic energy. Electromagnetic energy can be generated by a variety of sources: a radio transmitter, the sun, the galaxies, neon lights, automobile ignition systems. We measure this energy by frequency and arrange the frequencies in consecutive order on a map we call "the electromagnetic spectrum." The resulting classificatory schema makes it easier for us to understand the behavior of electromagnetic transmitters and receivers. But the spectrum, the arrangement, is our own creation. No Platonic entity or "invisible resource" (Harvey Levin, The Invisible Resource: Use and Regulation of the Radio Spectrum (Baltimore: The Johns Hopkins Press, 1971) exists independently of a specific transmitter at a specific location. Conversely, no knowledge of a transmission can be gained without setting up a specific receiver in a specific location.

This opinion is echoed by other authors[7,8,9] suggesting that spectrum is our own creation, a legal and engineering entity controlled and managed by governments. Borrowing another mathematical term, we could provisionally call this an intuitionist school of spectrum thought (everything in mathematics is a result of our creation, does not really exist), avoiding the notion of nihilism (nothing exists or has any meaning). Just like the intuitionists of mathematics have their contribution and their merit, but do

[3] An apocryphal joke quote, often attributed to Einstein is an explanation of wireless telegraph. “Well, if you had a very long cat, reaching from New York to Albany, and you trod on its tail in New York, it would throw out a wail in Albany. That’s telegraphy; and wireless is precisely the same thing without the cat.” `https://quoteinvestigator.com/2012/02/24/telegraph-cat/`

[4] The Radio Act of 1927 uses the term ether (and wavelengths) and so does then Secretary of Commerce Hoover in his public addresses and correspondence. See: Bensman, M.R., 2000. The beginning of broadcast regulation in the twentieth century. McFarland.

[5] The Communications Act of 1934, after revisions by the FCC now mentions radio spectrum in the definition. Original text used the term “frequencies”. Radio Acts of 1912 and 1927 used the term wavelengths.

The Radio Act of 1912, Pub. L. No. 62-264, 37 Stat. 302 (1912)

The Radio Act of 1927, Pub. L. No. 69-632, 44 Stat. 1162, 1166 (1927)

Communications Act of 1934, Pub. L. No. 73-416, 48 Stat. 1064

[6] Mueller, M., 1982. Property rights in radio communication: the key to the reform of telecommunications regulation. Cato Institute

[7] Huber, P.W., 1997. Law and disorder in cyberspace: abolish the FCC and let common law rule the telecosm. New York: Oxford University Press.

[8] Carter, K.R., 2009. Unlicensed to kill: a brief history of the Part 15 rules. info, 11(5), pp.8-18.

[9] Chaduc, J.M., Pogorel G., 2010. The radio spectrum: managing a strategic resource (Vol. 9). John Wiley & Sons.

not change the usefulness and meaningfulness of constructive mathematics, so do the spectrum intuitionists.

The spectrum construct provides a way for analysis, management and regulation, as well as for the analogies, good and bad. It is easier to imagine something we can grasp, the "thing" needs to exist for us to appreciate it. We have an existence fetish, grounded in a materialistic view of the world. While regulating the "thing" has many problems as discussed throughout, the question of does the "thing" exist or not is not one of them. However, the doubts make the basis for discussing the uniqueness of spectrum as existence of other resource is never questioned.

In our opinion, the analogies in spectrum theory and practice come from the misunderstanding of spectrum's uniqueness. The FCC's governance framework was inherited from the regulation of railways, the language and the mentality is borrowed from the land management. Territorial association, combined with the lure of spectrum's invisibility and occult qualities[10], gave birth to the idea that it needs to be protected and preserved. Spectrum became a thing and a natural one[11]. The notion of natural resource is a double edged sword. On one hand, it recognizes the role and some defining aspects of electromagnetic spectrum but on the other hand, it leaves space for regulators to try and apply their generic natural resource control kit on it.

The basic categorisation of a resource in micro-economic theory is defined by two axes: *excludability* (or exclusiveness, deals with property rights to use and access) and *rivalry* (deals with simultaneous use and depletion). Spectrum resource lies on a *continuum*[12], i.e. can lie anywhere in the plane depending on by which spectrum management regime it is governed. In other words, spectrum is sometimes excludable and sometimes it is non-excludable, depending on which regulatory scheme it follows and how it is governed. The argument of this work that what places radio spectrum on a continuum between the two axes is the choice of spectrum management is expanded in the work of Doyle et al.[13] to allow spectrum to move on a continuum based on the technology used. We see the reflection of our definition of spectrum in which the resource is necessarily coupled with the technology in that work. The point we aim to make though is that one way in which spectrum is a unique resource is that it shares spectrum of properties with other resources and can be seen as a public or a private good, a club or a commons good, therefore in a way it defies categorisation. It is hard to put a finger on airwaves, categorise spectrum clearly or claim it is a fully measurable commodity.

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[10]Keel, M., 2015. To Radio Waves, Are We The Ghosts? WAI 776: the Māori Claim to the Electromagnetic Spectrum at the Waitangi Tribunal.

[11]For extensive evidence of spectrum being acknowledged as a natural resource in regulation worldwide, see Ryan, P.S., 2005. Treating the wireless spectrum as a natural resource, Environmental Law Reporter, Vol. 35, p. 10620

[12]Freyens, B., 2007. The Economics of Spectrum Management: A Review Paper commissioned by the Australian Communication and Media Authority (ACMA), pp40

[13]Doyle, L., McMenamy, J. and Forde, T.K., 2012, October. Regulating for carrier aggregation & getting spectrum management right for the longer term. In Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on (pp. 10-20). IEEE.

Another attribute by which spectrum is a unique resource which does not depend on the choice of spectrum management regime or the technology used, is the *naturality* of spectrum. Some authors claim that spectrum is not always a natural resource, while other authors and the regulators on international scene claim that it is a natural resource. And that is the debate based on imperfect definitions. De Vries finds that wherever spectrum is a resource by definition, it is not a natural one, and wherever it could be (under certain assumptions, it is never clearly a natural resource) it is not a scarce one[14]. This explicit inconsistency is an indicator of the ambiguity and in support of the strong dependence of analytical results on working definitions. Our generalistic definition is useful, as it ensures that no dimension of spectrum space is left out. Ryan, on the other hand, advocates for applying principles of law and protection for natural resources to spectrum based on the evidence that even regulators say that spectrum is natural[15]. This is an example of a stretched analogy, i.e. ignores the nuances of spectrum. While we do agree that spectrum is a natural resource, we do not agree that the solutions to all spectrum problems would be to read the definition and treat spectrum in regulation and management as all other natural resources. Unlike most of natural resources, spectrum is also as Benkler writes[16], a non-depletable, perfectly renewable resource. In our view as well, spectrum is a fast-cleansing recyclable resource: once it is used by someone it is instantaneosly renewable for another use without degrading quality. In wireless communication realm, the necessary frequency resource lies in the range 3 Hz-3 THz. The undeniable finiteness of spectrum coming from quantum physicists is not the finiteness of the resource we experience: the bounds we hit are caused by propagation and technology. Our radio technology will most probably never reach the splitting hair precision on Planck length scale that physicists mark as the border of spectrum.

Another unique property of spectrum is its *dimensionality* and it is inseparable from the alleged scarcity of spectrum. If spectrum is finite, why do we refer to spectrum electrospace [17,18]constantly looking at ways to extend its dimensionality? Spectrum is finite in the range that can be used for communication. But within that range spectrum is theoretically infinite, because it can be used again once it is used by someone else, the resource is non-exhaustable. And yet, riding on the wave of propagation and technology limitations as well as not recognising (ignoring) the process of spectrum resource distribution, production and consumption, scarcity was introduced straight

[14]De Vries, Jean Pierre and Westling, Jeffrey, Not a Scarce Natural Resource: Alternatives to Spectrum-Think (October 2, 2017). Available at SSRN: `https://ssrn.com/abstract=2943502`or `http://dx.doi.org/10.2139/ssrn.2943502`

[15]Ryan, Patrick S., Treating the Wireless Spectrum as a Natural Resource. Environmental Law Reporter, Vol. 35, p. 10620, September 2005. Available at SSRN: `https://ssrn.com/abstract=793526`

[16]Benkler, Y., 2004. Sharing nicely: On shareable goods and the emergence of sharing as a modality of economic production. Yale Law Journal, pp.273-358.

[17]Matheson, R., 2003, March. The electrospace model as a frequency management tool. In Int. Symposium On Advanced Radio Technologies (pp. 126-132).

[18]Weiss, M.B., Krishnamurthy, P. and Gomez, M.M., 2017, March. How can polycentric governance of spectrum work?. In 2017 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN) (pp. 1-10). IEEE.

from the early days of radio regulation[19]. As the control, management and distribution of the rights to use spectrum grew in complexity, the term spectrum grew in dimensionality, overloaded with the aspects of space, time, frequency, transmission power,... Whether the spectrum is occupied in terms of frequency, or in terms of space or at certain times, or there is a limitation on transmission power to operate the frequencies, scarcity spans multiple dimensions. Starting from three dimensions of time, area and spectrum in De Vany's[20] work, the spectrum dimensionality expanded to seven dimensions of the electrospace in the work of Matheson[21], which are: location (latitude, longitude and elevation), angle of arrival (azimuth and elevation angles), frequency, time and possibly others. This shows how from at first having only frequency axis attached to it, the spectrum diverged from the original physics term, as the axes of time, power, space, technology were added gradually to its nature.

Regulation was done in this way, putting patches and stitches, as the technology was dictating new usage of spectrum. The first regulators were bounded by "what is?" instead of with "what will be?". If Hedy Lamarr were to show Hoover frequency hopping and spread spectrum technology two decades earlier, he would be very much in doubt of alleged spectrum scarcity. And yet if we, as time-travellers ourselves could tell him about 5G, he would be certain of that being magic: "Any sufficiently advanced technology is indistinguishable from magic."[22]

This today-tomorrow metaphor aptly gives the timescale of the development of regulatory thought. While the failure to grasp tomorrow has hindered Hoover's ideas of governance, that he chose over markets[23], the inability to grasp today has dominated the judicial side of spectrum regulation. As Coase writes in his essay "The Federal Communications Commission" (1959),

> "Mr. William Howard Taft, who was Chief Justice of the Supreme Court during the critical formative period of the broadcasting industry, is reported to have said: "I have always dodged this radio question. I have refused to grant writs and have told the other justices that I hope to avoid passing on this subject as long as possible." Pressed to explain why, he answered:
>
> "...interpreting the law on this subject is something like trying to interpret the law of the occult. It seems like dealing with something supernatural. I want to put it off as long as possible in the hope that it becomes more understandable before the court passes on the questions involved."

[19]Rossini, M.J., 1985. The Spectrum Scarcity Doctrine: A Constitutional Anachronism. Sw. LJ, 39, p.827.

[20]DeVany, A.S., Eckert, R.D., Meyers, C.J. and O'Hara, D.J., 1968. A property system for market allocation of the electromagnetic spectrum: A legal-economic-engineering study. Stan. L. Rev., 21, p.1499.

[21]Matheson, R., 2003, March. The electrospace model as a frequency management tool. In Int. Symposium On Advanced Radio Technologies (pp. 126-132).

[22]Arthur C. Clarke's third law, published in an aptly named essay: "Hazards of Prophecy: The Failure of Imagination", in Profiles of the Future (1962).

[23]Huber, P.W., 1997. Law and disorder in cyberspace: abolish the FCC and let common law rule the telecosm. New York: Oxford University Press.

and Supreme Court has never considered a case about radio, while Taft was the Chief Justice. This significantly derailed progress of radio regulation in a country which is based on case law. More than a decade later, another judge of the Supreme Court, showed little understanding of later today[24]. As Huber writes [25], quoting Justice Frankfurter:

> "There is a fixed natural limitation upon the number of stations that can operate without interfering with one another."; "A comprehensive federal licensing scheme was thus needed to prevent "etheric bedlam"." It has been said that if all else fails, immortality can always be assured by spectacular error. This was how Frankfurter assured his.

Later that day, the non-time traveller Hedy Lamarr showed just how wrong this was. While it is true that spread spectrum technology does not eliminate interference completely (it will probably always exist especially in dynamic spectrum sharing environments), the new technologies do increase utilisation of available spectrum[26]. This in turn asks for moving away from the described legal foundations for regulating spectrum and introducing more flexible ones. The ability of technology to increase usage of available spectrum has not yet been recognised in regulations, which are still mainly based on command and control approach to spectrum management (all government spectrum and a lot of commercial spectrum (e.g. broadcasting, satellite) is command and control).

In summary, regulation did not follow technology capable of sharing. As Peha notes, regulation of spectrum, when it comes to sharing, has to evolve with technology, but it does not[27]. Marcus[28] gives a first-hand experience:

> "As I got more involved with existing policies at FCC it became clear that spectrum regulations are generally written to reflect the technologies available at the time and reasonably anticipated in the future. So it is inevitable that the underlying assumptions of spectrum regulations will become dated as new technology is introduced and new services become of interest. As these regulations become dated they unintentionally discourage investment in alternative technologies that are explicitly or implicitly prohibited or put at a disadvantage in the applicable regulations."

Even the simplest solutions were ignored[29]:

[24]Here we return to the today-tomorrow metaphor from the previous paragraph, as it aptly gives the timescale of the development of regulatory thought.

[25]Huber, P.W., 1997. Law and disorder in cyberspace: abolish the FCC and let common law rule the telecosm. New York: Oxford University Press.

[26]Jackson, C., Pickholtz, R. and Hatfield, D., 2006. Spread spectrum is good-but it does not obsolete NBC v. US. Fed. Comm. LJ, 58, p.245.

[27]Peha, J.M., 2005. Approaches to spectrum sharing. IEEE Communications magazine, 43(2), pp.10-12.

[28]Michael J. Marcus, (2009) "Wi-Fi and Bluetooth: the path from Carter and Reagan-era faith in deregulation to widespread products impacting our world", info, Vol. 11 Issue: 5, pp.19-35

[29]Carter D, Garcia AN, Pearah DA, Buck ST, Dutcher DO, Kumar DE, Rodriguez AN. Spread spectrum: Regulation in light of changing technologies. Massachusetts Institute of Technology and Harvard Law School1998. 1998.

"The other problem with the FM allocation plan was that it ignored the potential of directional antennas. This serves as another good example of a regulatory scheme that ignores technological solutions to spectrum scarcity."

2.1.2 *The Scarce Resource?*

While previous discussion questioned the existence and uniqueness of spectrum, here we discuss its size, the wealth (goods' space) as well as spectrum welfare (our perspective on the wealth of spectrum, which we argue is more suitable for contemporary policy).

As spanning vectors for the goods' space, *rivalry* (ability to use spectrum simultaneously) and *excludability* (possibility to preclude another use) are closely tied with the twinned scare of *scarcity* and *interference*[30]. Degree of rivalry depends on the scarcity. Degree of excludability depends on the need to be protected from harmful interference. In the early days of regulation, spectrum was non-rival (very few people were transmitting, there was no interference) and non-excludable (it was difficult to exclude experimental uses, there was no need to be licensed to conduct an experiment) public good. But from the very beginning of the wireless era, a wealth in the ether was recognised, and the need to collar and tag the wireless cat was expressed.

There are two types of players who were able to recognise the wealth and protect its preciousness: those early to the game and those powerful enough not to care when they enter. Marconi was the typical representative of the former, and the state of the latter. The common point of their histories is the tragedy of Titanic in 1912. Marconi's radios formed a Marconi-company-certified-eqiupment-members-only club, preventing distress calls from the Titanic to reach the rescuers. This was a wake up call, drawing attention to the chaos in the airwaves. And now, enter the state. Radio Act of 1912 was created and followed by the Radio Act of 1927.

The wealth the two players were after was not the same (and it is not the same wealth we have in mind either). When we talk of spectrum wealth, we do not have a mental image of hoarded bands or the assets worth the weight of all base stations in gold. We have in mind a *spectrum welfare*, the state of availability where no one is precluded or cut short from their needs. In a spectrum welfare, any shortage is merely an indicator of poor management. Marconi was after the equipment and frequency monopoly, the state was after the power to control who will get on the airwaves and how under the appeal of "public good". While the former is easily monetisable, the latter is a political issue more than anything else.

This is the atmosphere in which the *command and control* spectrum management regime was born. Both Radio Acts (of 1912 and of 1927) micromanaged the airwaves by imposing hierarchy in priority to access (government users should get bandwidths they prefer), separating types of transmissions into use classes - in a nutshell, deciding

[30] Krattenmaker, T.G. and Powe Jr, L.A., 1994. Regulating broadcast programming. American Enterprise Institute.

who will get the license, what kind of service to provide and how. Spectrum license was free but limited to three years with the Act of 1927, which also precluded private ownership of spectrum. The state owns all of it.

And according to the state, there was not much of it. Scarcity became the prevailing doctrine. This statement is corroborated in many different texts. According to Nekovee, the scarcity of spectrum resource is "perceived"[31], and a "feeling"[32]. According to Ryan it is presented as "a statement of fact ("The radio spectrum has to be considered as a scarce medium") rather than an argument that requires supporting evidence"[33]. It is the regulator who was pushing forward the scarcity agenda continuously[34] even though the voices about the artificial nature of this scarcity were present for decades[35,36,37,38,39,40]. The physical component of spectrum scarcity is an extrapolation from the fact that the spectrum resource is finite[41] and it accounts for a smaller part of the overall issue. It is suggested that the major part of scarcity is the consequence of poor management and allocation, the "administrative scarcity"[42] as the main obstacle[43] that cannot be solved with new and improved technology.

After a century of the scarcity narrative, the regulators: (1) acknowledged the role of advanced technology in alleviating physical issues[44] and (2) admitted the dominant role of administrative scarcity in spectrum resource[45] in the Spectrum Policy Task Force report, while using the term artificial scarcity (scarcity caused by wrong distribution and barriers to access). In addition, going through the report, one could argue that it converted the previously omnipresent scarcity of command and control approach into means of persuasion. In this report, the scarcity is coupled with the transaction costs of moving spectrum from inefficient to more efficient use. With such

[31] Glover, B. and Nekovee, M., 2007, April. Dynamic spectrum: Going full circle. In New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on (pp. 283-287). IEEE.

[32] Nekovee, M., 2008, May. Impact of cognitive radio on future management of spectrum. In Cognitive Radio Oriented Wireless Networks and Communications, 2008. CrownCom 2008. 3rd International Conference on (pp. 1-6). IEEE.

[33] Ryan, P.S., 2005. Questioning the scarcity of the spectrum: the structure of a spectrum revolution.

[34] Red Lion Broadcasting Co. v. FCC, FCC v. League of Women Voters

[35] I. De Sola Pool, Technologies Of Freedom 151 (1983); Fowler & Brenner, A Marketplace Approach to Broadcasting Regulation, 60 TEX. L. REv. 207, 221-22 (1982).

[36] E. Diamond, N. Sandler & M. Mueller, Telecommunications In Crisis: The First Amendment, Technology, And Deregulation 9-12 (1983)

[37] Bazelon,The First Amendment and the "New Media"--New Directions in Regulating Telecommunications, 31 FED. COM. L.J. 201, 202-03 (1979);

[38] Fowler, Forward, 32 CATH. U.L. REV. 523-28 (1983);

[39] Goldberg & Couzens, "Peculiar Characteristics": An Analysis of the First Amendment Implications of Broadcast Regulation, 31 FED. COM. L.J. 1, 29 (1978);

[40] Powe, "Or of the [Broadcast] Press," 55 TEX. L. REV. 39, 57 (1976).

[41] Herter, C.A., 1985. The electromagnetic spectrum: A critical natural resource. Natural Resources Journal, 25(3), pp.651-663.

[42] Bernthal, J.B., Brown, T.X., Hatfield, D.N., Sicker, D.C., Tenhula, P.A. and Weiser, P.J., 2007, April. Trends and precedents favoring a regulatory embrace of smart radio technologies. In New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on (pp. 633-648). IEEE.

[43] Werbach, K., 2002. The New Wireless Paradigm. Spectrum Series Working Paper, 6.

[44] NTIA Telecom 2000 : charting the course for a new century / [National Telecommunications and Information Administration], 1988.

[45] The Federal Communications Commission, "Spectrum policy task force," Nov. 2002. (Rep. ET Docket no. 02-135)

a regulatory discourse, scarcity is monetised. But it is not only monetised, it is also relativised: the report implies that it is possible to avoid scarcity depending on how much money one is ready to invest. Despite being characterised as artificial, this coupling of scarcity and transaction costs of moving from more to less efficient use of spectrum re-established the place of the term scarcity in regulations.

As spectrum management is guided by the need to protect users from interference, the particular reduced vocabulary that the regulators and stakeholders use when discussing spectrum, the *coded language*[46] of spectrum space, is filled with fear and loathing of interference. The players in spectrum markets have a problem with interference[47]. The definition of "harmful interference"[48] is in every regulatory document about spectrum and yet, one cannot deny that the question of what constitutes harmful interference changes with the technology. The classical understanding of interference and scarcity is anachronous in the modern technological frame. As Johnston writes[49]:

> "Despite technological advances, personal property proponents hold strong and fast to the concepts of interference and scarcity."

The way we see scarcity and interference is no different from the term "twin myths" used by Krattenmaker and Powe in their book "Regulating Broadcast Programming" while describing the role of interference and scarcity in the state making a firm grip on the spectrum[50]. That's how the two twins merged, with Judge Frankfurter's decision in the NBC v. USA case, as Winer writes[51]:

> "By combining the notions of scarcity and interference, instead of considering them as distinct and separate rationales for different kinds of regulation, Justice Frankfurter inappropriately made the leap from necessary but limited technical regulation to a comprehensive scheme for government control of broadcasting."

In early days of regulations scarcity and interference were dominating the narrative, but they do not fit the narrative of the new, evolved technology and yet they still exist in the same world with it. The definitions were set for the times when we used more

[46] Radio Acts of 1912 and 1927, Communications Act of 1934 and the Telecommunications Act of 1996, are the four main regulatory documents of the US radio regulation and at the same time, primers of radio regulation coded language. For an examplary text containing the illustrative terms (guard bands, harmful interference, protection) see:`http://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title47-section1454&num=0&edition=prelim`

Also refer to the introductory dialogue of this chapter, for our take on the coded language.

[47] Littman, L. and Revare, B., 2014. New times, new methods: Upgrading spectrum enforcement. Silicon Flatirons Center.

[48] "Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the ITU] Radio Regulations.", `https://www.law.cornell.edu/cfr/text/47/2.1`

[49] Johnston J. The Paradise of the Commons of Privileged Private Property: What Direction Should the FCC Take on Spectrum Regulation. J. High Tech. L.. 2004;4:173.

[50] Krattenmaker, T.G. and Powe Jr, L.A., 1994. Regulating broadcast programming. American Enterprise Institute.

[51] Winer LH. The Signal Cable Sends-Part I: Why Can't Cable Be More Like Broadcasting. Md. L. Rev.. 1986;46:212.

primitive technology and for frequencies where harmful interfering would occur from the neighboring systems but within simple propagation challenges of ionosphere and troposphere[52]. There was a shift in technology and information theory after which the understanding of interference changed and the channel became usable as never before[53,54,55]. Today's technology unlocked other frequencies with significantly different propagation properties; the effects of interference are often comparable to those of nature (e.g., multipath fading) which we don't find in regulatory rules. In literature, the solution for the problem of interference[56] and the solution proposed for scarcity[57], are in fact the same - the literal deus ex machina, a less occult spirit we will discuss in Section 2.3. Technology is the point, whatever it is called: cognitive radios, smart radios, new radios. And again, the twinnned scare[58] is a single entity in the traumatic world of spectrum decision making: our fear of interference is actually the fear of not having a place to hide from it in a claustrophobic, scarce spectrum.

We would expect to see a scarce resource used all the time, but it is scarce because it is not used efficiently. Many reportings on spectrum measurements have documented around 10% overall utilisation of spectrum, performed in specific bands, countries and regions.[59,60,61,62,63,64,65]. The reports that measure spectrum occupancy are often reduced to a single numerical result showing spectrum underutilisation (e.g., the cited reports point to only ~10% spectrum used in total, in all bands) which collapses spatial, temporal and frequency dimensions into a single point, by averaging. Obviously infor-

[52]Marcus, M.J., 2008. Harmful interference: the definitional challenge. IEEE Wireless Communications, 15(3).

[53]Katti, S., Gollakota, S. and Katabi, D., 2007. Embracing wireless interference: Analog network coding. ACM SIGCOMM Computer Communication Review, 37(4), pp.397-408.

[54]Shannon, C.E., 1961. Two-way communication channels. In Proceedings of the Fourth Berkeley Symposium on Mathematical Statistics and Probability, Volume 1: Contributions to the Theory of Statistics. The Regents of the University of California.

[55]Cover, T. and Gamal, A.E., 1979. Capacity theorems for the relay channel. IEEE Transactions on information theory, 25(5), pp.572-584.

[56]Roberson, D.A. and Webb, W., 2007. Interference and Our Wireless Future. Wireless Communications: The Future, pp.155-166.

[57]Gilder, G., 2000. Telecosm: How infinite bandwidth will revolutionize our world. Simon and Schuster.

[58]For more arguments on how scarcity and interference are not related, see: Benjamin, S.M., 2002. The Logic of Scarcity: Idle Spectrum as a First Amendment Violation. Duke LJ, 52, p.1.

[59]Spectrum occupancy measurement reports have been performed by Shared Spectrum Company and can be found at: `http://www.sharedspectrum.com/papers/spectrum-reports/`

[60]McHenry, MA, PA Tenhula, and D McCloskey. "Chicago spectrum occupancy measurements & analysis and a long-term studies proposal" (2006).

[61]Islam, MH, CL Koh, SW Oh, and Xianming Qing. "Spectrum survey in Singapore: Occupancy measurements and analyses." Cognitive Radio (2008): 7-13.

[62]Harrold, Timothy, Rafael Cepeda, and Mark Beach. "Long-term measurements of spectrum occupancy characteristics." 2011 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN) (May 2011): 83-89.

[63]S. W. Ellingson, "Spectral occupancy at VHF: implications for frequency-agile cognitive radios", IEEE Vehicular Technology Conference, vol. 62, no. 2, pp. 1379, September 2005

[64]Vaclav Valenta, Roman Marsalek, Genevi Baudoin, Martine Villegas, Martha Suarez, et al.. Surveyon Spectrum Utilization in Europe: Measurements, Analyses and Observations. 5th InternationalICST Conference on Cognitive Radio Oriented Wireless Networks and Communications, Jun 2010,Cannes, France. pp.ISBN: 978-963-9799-94-3, 2010.

[65]M. Mehdawi, "Spectrum occupancy survey in Hull-UK for cognitive radio applications: measurement & analysis", International Journal of Scientific & Technology Research, vol. 2, no. 4, pp. 231-236, April 2013.

mation is lost in that process. Meaningful statistics are those from particular bands, at particular times, in particular places. The literature is still lacking comprehensive measurements of spectrum occupancy which needs to be a part of a regulatory strategy. As an item on a policy agenda, it would represent one way of addressing underutilisation in search for ways to use spectrum more efficiently.

2.1.3 *Takeaway points*

In conclusion, spectrum is unique not because it is not really a resource (does not exist) but because it is treated in regulation as a resource for economic reasons. One could argue that every resource is unique, but the thing with spectrum is that it is treated as a tabletop game resource: sliced, measured and sold like a tangible commodity to the highest bidder, as we discuss in the next section.

Spectrum is a useful construct with unique properties. As a construct, spectrum is a multidimensional generalisation of ether. As a unique resource, spectrum asks for less generalisation and comparison with a range of other resources that it shares some of the properties with. In other words, it seeks a management approach uniquely tailored for all of its properties. The management problems are grounded in lack of understanding for the uniqueness of spectrum and the ways in which technology exploits uniqueness and gets spectrum moving.

The imposed discourse is to fear scarcity and interference only. No one ever suggested a fear of inefficient use or lack of diverse users coexisting in spectrum space. Seldom is anyone afraid of poor equipment and "dumb" receivers or lack of dynamic policies, able to adapt to technological drivers. We have been taught to fear the consequences, not the causes. Scarcity is an artificial construct of the regulator, which can be alleviated through better policies. The fear of interference imposed the management style in which protection is the priority in spectrum use, and not sharing. And yet, sharing is the natural state of spectrum: the spectrum forms a communication channel shared by at least one transmitter and one receiver.

The legacy approach to managing spectrum has made it effectively underutilised while at the same time there is no place for new uses in allocation chart. This kind of paradox also left the spectrum bands without mechanisms of continuous monitoring of actual spectrum use.

At this point, the reader should already be aware of the spectrum abundance and should by trait of human nature, start asking how to get a piece of the wealth. Is it like cryptocurrencies, where is the nearest market?

2.2 BUSINESS

In this section, we take economics perspective on spectrum resource. Our main point is that the change of spectrum allocation method was not caused by the change in technology either. Instead, the auctioning off the licenses to use spectrum (moving away from administrative licensing under the command and control approach, like lotteries, hearings and "beauty contests") was motivated by economics. Our main goal is to address the issue of allocation efficiency when it comes to spectrum markets and their implementations currently, i.e. spectrum auctions. We discuss the methods of assignment and allocation in place in regulations, how the discussions around this problem evolved over the years. We also review the spectrum debates to give a fresher perspective from this point in time with the general goal in mind of examining current conditions for moving towards dynamic spectrum sharing systems which can be sustainable from markets perspective.

2.2.1 *Efficiency*

The efficiency of spectrum use is not defined concisely by the regulators, as they recognise three types of efficiency: spectrum efficiency (output/spectrum impacted), technical efficiency (output/cost of all inputs) and economic efficiency (value of output/cost of all inputs)[66]. Some uses of spectrum (e.g. broadcast television) are more spectrally and technically efficient than others (e.g. mobile telephony) depending on the number of users they cover by using less transmitters, but less economically efficient, as some users may consider a short phone call to have more value than a full hour of television. Spectral and technical efficiency creates an economic efficiency, because it is a matter of the cost of each service or technology weighed against the value created by each. There may be no market for technically and spectrally highly efficient technologies which create expensive services. In this section, we are looking at economic efficiency as the FCC focuses on spectrum efficiency but promotes economic efficiency by giving flexibility to the licensees by for example, allowing secondary markets[67].

In dynamic spectrum sharing perspective, a piece of spectrum should be in use constantly. Spectrum utilisation efficiency in such context means allowing spectrum to be more fully utilised by enabling its shared access use. Therefore we define spectrum utilisation efficiency *as an integral of spectrum sharing efficiency over time, where spectrum sharing efficiency is a measure of how much spectrum is in actual use across time, frequency and space.* Utilisation efficiency in this work is defined for a place, time, and frequency band as the measure of spectrum in use for these electrospace coordinates. More generally, we are interested in the marginal utilisation efficiency (a cumulative one), where these values are summed over a range of coordinates, but with a goal. The goal for efficiency is to be high and slowly varying, i.e. maximising the mean value and minimising the variance spectrum occupancy measurement. The metrics of

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[66] Federal Communications Commission, Spectrum Policy Task Force 2002. Report of the Spectrum Efficiency Working Group. (Nov. 2002). Available at: `https://transition.fcc.gov/sptf/files/SEWGFinalReport_1.pdf`

[67] Ibid.

As recognised in the report, the FCC considers the shortage of spectrum to be a problem of spectrum access. Traditional policies and traditional technologies balkanise and box the spectrum while new techniques for access and sharing spectrum can create quantum increases in achievable utilisation. This was done with the commercial introduction of trunking technology and then cellular-based systems.

spectrum efficiency are a topic on its own and not of this thesis, but the point is that we suggest that spectrum utilisation efficiency should be defined by desire to achieve high average usage with small variations in usage.

From an economics perspective, there is allocative and investment efficiency that could be placed under the term of economic efficiency for spectrum resource. It is assumed that auctioning off spectrum is efficient allocation. Cellular operators bid for the exclusive use licenses in auctions and the FCC issues the license to the highest-value bidder. These licenses are the property rights for spectrum, exclusive use, guaranteed QoS provisions and interference protection, long-term and infinitely renewable. The assumption here is that the winning bidders will indeed put the spectrum to its best value, but there is no guarantee for that. For that to be true, the value of spectrum would need to be determined prior to an auction, and the question of spectrum value is a complex one, as we stated before. The winning bidder in that auction simply offered the most money for spectrum. What actually happens is that monopoly is created out of spectrum resource - the auctions happen rarely, every 10-15 years, and that is few generations of telecommunications in technological sense. So, the winners do not have an incentive to put spectrum to its best use and innovate technologies and their deployments more. In this perspective, efficiency is coupled with scarcity: if spectrum becomes a scarce resource, then it pays off to invest in using it more efficiently. Otherwise, if the resource is not scarce, there is no need to have the markets, as they incur costs to organise and manage. As stated by the authors of Radical Markets, the superiority of property rights is supported by most economists today because property rights increase investment efficiency[68]. But the misunderstanding of Coase theorem is reflected in the assumption that bargaining can eliminate monopoly:

> "Vickrey (1961) showed that a type of common ownership—one in which the government auctioned use or possessory rights to people—could lead to allocative efficiency. His work helped initiate the literature that became known as "mechanism design" (Hurwicz & Reiter 2006). Two other economists writing in the literature—Myerson & Satterthwaite (1983)—finally identified the monopoly problem in a mathematically rigorous fashion, proving that private property was inconsistent with allocative efficiency. This work, along with Vickrey's, stimulated a search for efficient market mechanisms, and led to the widespread adoption of auctions for administrative property,

[68]Posner, E.A. and Weyl, E.G., 2018. Radical markets: Uprooting capitalism and democracy for a just society. Princeton University Press.

"This can be seen in the three major textbooks (in: Steven Shavell, Foundations of Economic Analysis of Law 11–19 (Harvard University Press, 2004); Robert Cooter & Thomas Ulen, Law & Economics 76–80 (Pearson, 6th ed., 2012); Richard A. Posner, Economic Analysis of Law 40–42 (Aspen Publishers, 9th ed., 2014).) on law and economics. All three books give great weight to the investment problem as a justification for private property: if private property did not exist, then people would not invest in improving property since they could not be sure that they would profit from the returns on the investment."

"The textbooks give only passing attention to the monopoly problem. While they acknowledge that holdout problems, and related problems of strategic behavior, can interfere with the transfer of property, they largely consider these problems as confined to cases where the use of property affects many people, as in the case of factory pollution."

> especially the radio spectrum (Milgrom 2004 - Putting Auction Theory to Work. Cambridge: Cambridge University Press.)"

The rivalry and excludability of spectrum resource make the economic struggle for the resource centered around the concepts of: scarcity, interference and ownership. This story is necessarily about the regulation; spectrum resource is "owned" and managed by the government. Our main proposal is that the existing spectrum markets and sporadic secondary markets should be reformed to align with the policy goal objective of efficient spectrum use while managing the demand.

2.2.2 *The Markets*

Let us break the bad news right away: there are no *efficient* spectrum markets. In this section, we discuss the past and the present of spectrum allocation and assignment practices.

As noted, spectrum is an engineering and legal construct and such nature of it had to have consequences in its management. This was the command and control approach to policies whose legacy is still embedded in spectrum policy of today (all government spectrum and a lot of commercial spectrum (e.g. broadcasting, satellite)), The idea is concisely captured by Huber[69]:

> "The first century or so of law in the telecosm was given to the top-down managers. Herbert Hoover gave it to them. As a Republican, he liked free markets and private property. But as an engineer, he wanted things nice and tidy. Markets aren't tidy. Hoover had to choose. He chose wrong."

The consequences of Hoover's Radio Act of 1927 and the choice he made spanned the next 70 years. Not much change in spectrum rights allocation and assignment happened until the 90s. This does not mean that fresh ideas did not exist all along. The most famous idea was that of a Nobel laureate Ronald Coase, the foundation stone of spectrum economics. It was laid out in his two influential publications[70,71]: The Federal Communications Commission (1959) in which he set the ground of what later became known as Coase theory, and further elaborated in The Problem of Social Cost (1960). It was a foundation stone for a building nobody wanted to build. Only 30 years after his proposal was the Commission and the community ready to go with it and reform the command and control policies. This was the atmosphere in which the *market-based approach* to spectrum management was born.

Coase introduced the *property rights model* to spectrum policy, criticising the FCC's approach of precluded private ownership of spectrum, legalised by the Radio Act of 1927. The property rights model is the central model in capitalist economy and its

[69] Huber, P.W., 1997. Law and disorder in cyberspace: abolish the FCC and let common law rule the telecosm. New York: Oxford University Press.

[70] Coase, R.H., 2013. The Federal Communications Commission. The Journal of Law and Economics, 56(4), pp.879-915

[71] Coase, R.H., 2013. The Problem of Social Cost. The journal of Law and Economics, 56(4), pp.837-877.

introduction for spectrum meant that the license for spectrum use became a property right. This license was to be auctioned to the highest bidder, under the assumption that the willingness to bid will reflect the incentive for efficient use of spectrum. In other words, this was a deconstruct of legacy thinking in spectrum allocation, introducing auctions as the most effective allocation method. Coase theory is based on the concept of bargaining[72] or negotiation and on addressing the harmful interference as an externality (a cost that affects neighboring spectrum user who is experiencing interference from the holder of spectrum license). The externalities he calls a problem of "social cost", the greatest market failure known to the economists[73]. Coasian economy is a school of thought[74] which perhaps[75] has diverged from the original path. Many authors write about misunderstanding of Coasian school of economic thought[76], including the Coase himself[77,78]. After all this time Coase theory is still criticised by members of other schools of thought, notably Demsetz[79]. A big part of misunderstanding and disagreements is caused by the imprecision of the term externality[80].

Prior to auctioning, the licenses were issued via lotteries and comparative hearing methods, i.e., beauty contests, where the regulator would select the most appropriate license holder, judging by how well they serve "public interest". Coase proposed this theory as an alternative to government regulation, arguing that any scarce resource is in fact limited in amount and calls for more people to use it, but does not call for more governmental regulation. Advocating for price mechanism as allocation method based on the market, he asserted the government should only define the initial rights to use spectrum and leave it to the markets[81]. Two takeaways from Coase: (1) he assumes scarcity of frequencies is real (because he believes that virtually any important resource is scarce) and (2) the most effective way to allocate is pricing mechanism. And that gave us a new way to distribute the wealth, i.e., to obtain rights to use spectrum resource.

The market-based approach was adopted once the FCC showed the ability to imagine the markets[82]. First auctions were implemented in the 90s and reinforced the pol-

[72]Coase theorem: Regardless of initial distribution of property rights, bargaining will lead to most efficient use of resources if the transaction costs are low.

[73]Both terms, the externalities and the market failure were first introduced in economics in 1956 by Francis Bator in his PhD thesis at MIT: Capital, Growth and Welfare: Essays in the Theory of Allocation.

[74]Butler, M.R. and Garnett, R.F., 2003. Teaching the Coase Theorem: are we getting it right?. Atlantic Economic Journal, 31(2), pp.133-145.

[75]Medema, S.G., 2014. Neither misunderstood nor ignored: the early reception of Coase's wider challenge to the analysis of externalities. History of economic ideas, 22(1), pp.111-132.

[76]Medema, S.G., 1994. The myth of two Coases: What Coase is really saying. Journal of Economic Issues, 28(1), pp.208-217.

[77]Coase, R.H., 1988. The Nature of the Firm: Origin. Journal of Law, Economics, & Organization, 4(1), pp.3-17.

[78]Coase, R.H., 1992. The institutional structure of production. The American Economic Review, 82(4), pp.713-719.

[79]Demsetz, H., 2003. Ownership and the externality problem. Property rights: Cooperation, conflict, and law, 282.

[80]Haddock, D.D., 2003. Irrelevant Internalities, Irrelevant Externalities, and Irrelevant Anxieties.

[81]The idea that allocation mechanism based on the market should replace government regulation is grounded in well known Adam Smith theory.

[82]Hazlett, T.W., 2017. The Political Spectrum: The Tumultuous Liberation of Wireless Technology, from Herbert Hoover to the Smartphone. Yale University Press.

icy of strict separation and protection of spectrum users in space, frequency and time. Soon enough, the auctioned licenses became long-term (up to 20 years), renewable and exclusive. Exclusivity meant the right to be protected from interference, but also the right to exclude other uses of your piece of spectrum land. The proposal of transmission exclusivity rights by Faulhaber and Farber[83] reflects the association of spectrum with the land. So, spectrum became a private property, excludable and rival. The level at which one use of spectrum precludes other uses is described via opportunity costs, which are usually societal. Other type of spectrum cost is the transaction cost, already appearing in our treatise bundled with scarcity.

Auction theory is a complex mechanism of resource allocation. The authority on auction design, Paul Milgrom[84], whose research in auction theory has guided the regulator and the economists alike, led the team who designed the first FCC auction in 1994. Regulatory goals for an auction were high economic efficiency and generating revenue under the conditions of reasonable speed and simplicity. Simultaneous multiple-round (SMR) bidding auction became the "FCC auction" beating the alternatives: sequential auctions and other types of simultaneous auctions, "silent auctions"[85]. More complex auctions designs, such as combinatorial clock auction were considered, but the risk of lower revenue, inefficiency and complex implementation, kept the regulator from adopting them. At least the FCC did not say it was an academic pastime[86]. McMillan[87,88] gives a first hand perspective on the early auction days of the FCC, explaining the apparatus and the motivations in depth. Beginning in New Zealand, Australia and US auctions continued to blossom as what was termed the most efficient way of assigning spectrum rights and were becoming adopted in other countries[89].

The auctions undoubtedly indicate the value of spectrum resource through setting the prices for spectrum license. The question of price of spectrum and the more complex question of the value of spectrum represent a thesis topic on their own and as such will not be discussed in depth here. Brief insight into just how much is spectrum valuable for the society is best captured in recent study by Connolly et al. [90] covering the 1997-2015 time interval, which along with other statistical indicators points out the interesting fact that the number of winning "small" bidders in the auctions is not as small as usually assumed (almost 50%!). Another source of economic analysis of

[83] G. R. Faulhaber and D. Farber, Spectrum Management: Property Rights, Markets, and the Commons, In re Issues Related to the Commission's Spectrum Policies, ET Docket No. 02-135, at 2 (F.C.C. filed July 15, 2002).

[84] Milgrom, P.R., 2004. Putting auction theory to work. Cambridge University Press.

[85] McAfee, R.P., McMillan, J. and Wilkie, S., 2010. The greatest auction in history. Better living through economics, pp.168-184.

[86] Smythe, Dallas W. (1952) "Facing Facts about the Broadcast Business," University of Chicago Law Review: Vol. 20 : Iss. 1 , Article 4. Available at: `https://chicagounbound.uchicago.edu/uclrev/vol20/iss1/4`

[87] McMillan, J., 1994. Selling spectrum rights. The Journal of Economic Perspectives, 8(3), pp.145-162.

[88] McAfee, R.P., McMillan, J. and Wilkie, S., 2010. The greatest auction in history. Better living through economics, pp.168-184.

[89] For more comprehensive treatise of auction models with exemplary case of auction model in the UK, see Klemperer, P., 2004. Auctions: theory and practice.

[90] Connolly, M.P., Sa, N., Zaman, A., Roark, C. and Trivedi, A., 2017. The Evolution of US Spectrum Values Over Time.

indicative numbers in these types of markets[91] are the Dotecon reports which cover data for more than 30 countries[92].

However, the auctions are far from being the only mechanism to allocate spectrum: (1) administrative incentive pricing (AIP)[93] as implemented by Ofcom[94] in the UK, and (2) the whole range of other pricing methods and license fees proposed over seven decades, which were rejected[95]. One such proposal coming from de Sola Pool in 1984 is interesting; it identified that what is lacking is legal and economic structure to create incentives to use existing technologies in ways that would provide broadcasting in abundance. The "squandering of spectrum" as he puts it, could be stopped if unregulated free publishing-like market is set[96]. This idea also reflects the treatise of a scarcity and interference in a bundle (to indicate inefficient allocation method) which we noted before. Scarcity is not what it seems, claims de Sola Pool and goes on with the argument:

> Another option that was totally overlooked in the early radio debates was for spectrum to be allocated, like paper, ink, and printing presses, by market mechanisms rather than by licensing. A common assumption of either a licensing or common carrier scheme is that the resource being allocated is either monopolized or at least very scarce. The assumption of distribution by a free market is, on the contrary, that scarcity is only moderate and thus manageable by the device of private property and its sale or lease. The policy makers in the 1920s and 1930s, wrongly it now appears, did not believe spectrum was abundant enough to be handled in that way.[97]

It goes to show the depth of coded language in spectrum space, with scarcity and interference inherited in the bundle of legalities which we call spectrum rights of use. Having attributes of legal, political, economic and technical constructs as inherent part of regulatory discourse, the problematic bundle has been a hindering element for the wealth of spectrum. If the coded language conundrum of scarcity and interference has shown its depth, the mystery of externalities and transaction costs is either its length or width. Neither externalities nor transaction costs were precisely defined in economics nor in law[98,99]. It is highly unlikely that engineers have solved this epistemological issue on their own in the realm of electromagnetic spectrum. A much more probable scenario is spectrum management running on the same ambiguities as the rest of economy leaving space for misunderstanding and manipulation.

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[91] For general and up to date information on FCC auctions, see:`https://www.fcc.gov/auctions-summary`

[92] Available at: `http://www.dotecon.com/publications/reports/`

[93] Cave, M., Doyle, C. and Webb, W., 2007. Essentials of modern spectrum management (p. 15). Cambridge: Cambridge University Press.

[94] Available at: `https://www.ofcom.org.uk/consultations-and-statements/category-1/srsp`

[95] For a nice overview of US policy history and pricing methods in particular proposed over the 70 years span see Hazlett, T.W., 1998. Assigning property rights to radio spectrum users: Why did fcc license auctions take 67 years?. The Journal of Law and Economics, 41(S2), pp.529-576.

[96] Ithiel de Sola, Pool, 1983. Technologies of freedom. Harvard University Press.p138-148.

[97] *Ibid*.

[98] Schlag, P., 1988. The problem of transaction costs. S. Cal. L. Rev., 62, p.1661.

[99] Dahlman, C.J., 1979. The problem of externality. The journal of law and economics, 22(1), pp.141-162.

Unlike other commodities, use of spectrum affects the neighbouring spectrum use by causing interference and imposing costs to it. This kind of externality can be included in the design of the market, whatever that market might be. Beside the lone proposal from de Sola Pool for unregulated market and the existing auction model, spectrum markets proposals came early and were dismissed early. Hazlett quotes reviewer of Rand Corporation commissioned and never published 1962 monograph on spectrum markets by Meckling and Minasian:

> "Time has somehow left the authors behind. On the domestic scene, they ignore the social, cultural, and political values which have come to inhere in mass communications, in particular, broadcasting, as well as fifty years of administrative law developments. On the international level, it would appear that it has been kept from them that everywhere but in the United States, communications are almost totally a state function and monopoly.
>
> ...I know of no country on the face of the globe – except for a few corrupt Latin American dictatorships – where the sale of the spectrum could be seriously proposed."

Hazlett: "That was the nice part."[100]

2.2.3 *Spectrum Debate: The Tale of Two Spectra*

Throughout the history of regulation (and radio dramas) a common recurrent theme can be observed: a dialogue. Starting from the clash of the economic spectrum perspectives embodied in Smythe and Herzel debate[101] and continuing with Coase and everyone else, both living (Demsetz[102]) and dead (Pigou[103]), the discourse rarely deviated into a multilogue. This was the bipolar world in which the spectrum debates were born.

The spectrum debates resemble a creation myth: an ancient tale of the earth vs. the heavens, the land vs. the air. Or in the ancient Greek pantheon, the story of Gaia and Uranus. In an autocratic and unjust dictatorship (the Empire as the one seen in the introductory dialogue) everyone with a mind of their own is an opposition. The opposition to command and control regime was not a single rebel faction but at least two camps. Think the Russian revolution of 1917 or, even better, the Titanomachy. The

[100] Hazlett, T.W., 2017. The Political Spectrum: The Tumultuous Liberation of Wireless Technology, from Herbert Hoover to the Smartphone. Yale University Press.

[101] As documented in Coase paper "The Federal Communications Commission", Herzel first proposed that the price mechanism should be used to allocate frequencies and assigned to the highest bidder. Smythe argued against it: "Surely it is not seriously intended that the noncommercial radio users (such as police), the nonbroadcast common carriers (such as radio-telegraph) and the nonbroadcast commercial users (such as the oil industry) should compete with dollar bids against the broadcast users for channel allocations." (Smythe, D.W., 1952. Facing facts about the broadcast business. The University of Chicago Law Review, 20(1), pp.96-106.) This was on par with the celebrated "Is this a joke?" question directed at Coase by the FCC.

[102] Demsetz, H., 2003. Ownership and the externality problem. Property rights: Cooperation, conflict, and law, 282.

[103] Coase, R.H., 2013. The problem of social cost. The journal of Law and Economics, 56(4), pp.837-877.

gods killed the titans but the division between the land and the air remained. As it usually goes with coups, the benefits for the end users (humans) were questionable. It is difficult to serve the needs of end users from three thousand meters high Mount Olympus. It is just one big macrocell tower, a monument of telecom greed, that feeds of high prices of telecom service for consumers. Today we observe that the market-based approach did not produce very competitive markets. It's an antediluvian artifact.

While fully aware of the pitfalls of metaphors and analogies and the inability to found good practices based on them ("Policies based on metaphors can be harmful.", Elinor Ostrom[104]), we proceed by presenting the two schools of spectrum thought in the air-land analogy. These are not analogies about spectrum *per se* but about human archetypal perception of ownership, production and distribution. The two schools of spectrum thought are represented by: (1) property rights theorists and (2) commons theorists. Both models emerged as alternatives to command and control regime of spectrum management that was in place until the 90s. We first present the rationales of the models and the main features each camp advocates for. Then we go in more depth of the clashes between them through a set of questions we derived as crucial points of disagreement, misunderstanding or simply strong policy positions. Then we give our reflections on the debates.

2.2.3.1 *Property Rights Model*

The land is divided, bordered, protected, precluded from trespassing, heavily legislated, owned. Exclusive licensing model of spectrum management is built on that. As one alternative to the command and control regime, exclusive use model allocates spectrum by using pricing mechanism of auctions. The other alternatives such as merit-based hearings and lotteries were abandoned, as mentioned earlier, and some other pricing mechanisms proposed over the years have never been adopted.

In order to have a market, you have to have a real resource that is also scarce. When the resource is abundant, its price is zero. The motivation for property rights model is the vision of spectrum as a scarce, physical and fixed resource, like land. Hence the abundance of spectrum-as-land-based publications, well documented by de Vries[105]. The existing language of spectrum helped them in making spectrum a land or a place. In this language, there are insiders, outsiders, borders, volumes, areas, bands as containers[106]. The "famous" parallels in arguments for propertyzation can be found in White's[107] paper which introduced the term of propertyzation as well:

> -- Land is finite; the same is true of spectrum. -- Productive land is "scarce"; the same is true of spectrum. -- Different types of land are often inherently

[104]Ostrom, E., 1990. Governing the Commons. Cambridge University Press.

[105]De Vries, J.P. and Westling, J., 2017. Not a Scarce Natural Resource: Alternatives to Spectrum-Think.

[106]De Vries, J.P., 2007, April. Imagining radio: Mental models of wireless communication. In New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on (pp. 372-380). IEEE.

[107]White, L.J., 2001. "Propertyzing" The Electromagnetic Spectrum: Why It's Important, And How To Begin. In Communications deregulation and FCC reform: Finishing the job (pp. 111-143). Springer, Boston, MA.

> better suited for different uses; the same is true of spectrum. -- Technological change can improve the efficiency of the use of land; the same is true of spectrum. -- Technological change can expand the amount of land that is considered usable and productive; the same is true of spectrum. -- Technological change can alter the uses to which land should economically be devoted; the same is true of spectrum. -- Changing economic demands (often intertwined with technological change) can alter the efficient uses to which land should be put; the same is true of spectrum. -- Some uses of land may interfere with neighboring uses of land; the same is true of spectrum.

The idea of property rights however predates White by 50 years. We will briefly trace the evolution of the property rights idea with the help of key publications of property theorists which shaped the discourse of the exclusively licensed spectrum in the debate. The discussion on markets (subsection 2.2.2) dealt with this evolution from the implementation viewpoint and in a different context, focusing on the choices between allocation and assignment methods that the regulator had over the years.

In the 1950s economists started to challenge government licensing model: the government should not control and manage the spectrum, but spectrum should be bought and sold like every other commodity. Herzel's proposal[108] was taken up by Coase[109] and property rights were proposed for spectrum.

In 1963, Coase, Meckling and Minasian in their never published work[110] presented the spectrum markets idea and caused a stir among the few readers of it: the general public was deemed not ready for it by the reviewers at Rand corporation. (We already wrote about it in subsection 2.2.2 and we will return to this case at the end of the section, through an interpretation of it with a hindsight from the 2000s.)

In the years to come, the challenge to define the form these rights should have and how to assign them was taken up by De Vany[111], Minasian[112], Mueller[113]. In 1968 De Vany et al. wrote:

> "The market mechanism as a theory cannot be offered as an alternative to FCC regulation; to make the debate useful it is first necessary to articulate a detailed system of property rights in spectrum usage."

This describes the path de Vany and his colleagues took: engineers, economists and legal scholars joined forces to come up with a market solution. De Vany prophesises the demise of the FCC system of administrative allocations with the need for flexible new

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[108] Herzel, L., 1951. Public Interest" and the Market in Color Television Regulation. University of Chicago Law Review, 18(4), pp.802-816.

[109] Coase, R.H., 1959. The Federal Communications Commission. JL & Econ., 2, p.1.

[110] Coase, R., Meckling, W. and Minasian, J., 1963. Problems of radio frequency allocation.

[111] DeVany, A.S., Eckert, R.D., Meyers, C.J. and O'Hara, D.J., 1968. A property system for market allocation of the electromagnetic spectrum: A legal-economic-engineering study. Stan. L. Rev., 21, p.1499

[112] Minasian, J.R., 1975. Property rights in radiation: An alternative approach to radio frequency allocation. The Journal of Law and Economics, 18(1), pp.221-272.

[113] Mueller, M., 1982. Property rights in radio communication: the key to the reform of telecommunications regulation. Cato Institute.

spectrum uses[114]. He continues with the same property right definition he started with in 1969 (a property right is defined as the right to use exclusively a spectrum density over a defined time and area), even the dated TAS (time, area, spectrum) units characterisation of spectrum which while appropriate for broadcasting and the static, fixed nature of such systems, are not tailored for modern wireless communications. This paper attempted to show "of how far along the way to the Herzel-Coase vision of a spectrum market we are and try to see what tasks remain." The five element to do list de Vany makes is: (1) creating an aftermarket, (2) refining the instruments of spectrum crediting, (3) moving spectrum to market, (4) preventing interference under a market system, (5) opening access to spectrum bandwidth. His main plan for the spectrum market is there is no plan. Auction the spectrum and the market will come. Everything else would be reviving the same old mentality of legal and administrative complexities of regulations, which led spectrum to the place where it is. To move to market-based policy, he proposed spectrum auctions to be designed beyond their present state. Definition of bounds in time, space and frequency within a license is his proposal towards redefining interference protection, reducing the question of interference to essentially trespassing. The shift of interference protection into field measurements brings flexibility to spectrum use and with it, the potential to gracefully accommodate new technologies. He based his line of thinking on natural evolution of policies and the observed shift of FCC's language and actions towards markets. This opinion is shared by other authors as well[115] and observable from the FCC statements.
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In 2001, Hazlett, the proactive champion of property rights model elaborates the case of 1963 unpublished work of Coase, Meckling and Minasian in a voluminous essay[116], answering questions raised until then in the spectrum community and posing new ones. In his view, the case for markets is the case for property rights. The reason why we do not have wireless markets is that it is not spectrum which is being auctioned, but it is the right to use:

> The economic result is that the "price of spectrum" is not evident in the sales price of a wireless license. Because the FCC has fixed the use of the spectrum, the opportunity cost of spectrum to the licensee is nil. What is valuable in the FCC license is the right to do business within the market designated by the FCC. Radio spectrum, as allocated to the license, is used at a price of zero.

Hazlett suggests returning spectrum back to the equation by auctioning spectrum and not the rights to use and he explains the mechanisms of maintaining innovation, competition and public interest in a spectrum-tailored market. He hails the emerging

[114] De Vany, A., 1998. Implementing a market-based spectrum policy. The Journal of Law and Economics, 41(S2), pp.627-646.

[115] Kwerel, E.R. and Williams, J.R., 1993. Moving toward a Market for Spectrum. Regulation, 16, p.53.

[116] Hazlett, Thomas W., 2001. The wireless craze, the unlimited bandwidth myth, the spectrum auction faux pas, and the punchline to Ronald Coase's 'big joke': an essay on airwave allocation policy. Harvard Journal of Law & Technology 14, 335–567.

technologies of ultra-wide band (UWB) and software-defined radio (SDR) (Section 2.3) advising faster action to the FCC and hoping that the new technology will make "block allocation" disappear. In the dilemma of consumer welfare vs. public interest (block allocation/government licensing model is based on "public interest" motives), for Hazlett the enabling policy is simply private property. Nobody knows what "public interest" is, and the consumer welfare means competitive markets. Even if considering market failures, it is hard to justify creation of specialised regulatory agency. Therefore he goes to propose spectrum courts and deregulating spectrum.

In 2004, with FCC making it legal[117], the idea of secondary markets gained momentum and real-time solutions were proposed[118].

In summary, property theorists proposed the auctions to assign spectrum, more flexibility in the license (government licensing model did not allow sell or lease of the rights without FCC approval), introduction of secondary markets and to eventually get to the full property rights regime. Spectrum then becomes a tangible commodity, and the spectrum license holder can sell, lease and trade its rights playing its part in what should in future become dynamic spectrum markets. The most important concept of property rights is that they are tradeable, transferable exclusive and excluding. In the spirit of this approach, spectrum is best used if it is privately owned and the license to use it is sold in spectrum auctions to the highest bidder, which should ensure it is used efficiently in economic terms. Spectrum licenses can be traded on secondary markets and the entire spectrum market would be price-based and competitive.

2.2.3.2 *Commons Model*

As opposed to the land, air is breathable by everyone, always free to access, with no visible borders, hard to own, bound, protect, conserve. In the classical spectrum interpretation of the air mythos, a dystopian twist is added: breathing masks. The right to use spectrum in the unlicensed regime is governed by equipment standards: providing you put this mask on, you can share the air (spectrum in these bands)[119]. This is one way to implement the commons: as the other alternative to command and control management which allocates spectrum based on equipment standards, to assure the non-interfering environment for users in the band which do not pay for the spectrum license. The success of unlicensed bands (license-exempt in EU terms) is an anomaly in spectrum world: it is the proof of how technology can win the battle of scarcity and interference even in the environment where potential conflicts are more real than in any other regime.

The spectrum analogy in the commons is the one of a vast fluid resource. While we have chosen the air as the representative here, following the Goodman[120] metaphor,

[117] `https://www.fcc.gov/document/promoting-efficient-use-spectrum-through-elimination-barriers-1`

[118] Peha, J.M. and Panichpapiboon, S., 2004. Real-time secondary markets for spectrum. Telecommunications Policy, 28(7), pp.603-618.

[119] Goodman, E.P., 2004. Spectrum rights in the telecosm to come. San Diego L. Rev., 41, p.269.

[120] Goodman, E.P., 2004. Spectrum rights in the telecosm to come. San Diego L. Rev., 41, p.269.

Werbach[121], Gilder[122] chose the ocean. The flow of the ocean and the air reflect the ideas of the commons: dynamic, renewable, recycling; and their vastness is the epitome of abundance. Commons theorists do not believe in spectrum scarcity. Furthermore, the big fluids of nature, air and ocean, do not submit to ownership.

Commons is not just a paradigm and economic model, commons is also a culture and a language[123]. The Nobel laureate Elinor Ostrom, while an important figure in the commons context and a big contributor to the language of commons[124], is often considered the representative of the new generation of Coasian economists, as she follows up on his imperative to study the world of transaction costs[125].

The introduction of auctions moved the spectrum property closer to reality in the property rights movement. At the same time the critique began to rise influenced by the technological development at the time. The origins of the idea can be found in Benkler's article Overcoming Agoraphobia[126] followed by Lessig[127], Werbach[128] and Ikeda[129].

Benkler shows that the commons is at least as good/as bad as property rights model. And then offers a roadmap for choosing the future path of "society's information environment". In this work, he fundamentally explains the philosophy behind "spectrum commons" as an approach which treats bandwidth as common resource that all equipment can jump on under the sharing protocols (as opposed to being a controlled resource, by government or property owner, or both.) Benkler's vision is technological. Through a comparative economical analysis of licensing/auctioning and unlicensed/-commons he shows the centralisation of the former opposed to decentralisaton/distribution of the latter and proceeds with proposals "to reserve institutional judgment". Firstly, he advocates to stop talking about wireless regulation in terms of resource management. It was the wrong question of how should spectrum be allocated. The right question is the question of coordinating the use of equipment. Secondly, he lists three institutional proposals to determine the future path of wireless communications: (1) FCC needs to reopen UNII proceeding (5GHz band unlicensed spectrum)[130], (2) the process of spectrum auctioning should be slowed, (3) losing the renewal guarantee (FCC should begin observing the licenses as leases and not fee simple rights). His economic analysis offers indications that a market in equipment for individual use

[121] Werbach, K., 2002. The New Wireless Paradigm. Spectrum Series Working Paper, 6.

[122] Gilder, G., 1994. Auctioning the airways. Forbes.

[123] Bollier, D., 2007. The growth of the commons paradigm. Understanding knowledge as a commons, p.27.

[124] Ostrom, E., 1990. Governing the Commons. Cambridge University Press.

[125] Mrd, C. and Shirley, M.M., 2014. The future of new institutional economics: from early intuitions to a new paradigm?. Journal of Institutional Economics, 10(4), pp.541-565.

[126] Benkler, Y., 1997. Overcoming agoraphobia: Building the commons of the digitally networked environment. Harv. JL & Tech., 11, p.287.

[127] Lessig, L., 2002. The future of ideas: The fate of the commons in a connected world. Vintage.

[128] Werbach, K., 2001. Open spectrum: the paradise of the commons. Esther Dyson's Monthly Report Release, 1(19), p.10.

[129] Ikeda, N., 2002. The spectrum as commons.

[130] Revision of Part 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII),
`https://www.fcc.gov/document/5-ghz-unlicensed-spectrum-unii`

would be better than a market in infrastructure. Benkler's Economics of wireless communications[131] is a cautionary tale against "any kind of big bang approach that will preempt future policy making". After discussing comparative technical advantages of property rights and open wireless networks, in terms of capacity increase (in favor of open wireless networks) and capacity allocation (in favor of property rights), Benkler calls for an experiment in both markets. The experiment should both be in the field of equipment deregulation and spectrum property allocations.

Lessig[132] was fast in noting that technology, and in particular spread-spectrum, is the enabler of spectrum becoming a commons. And if spectrum is "free" it will be put to competitive use.

From the analysis of the literature, we conclude that the commons model rests on two principles: (1) the greater social welfare of wireless communications and more importance to social values such as autonomy, diversity and innovation, and (2) acknowledging property rights theorists' diagnosis of the problem of artificial scarcity and agreeing that spectrum should be managed through market forces rather then government. But the commons shifts the debate by adding the force of technology to the market force, underlining the same problem of exclusivity in property rights model which government licensing model is also built on. As Werbach puts it, to solve the problem of exclusivity, commons theorists propose "lightly controlled forms of shared access"[133].

In summary, for the commons theorists, spectrum is best used if it is free for anyone to access it over the airwaves, providing their networks are certified by the regulator on technical interference thresholds. This is the environment where everyone is free to enter the band and interfere with each other or avoid interfering. This model is built on the concept of: Internet is owned by everyone and by no one.

2.2.3.3 *Reviewing The Clash*

Through presenting the evolution of spectrum school of thought, we traced some of the ideas and methods proposed for allocation and assignment that have either been abandoned or rejected over the years - but the spectrum debates are very much real (and alive in Washington). This fact deserves a story about evolution of opinions, without metaphors or sugar-coating. This debate is not a fight over spectrum, it is a fight over different configurations of rights.

The debate between the two alternatives for the succession of the existing government licensing model came as a refreshing change. Before that there was a 100 years old conversation about should it stay as it is (command and control) or should we start following market trends. Finally, the question transformed from "Should something

[131] Benkler, Y., 2002. Some economics of wireless communications. Harv. JL & Tech., 16, p.25.
[132] Lessig, L., 1998. Keynote Address: Commons and Code. Fordham Intell. Prop. Media & Ent. LJ, 9, p.405.
[133] Werbach, K., 2003. Supercommons: Toward a unified theory of wireless communication. Tex. L. Rev., 82, p.863.

be changed?" to "What should it change into?". Coup was successful, the command and control was abandoned. What remains is the question of succession.

We identified several issues which we nominate for the litmus test in the debate.

THE ISSUES OF ANALOGIES AND ROLE MODELS. Both sides of the debate have utilised analogies for spectrum in order to explain its nature and/or adopt practices from other resource managements. Property theorists use real estate as a role model and analogy of spectrum with land. Commons theorists use Internet as a role model and analogy of a fluid spectrum resource, such as air or ocean. Peha[134] explains that spectrum and land cannot be compared because you can stop trespassing of the land but cannot stop adjacent interference in spectrum. Weiser and Hatfield[135] would disagree, proposing spectrum zoning[136] through their own land metaphor, orienting spectrum rights design more to the use of the rights. The proper analogy, as Werbach wrote[137], would be between wireless communications rights and certain uses of land. Werbach objects the land analogy by suggesting that, unlike spectrum,

> A meadow has a specific amount of grass, and one sheep eats so much of that grass each day. Wireless communication works differently.

It is the advances in both the grass-growing and the grass-eating technology Werbach has in mind here, allowing for more capacity and more users in wireless communications.

The dual nature of spectrum has been adopted by Levin[138], akin to minerals and water, fixed and flow resources at the same time. For Eli Noam[139], "it is about flows, not stocks" to which Hazlett replied[140] that "real estate is all about flows". Hazlett[141] concedes that "the land analogy is sometimes helpful in spectrum, sometimes not." Coase's relationship with the "spectrum as land" metaphor has been differently interpreted on the two sides of the debate. Werbach[142] suggests that "even Coase, who later in his article stated quite clearly that spectrum was not a physical resource, fell into the trap of drawing parallels between spectrum and land in connection with interfer-

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134 Peha, J.M., 2005. Approaches to spectrum sharing. IEEE Communications Magazine, 43(2), pp.10-12.

135 Weiser, P.J. and Hatfield, D., 2007. Spectrum policy reform and the next frontier of property rights. Geo. Mason L. Rev., 15, p.549.

136 Hazlett, T.W., 2007. A Law & (and) Economics Approach to Spectrum Property Rights: A Response to Weiser and Hatfield. Geo. Mason L. Rev., 15, p.975. Hazlett disagrees, explaining how land zoning arises in a different setup, "from resource conflicts (spillovers) where transactions are difficult due to bargaining among a large number of parties".

137 Werbach, K., 2003. Supercommons: Toward a unified theory of wireless communication. Tex. L. Rev., 82, p.863.

138 Levin, H.J., 2013. The invisible resource: use and regulation of the radio spectrum. Routledge.

139 Noam, E., 1998. Spectrum auctions: yesterday's heresy, today's orthodoxy, tomorrow's anachronism. Taking the next step to open spectrum access. The Journal of Law and Economics, 41(S2), pp.765-790.

140 Hazlett, T.W., 1998. Spectrum flash dance: Eli Noam's proposal for "open access" to radio waves. The Journal of Law and Economics, 41(S2), pp.805-820.

141 Hazlett, T.W., 2008. A Law & (and) Economics Approach to Spectrum Property Rights: A Response to Weiser and Hatfield. Geo. Mason L. Rev., 15, p.975.

142 Werbach, K., 2003. Supercommons: Toward a unified theory of wireless communication. Tex. L. Rev., 82, p.863.

ence." Hazlett[143] on the other hand, says that Coase's "departure from land was not a helpful one", claiming that "Coase sabotaged his own argument...the land analogy was extremely useful in defining spectrum property but Coase cast it aside." It seems that Coase's writing was a worthy contribution to theology of spectrum, as most holy scriptures it is open to interpretation.

The Internet, the holy grail of commons, has been an inspiration to spectrum commons advocates, largely based on philosophy and ideology. The Internet is a synergy of two things: the network of infrastructures and the network of users. It is the network of users, humans, that aims to expand the availability of content and services. As Cory Doctorow[144] says,

> The information does not want to be free... People do.

This is where the commons supporters come from, recognising spectrum as a social value, information and free speech venue[145].

The first round of the debate was *open spectrum access vs. property rights* clash, started by Eli Noam[146] with his proposal of extending the auctions to more dynamic, spot, real-time markets with tokens exchanged for access to spectrum and removing the exclusivity inherited in auction based assignments. Hazlett's response[147] largely relied on the argument against Internet as a commons success story, calling it wasteful, that it "seriously misallocates scarce bandwidth" and just creates chaos. In a picturesque example, he speaks of a brain surgeon who "cannot read the life-or-death CT-scan because the Internet backbone is clogged with junk e-mail". Benkler[148] concedes in Internet (and open wireless networks) not distributing capacity optimally, but producing capacity at much larger scales than optimally-capacity-distributing property based solutions. To the technologists of commons, Hazlett says[149]:

> The tragedy of commons[150] is not solved by science, it is, was and will continued to be solved by rules.

Lessig[151] wonders why Hazlett claims that the Internet misallocated bandwidth because that means he completely ignores the innovation the original Net created, implying it was not beneficial! And calls him on to demonstrate such a bold claim, to show that it would not be beneficial for spectrum.

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143 Hazlett, T.W., 2007. A Law & (and) Economics Approach to Spectrum Property Rights: A Response to Weiser and Hatfield. Geo. Mason L. Rev., 15, p.975.

144 Doctorow, C., 2014. Information doesn't want to be free: Laws for the Internet age. McSweeney's.

145 Lessig, L., 1998. Keynote Address: Commons and Code. Fordham Intell. Prop. Media & Ent. LJ, 9, p.405.

146 Noam, E.M., 1995. Taking the next step beyond spectrum auctions: open spectrum access. IEEE Communications Magazine, 33(12), pp.66-73.

147 Hazlett, T.W., 1998. Spectrum flash dance: Eli Noam's proposal for "open access" to radio waves. The Journal of Law and Economics, 41(S2), pp.805-820.

148 Benkler, Y., 2002. Some economics of wireless communications. Harv. JL & Tech., 16, p.25.

149 Hazlett, T.W., 1998. Spectrum flash dance: Eli Noam's proposal for "open access" to radio waves. The Journal of Law and Economics, 41(S2), pp.805-820.

150 Refers to Hardin, Garrett J., 1968. The tragedy of the commons. Science 162, 1243– 1248.

151 Lessig, L., 2002. The future of ideas: The fate of the commons in a connected world. Vintage.

> But the response to Hazlett's example is not to criticize the Internet. The response is to ask who is this "brain surgeon" reading a CT scan over the Internet? And how does her ability to use the Net determine whether the Net "seriously misallocates" resources? Hazlett offers no data to support the claim that the "tragedy of the commons appears frequently." In fact, capacity has consistently outstripped demand (International Bandwidth 2001, Washington, D.C.: TeleGeography, 2001). [...] Given the creativity and innovation that the original Internet produced, and given how different that innovation is relative to other computer networks and other telecommunications systems, my bet for spectrum would be that an architecture modeled on the Internet would not be so bad.

SUCCESS STORIES. In the survivorship biased debate, success stories of both sides carry substantial weight. In case of property model, it is the hundreds of billions of dollars revenue generation by the auctions. In case of commons model, it is the "anomaly" success of Wi-Fi bands.

While auctions have been subject to stringent scrutiny by experts[152], the simple statistics extractable from the reports serve as an important argument to the opponents of commons[153].

> In fact, while abundance advocates criticise FCC auctions they ignore the powerful evidence competitive bidding reveals. Investors are willing to pay substantial amounts to avoid the spectrum commons. That is the choice made in buying an FCC license as it offers exclusivity in spectrum use.

To continue with Hazlett, in the aptly named article Spectrum Tragedies[154], he chooses the path of relativisation the Wi-Fi explosion, citing anecdotal evidence of overuse and discussing just how free Wi-Fi is. This has been directly opposed by Sicker *et al.*[155] as they argue that "a better understanding of how devices operate in the unlicensed bands is required and that anecdotal and even empirical evidence should be looked at with more skepticism" in their pursuit of mechanisms by which tragedy could occur in Wi-Fi.

The technologist pioneers of the commons Gilder[156] and Baran[157] are all in favor of understanding devices. Technologist David E. Reed in his article Why spectrum is not a property[158] captures the idea:

[152] Cramton, P., 1998. The efficiency of the FCC spectrum auctions. The Journal of Law and Economics, 41(S2), pp.727-736.

[153] Hazlett, Thomas W., 2001. The wireless craze, the unlimited bandwidth myth, the spectrum auction faux pas, and the punchline to Ronald Coase's 'big joke': an essay on airwave allocation policy. Harvard Journal of Law & Technology 14, 335–567.

[154] Hazlett, T.W., 2005. Spectrum tragedies. Yale J. on Reg., 22, p.242.

[155] Sicker, D., Doerr, C., Grunwald, D., Anderson, E., Munsinger, B. and Sheth, A., 2006. Examining the wireless commons.

[156] Gilder, G., 1993. The new rule of the wireless.

[157] Baran, P., 1994, November. Visions of the 21st Century Communications: Is the Shortage of Radio Spectrum for Broadband Networks of the Future a Self Made Problem. In 8-th Annual Conf. on Next Generation Networks, Washington, DC.

[158] `http://www.reed.com/dpr/locus/OpenSpectrum/OpenSpec.html`

> We need a regime that allows RF networks to interoperate and cooperate in use of "spectrum" in an open and experimental way, just as the Internet did. The design of this regime, which spans physics, architecture, economics, and policy, is a worthy goal. It is more than a "research project" and more than a "spectrum allocation policy", because it needs to consider all four areas at the same time.

He envisions cooperative wireless networks which create more value, because cooperation can create additional capacity (based on research developments on scaling laws at the time). The problem of property rights model is that it allocates fixed capacity, he claims.

In the center of commons model is the user with freedom and effective control over her place in the ground of communications, media, and technology that respect social values promoted by the commons and the innovation that comes with it[159].

THE FEARMONGERS: SCARCITY AND INTERFERENCE. Can you guess who said this?

> Instead of regulation being mandated by a peculiar form of scarcity, open access to spectrum is mandated by a peculiar form of abundance.

Often exploited argument when it comes to commons is that it functions only in the state of abundance. It is not only Hazlett (yes, that was his quote) but also Faulhaber and Farber[160] in their attempt of an objective consideration of both models potentially finding their place in spectrum policy. In this paper, they provisionally classify property rights as preferred policy option of the economists and the commons as the preference of engineers, arguing that the economists have a misunderstanding of technology and the engineers have a misunderstanding of the markets. They prophesise the scarcity turning into abundance in the short run after a hypothetical establishment of markets but in the long run, scarcity is inevitable: physical, not artificial. This is where they see the breakdown of the commons model, implying that the commons can function only as long as spectrum has no price (zero price). But that is when there is no market also, commons people would agree. Hazlett's variant of the inevitable scarcity is based on his interpretation of Say's law[161] (supply creates its own demand), an argument dismissed by Werbach on the grounds of wireless communication being just one input of the communications system and hence not subject to Say's law on its own.

Scarcity, as noted before, citing the SPTF report, has been one of the two decision factors for market model choice (the other factor being transaction cost) - implying that property rights require a scarce resource.

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[159]Benkler, Y., 1999. From consumers to users: Shifting the deeper structures of regulation toward sustainable commons and user access. Fed. Comm. LJ, 52, p.561.

[160]Faulhaber, G.R. and Farber, D.J., 2003. Spectrum management: Property rights, markets, and the commons. Rethinking rights and regulations: institutional responses to new communication technologies, pp.193-206.

[161]Sowell, T., 2015. Say's Law: An historical analysis. Princeton University Press.

> If resources are not scarce, if consumers can pick their food of trees that are never exhausted and if there is infinite bandwidth then there is simply no need to have markets which have costs to organize, administer and maintain. Early hunter gatherer cultures existed in such a world of plenty; unfortunately, as populations expand, the previously plentiful becomes scarce and people must find a way to allocate these scarce resources[162].

This is the rationale behind both Faulhaber and Farber and SPTF co-opting commons in parks, where spectrum has mostly been unutilised or underutilised. Co-opting is not a rare solution in the debates: both sides have suggested "compromises" in which their solution is the basic underlying one, and the opposing one is confined to reserves.

There are hardliners[163,164] among property theorists who would take interference[165] rules as tomorrow's property rules. Hazlett is in favor of "new technologies craze", UWB, SDR, underlay rules when talking about interference in property rights models. But when he talks about interference in the commons, it is a chaotic system in which interference presents an enormous danger. In Hazlett's coded language there are obviously two interferences. Werbach addresses the interference issue for property theorists well[166]:

> De Vany's system, like Hazlett's aspirational common law, implicitly assumes the static broadcast world of the past rather than the dynamic environment today's technologies make possible. It is a means to resolve interference among users of frequencies, when neither interference nor frequency hold sway in the way they once did. For example, the De Vany system delineates rights in terms of total received field strength. Consequently, it always treats multipath propagation as a harmful phenomenon. A transmitter is liable if multipath reflection causes another receiver to encounter more unwanted energy than the transmitter is permitted to radiate. However, as described above, today's intelligent systems can use multipath effects to enhance communication. There is no way to match the capacity-enhancing value of a multipath-aware system against the increased costs the unwanted energy imposes on other systems, because the multipath effect is always treated as harmful. The De Vany proposal would have the perverse effect of restricting techniques that improve spectral efficiency.

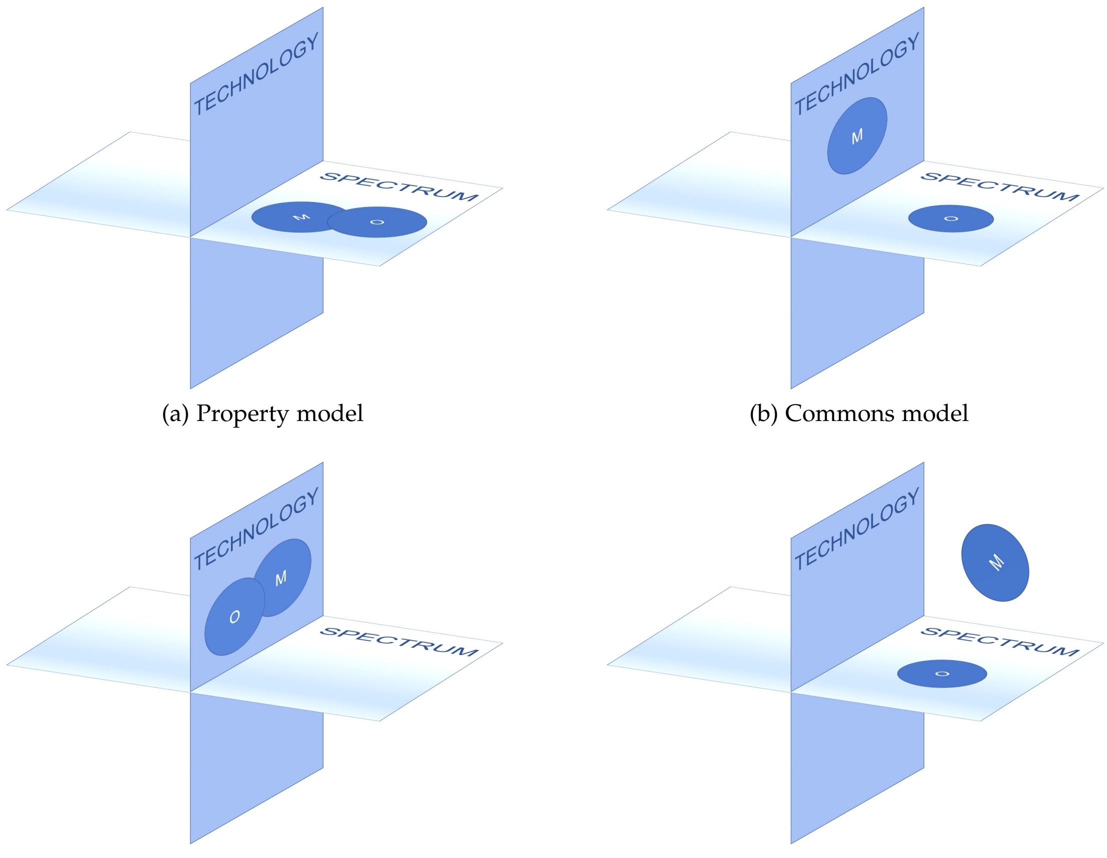
[162] Faulhaber, G.R. and Farber, D.J., 2003. Spectrum management: Property rights, markets, and the commons. Rethinking rights and regulations: institutional responses to new communication technologies, pp.193-206.

[163] DeVany, A.S., Eckert, R.D., Meyers, C.J. and O'Hara, D.J., 1968. A property system for market allocation of the electromagnetic spectrum: A legal-economic-engineering study. Stan. L. Rev., 21, p.1499

[164] Hazlett, Thomas W., 2001. The wireless craze, the unlimited bandwidth myth, the spectrum auction faux pas, and the punchline to Ronald Coase's 'big joke': an essay on airwave allocation policy. Harvard Journal of Law & Technology 14, 335–567.

[165] The FCC expresses the licensee's exclusivity as freedom from "harmful interference," which is defined as unwanted energy that "seriously degrades, obstructs or repeatedly interrupts" a licensed radio communications service (47 C.F.R. 97.3(a)(23). (Werbach, K., 2003. Supercommons: Toward a unified theory of wireless communication. Tex. L. Rev., 82, p.863)

[166] Werbach, K., 2003. Supercommons: Toward a unified theory of wireless communication. Tex. L. Rev., 82, p.863



(a) Property model (b) Commons model

(c) Supercommons model (d) Eli Noam's model

Figure 2.1: Perception of technology and spectrum in different spectrum models; **O** - where you operate; **M** - where the market is;

WHERE IS THE MARKET? To illustrate the standpoints of different spectrum management models, we use a simple representation shown in Fig. 2.1, which consists of two orthogonal planes, representing spectrum and technology.

For property theorists, spectrum plane is where you operate and where the market is, Fig. 2.1a. For commons theorists, spectrum plane is where you operate and technology plane is where the market is Fig. 2.1b. This is why Hazlett is frustrated with the notion of spectrum auctions (not really selling spectrum), and why Werbach proposes the third model, supercommons. Werbach takes the technology plane as the only real one, dismissing spectrum as an entity and consequently the plane it creates. In supercommons, a model beyond commons, the technology plane is where you operate and where the market is, Fig. 2.1c. He notes that the original market pricing paradigm proposed by Herzel actually states that the pricing mechanism is intended for the equipment and not spectrum[167].

[167]"Herzel suggested a market mechanism to address competing transmission standards for color television, which had been the subject of controversy at the FCC. He did not recommend treating the spectrum as freely alienable private property. What he actually proposed were long-term leases with complete technical flexibility. It was Coase who, while stating that spectrum was not a thing, redirected the property approach toward interference optimization in a hypothetical spectrum resource." (Werbach, K., 2003. Supercommons: Toward a unified theory of wireless communication. Tex. L. Rev., 82, p.863)

Truth to be told, supercommons is in fact the second third model, first being Eli Noam's proposal:

> Present auction system should be updated by a system of open spectrum access coupled with a dynamic access fee. Technology seems within reach, will require policy makers to think of spectrum in terms of exclusive ownership but of multiple access. The dominant paradigm for spectrum allocation has to change: from *Occupancy* and *Licensed Privilege* in the past, to *Ownership* or long term lease at present, to *Access* in the future[168].

For Eli Noam, the spectrum plane is where you operate, and the market is placed between the spectrum plane and the technology plane, Fig. 2.1d - as this model combines the reliance on technology from the commons, and the entry fees as an alternative to auctions. Auctions may be a good choice in the short term (better than lotteries and comparative hearings which carry the administrative burden and can lead to corruption) as tools which remove politics out of the process and get spectrum fast to the hands of the highest bidder who values it the most. But in the long term run, auctions have some negative effects: (1) lead to oligopoly, (2) up-front payments are a barrier to entry (unless capital markets are perfect, which they not), reducing diversity, (3) they squeeze out free public access and non-profit educational activities out of the spectrum bands, (4) even auctions proponents agree that market prices do not necessarily reflect social value, there is a consumer surplus as well (the benefit to a consumer above the market price). He proposes an open access system, as a free market alternative to auctions.

> In those bands in which it applies nobody would control any particular frequency. In this system no oligopoly can survive because anyone can enter at any time - large, small, white, black, male, female, American, foreign. There is no license and no up-front spectrum auction. Instead, all users of those spectrum bands pay an access fee that is continuously and automatically determined but the demand and supply conditions at the time, i.e., by existing congestion in the various bands. The system is run by clearinghouses of users.

Is it time for Eli Noam to find his market?

DEBATES IN OUR PERSPECTIVE. The debates are an ideological and philosophical confrontation more than anything else. They reflect the problem of relying on duopoly of management regimes "either or" to govern complexities of spectrum applications diversity. Property theorists criticise commons model as an utopian model that could work on a level of small community and its etiquette but never in economic-wide policy. Commons theorists criticise property market model because it reinforces the privileges given to big carriers by command and control model. Both sides are ready

[168] Noam, E.M., 1995. Taking the next step beyond spectrum auctions: open spectrum access. IEEE Communications Magazine, 33(12), pp.66-73.

for compromises as long as their solution is the underlying one, but the solution is in coexistence.

1. **Spectrum politics and ideologies**. What we observed from the spectrum debates is the *non-equivalence of these two spectrum management regimes with the economic systems*. Former FCC chief economist Dallas Smythe wrote extensively about the marxist perception of mass communication and spectrum[169,170], while Herzel's[171] introduction of pricing mechanism in spectrum was inspired by socialist ideas of Abba Lerner[172], whose influence was also thrown into direction of Eli Noam, by Hazlett[173]. Benkler also writes that, while they are radical, neither of the critiques of licensing regime is traditionally left or traditionally right[174]. Property regime emerged from Reagan-era agenda but later was supported by left-leaning media advocates (spectrum being the main topic in broadcasting and a political weapon as such). Commons on the other hand was supported by libertarians and progressives alike. Werbach[175] also writes "unlike communism, commons is neither anti-property nor anti-market". However, whatever the econo-political alignment of the two camps it is still a line in the plane defined in the common depiction of two-dimensional political spectrum and as such it represents a reduction of dimensionality. It goes from Flatland to Lineland[176] and prohibits the participants in the spectrum debate to see solutions out of the line.

2. **Generic resource treatment in both camps.** Both sides of the debate have adopted bits and pieces of the old management model as the initial condition for their solutions and as the rules of the game. While this has been necessary there is always a possibility of inheriting old misconceptions and mistaking variables for constants. In this regard, we observe *the survival of the dinosaurs embodied in scarcity and interference* on both sides of the debate, adopted as constants. A widely accepted view is that all resources are eventually scarce and need to be put to more efficient use. That view together with the threat of interference led to spectrum being treated as a generic resource on both sides. The difference is just that in the commons model, technology is presented as the force to alleviate the effects of scarcity and interference. In the property rights model it is the market force and the power of no trespassing sign.

[169] Smythe, D.W., 1981. Dependency road: Communications, capitalism, consciousness, and Canada. Praeger Pub Text.

[170] Smythe, D.W., 1977. Communications: blindspot of western Marxism. CTheory, 1(3), pp.1-27.

[171] Herzel, L., 1951. Public Interest" and the Market in Color Television Regulation. University of Chicago Law Review, 18(4), pp.802-816.

[172] Lerner, A.P., 1946. The economics of control.

[173] Hazlett, T.W., 1998. Spectrum flash dance: Eli Noam's proposal for "open access" to radio waves. The Journal of Law and Economics, 41(S2), pp.805-820.

[174] Benkler, Y., 2002. Some economics of wireless communications. Harv. JL & Tech., 16, p.25.

[175] Werbach, K., 2003. Supercommons: Toward a unified theory of wireless communication. Tex. L. Rev., 82, p.863.

[176] Abbott, E., Flatland: A Romance of Many Dimensions. Seeley & Co. of London (1884).

This is a first of the few references we make on the 19th book by mathematician Abbott which is about two-dimensional creatures (polygons) unable to perceive the 3D world.

In a dream, the two-dimensional protagonist of Flatland observes a one-dimensional world of Lineland and its inhabitants, unable to see the plane outside their line.

3. **Shared use of the bands** is entering the debate in a way that it shows how polarisation makes no sense, since sharing is possible in both regimes and there should be no bands exclusively exclusive or unlicensed. Sharing models address the demand side by introducing coexistence, instead of freeing the bands. They address the idle bands by proposing sharing as a norm and a share it or lose it principle via mix of licensed and unlicensed use.

2.2.4 *Takeaway points*

Due to power of legacy and strategic importance of the resource for the government, the command and control approach to spectrum management dominated the spectrum bands. The question of what model will come after the inevitable end of the command and control is the central point of spectrum debates.

Competition is the pillar of success for property model. And technology is that pillar for the commons. Under the assumption of competition (and of course, scarcity), the market is good. Under the assumption of abundance, the commons is good. Both of these models are market-based because decision making about how the spectrum rights should be used is decentralized via the market, unlike command and control centralized decision making regime, where regulator decides how spectrum will be used. Also, both models assume shared use: in licensed model operators are sharing their spectrum with end users, in unlicensed model rights to use is shared among users (user that runs a network essentially scales down to an end user). And both models battle over the bundle: scarcity and transaction costs, which are introduced by the SPTF report as a metric of success of one model over the other.

In the domain of economics, the concept of ownership joined the scarcity and interference holding the spectrum hostage. The auctions as allocation mechanism define competitive bidding procedures to win the rights to use spectrum when mutually exclusive requests for rights exist. The configuration of rights is described in spectrum licenses won in spectrum auctions and they provide the winning cellular carrier with the right to: (1) be protected, (2) exclude others even when not using the spectrum. The licenses are expensive, long-term, renewable, exclusive and nationwide.

2.3 TECHNOLOGY

In this section, we take technology perspective on spectrum. Our motivation for discussing technological enablers and progressive regulatory designs to fully unlock the potential of dynamic spectrum sharing is focused on exploring the trends and challenges in spectrum sharing, to discover where is the cause of its poor proliferation: this is why from this point on in the thesis, we will discuss only sharing of spectrum as a mode of use. The thesis aims to introduce the sharing of spectrum resource as a way to get to its abundance and this discussion has to start with the technology[177]. Technological development has always been recognised as the primary mean of increasing available spectrum resource[178]. The available technology enabling spectrum sharing continues this trend and provides ground for implementations within sharing models.

The reflections of the property rights vs. commons spectrum debate are encountered in Internet culture, proprietary vs. open source debate. Internet culture now also hosts digital economy. The main message from information and knowledge sharing and digital economy (sharing economy) is that the type of use gives the whole new meaning to the resource. This also resonates with the metaphysics of spectrum, it being non-existent until put to use by technology.

A sustainable dynamic spectrum sharing system needs several components on the technical side of things. The shareable nature of the resource does not enable sharing on its own: as said above, spectrum can be said not to even exist on its own. The components for such a system could be broadly categorised as (1) technological frameworks, (2) databases, and (3) coexistence enablers and interference mitigators. The following subsections present these categories using some representative examples.

2.3.1 *A technological framework*

We begin with the concrete example of a technological idea that has shaped the perception of spectrum sharing. Cognitive radio (CR)[179] was introduced to put all available wireless resources to better use through self-organisation and autonomous planning[180], hence mitigating the existing management shortcomings[181]. Cognitive radio (CR) introduced primary users (PU), a fee paying entities with exclusive rights to a spectrum portion and cognitive radio users (CR users) being the users with cognitive radio technology who use the white space opportunistically but without harmful

[177]We would start with the discussion of sharing sooner, in the domain of business, but there is no sign of successful business models made on spectrum sharing and widely implemented in telecom markets

[178]Staple, G. and Werbach, K., 2004. The end of spectrum scarcity [spectrum allocation and utilization]. IEEE spectrum, 41(3), pp.48-52.

[179]Doyle, L., 2009. Essentials of cognitive radio. Cambridge University Press.

"A cognitive radio is a device which has four broad inputs, namely, an understanding of the environment in which it operates, an understanding of the communication requirements of the user(s), an understanding of the regulatory policies which apply to it and an understanding of its own capabilities. In other words a cognitive radio is fully *aware* of the context in which it is operating. A cognitive radio processes the inputs it receives and makes *autonomous decisions* on how to configure itself for the communication tasks at hand. In deciding how to configure itself, the radio attempts to match actions to requirements while at the same time being cognisant of whatever constraints or conflicts (physical, regulatory, etc.) may exist. A cognitive radio has the ability to *learn* from its actions and for this learning to feed into any future reactions it may have. A cognitive radio is made from software and hardware components that can facilitate the wide variety of different configurations it needs to communicate."

[180]Mitola, J. and Maguire, G.Q., 1999. Cognitive radio: making software radios more personal. IEEE personal communications, 6(4), pp.13-18.

[181]While CR was instrumental in TVWS sharing in the beginning, an argument of it being a limiting factor in TVWS utilisation has been raised, see Forde, T. and Doyle, L., 2013. A TV whitespace ecosystem for licensed cognitive radio. Telecommunications Policy, 37(2), pp.130-139.

interference with the PUs. While it marked a revolution, cognitive radio was also a product of a technological evolution and rested on existing enabling concepts. The technological enabler behind cognitive radio was the softwareisation of radio, leading to feasible software defined radio (SDR) units[182], as well as the frequency agile radio capable of learning about the vacant and occupied bands in its working range[183].

When the notion of dynamic spectrum access (DSA) proliferated in the literature and discussions[184] in academia, industry and regulation[185], it was recognised as an important application of cognitive radio. At the same time, the pitfalls of the wide scope of cognitive radio implementations, rich in ideas and problems alike, were recognised - and running away from the term was suggested[186]. DARPA's take on DSA named neXt Generation (xG)[187] allowed centralised and distributed spectrum sharing in the dynamical setting, where it could be collaborative or selfish, overlay or underlay, aiming to give opportunistic access to the licensed spectrum using unlicensed users[188].

XG systems are seen as systems that can reshape the spectrum underutilisation[189], due to their automated sensing and adaptive capabilities which promote dynamic usage as they allow moving through the frequencies in response to interference. Bernthal et al. also discuss XG systems reshaping the spectrum management policies, enabling a leap from command and control towards more dynamic sharing, as they enable more localised autonomy:

> "The move away from "wise-man" regulation leverages two powerful forces: (i) the general technological trend of greater intelligence at the "edge" of a network; and (ii) the recognition that decentralized decision-making is better informed as it uses more localized information than centralized regulators can collect and assimilate. In short, decentralized mechanisms allow for more nimble and tailored uses and decision-making."[190]

They further discuss that even though the sharing that XG systems enable is different than sharing with conventional radios that regulators have deployed in spectrum

[182] SDR is a radio technology with which a majority of signal processing on PHY layer is done by software (modulation, filtering, synchronisation, forward error correction, etc.) For a review of SDR, see: Mitola, J., 1993. Software radios: Survey, critical evaluation and future directions. IEEE Aerospace and Electronic Systems Magazine, 8(4), pp.25-36.

[183] Sanderford Jr, H.B., Axonn Corporation, 1994. Frequency agile radio. U.S. Patent 5,377,222.

[184] The first in the ongoing series of IEEE Symposiums on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) was organised in 2005

[185] Buddhikot, M.M., Kolodzy, P., Miller, S., Ryan, K. and Evans, J., 2005, June. DIMSUMnet: new directions in wireless networking using coordinated dynamic spectrum. In World of Wireless Mobile and Multimedia Networks, 2005. WoWMoM 2005. Sixth IEEE International Symposium on a (pp. 78-85). IEEE.

[186] Buddhikot, M.M., 2007, April. Understanding dynamic spectrum access: Models, taxonomy and challenges. In New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on (pp. 649-663). IEEE

[187] Ramanathan, R. and Partridge, C., 2005. Next generation (XG) architecture and protocol development (XAP). BBN TECHNOLOGIES CAMBRIDGE MA.

[188] Akyildiz, I.F., Lee, W.Y., Vuran, M.C. and Mohanty, S., 2006. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. Computer networks, 50(13), pp.2127-2159.

[189] Bernthal, J.B., Brown, T.X., Hatfield, D.N., Sicker, D.C., Tenhula, P.A. and Weiser, P.J., 2007, April. Trends and precedents favoring a regulatory embrace of smart radio technologies. In 2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (pp. 633-648). IEEE.

[190] Ibid.

bands, there are identifiable precedents of this kind of dynamic sharing that regulators have initiated in the past, which we describe in Subsec.2.3.4.

2.3.2 *Keeping track of the spectrum: databases*

The need for a database keeping track of the spectrum resource and its users is not an exclusivity of spectrum sharing: libraries had their card system long before computer databases. The need for a dynamic, fast and well-coordinated database for management of dynamic spectrum sharing stems, however, from the inherent dynamics of spectrum. As the spectrum is reusable right after the previous user ceased using it in a location, the database has to be able to update records in real time and enable immediate use. Since it is location-specific, we are interested in geolocation databases as a special case: on top of the geospatial data, other dimensions of spectrum electrospace are added (e.g. time, frequency, power). Databases and database management were an active topic in the computer world since the early seventies[191] and have been adopted gradually in telecommunications world throughout the last decades[192]. Here we mention the application they found in the (somewhat conservative) spectrum sharing framework of TV White Space (TVWS) sharing.

White space is the unused spectrum space (temporarily) available in a spectrum band. In the context of VHF/UHF bands (TV bands), we speak of TV White Space (TVWS) which appears in specific times at specific locations. This temporal and spatial dynamics of TVWS poses a challenge for its sharing: automated scheduling of use within a certain location. The TVWS sharing standard[193] solves this by using geolocation databases[194,195] and allows spectrum sharing among unlicensed white space devices (WSD) and licensed protected users of the band.[196] The idea of database assisted geo-location was introduced early[197] synchronised with the emergence of operating geo-location databases in other fields of communications[198]. While the standard allows both open and closed-loop operation of geo-location database dependent systems, the fast dynamics of the closed-loop system allow tighter control and timely allocation of additional spectrum resource once it is available.[199]. The first tests have

[191] Brodie, M.L., 1986. Database management: A survey. In On Knowledge Base Management Systems (pp. 201-218). Springer New York.

[192] Raatikainen, K.E., 1997. Real-time databases in telecommunications. In Real-Time Database Systems (pp. 93-98). Springer US.

[193] IEEE 802.11 Working Group, "IEEE 802.11af Draft 5.0, Amendment 5: TV White Spaces Operation," June 2013.

[194] Gurney, D., Buchwald, G., Ecklund, L., Kuffner, S.L. and Grosspietsch, J., 2008, October. Geo-location database techniques for incumbent protection in the TV white space. In New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on (pp. 1-9). IEEE.

[195] e.g. see the solutions by SpectrumBridge, `https://spectrumbridge.com/`.

[196] IEEE 802.11 Working Group, "IEEE 802.11af Draft 5.0, Amendment 5: TV White Spaces Operation," June 2013.

[197] Berggren, F., Queseth, O., Zander, J., Asp, B., Jnsson, C., Stenumgaard, P., Kviselius, N.Z. and Thrngren, B., 2004. Dynamic spectrum access, phase 1 scenarios and research challenges.

[198] Svantesson, J.B., 2004. Geo-Location Technologies and Other Means of Placing Borders on the Borderless Internet. J. Marshall J. Computer & Info. L., 23, p.101.

[199] Flores, A.B., Guerra, R.E., Knightly, E.W., Ecclesine, P. and Pandey, S., 2013. IEEE 802.11 af: A standard for TV white space spectrum sharing. IEEE Communications Magazine, 51(10), pp.92-100.

shown superior ability of geo-location database supported systems to identify occupied channels, but occasional failures to identify the unoccupied ones, due to incomplete information[200]. The challenge of information gathering was not the only one driving research in TVWS sharing, as the question of heterogeneous coexistence has also been posed.[201] The use of geo-location database in TVWS was driven by the increasing ability to collect relevant data for it in the present times as much as the ability to manage the data purposefully. The concept and the technology has the potential to extend further from its current application in the future.[202] When discussing the future of TVWS's databases, researchers have expressed the desire to abandon conservative database control[203], but also a fear of turning a geo-location database into a killswitch for the whole network[204].

Another concept entering the telecommunications arena was the cloud. While we may observe it as a technological enabler for revolutionising the telecommunications industry, cloud computing[205] itself stood on the basis of its own technological enablers which were looped back to the communications world, namely the advancement of networks. In 2006 the boom of cloud computing started[206] and it continues to this day, with enhanced abilities and widened scope of applications, as well as new architectures like the edge and the fog[207]. Cloud resource pooling has allowed resource pooling in telecommunications to take a new form, in particular enabling pooling of baseband signal processing units in the cloud and resulting in Cloud Radio Access Networks (C-RAN) lowering power consumption and resource count.[208] It is not the only use for cloud computing we are interested in this context: we will later see how a cloud based database and a system surrounding it is planned to manage the 3.5 GHz band[209].

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[200]Pawelczak, P., Nolan, K., Doyle, L., Oh, S.W. and Cabric, D., 2011. Cognitive radio: Ten years of experimentation and development. IEEE Communications Magazine, 49(3).

[201]Ghosh, C., Roy, S. and Cavalcanti, D., 2011. Coexistence challenges for heterogeneous cognitive wireless networks in TV white spaces. IEEE Wireless Communications, 18(4).

[202]Barrie, M., Delaere, S., Sukarevičienė, G., Gesquiere, J. and Moerman, I., 2012, October. Geolocation database beyond TV white spaces? Matching applications with database requirements. In Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on (pp. 467-478). IEEE.

[203]Ramjee, R., Roy, S. and Chintalapudi, K., 2016. A Critique of FCC'S TV White Space Regulations. GetMobile: Mobile Computing and Communications, 20(1), pp.20-25.

[204]Horvitz, R., 2016. Geo-database management of white space vs. open spectrum.

[205]Mell, P. and Grance, T., 2011. The NIST definition of cloud computing.

[206]Weiss, A., 2007. Computing in the clouds. networker, 11(4), pp.16-25.

[207]Chiang, M., Ha, S., Chih-Lin, I., Risso, F. and Zhang, T., 2017. Clarifying Fog Computing and Networking: 10 Questions and Answers. IEEE Communications Magazine, 55(4), pp.18-20.

[208]Checko, A., Christiansen, H.L., Yan, Y., Scolari, L., Kardaras, G., Berger, M.S. and Dittmann, L., 2015. Cloud RAN for mobile networks—A technology overview. IEEE Communications surveys & tutorials, 17(1), pp.405-426.

[209]COMMSCOPE: Citizen's Broadband Radio Service, `http://nsma.org/wp-content/uploads/2017/05/2017-03-nsma-citizens-broadband-radio-service.pdf`, Kim, C.W., Ryoo, J. and Buddhikot, M.M., 2015, September. Design and implementation of an end-to-end architecture for 3.5 GHz shared spectrum. In Dynamic Spectrum Access Networks (DySPAN), 2015 IEEE International Symposium on (pp. 23-34). IEEE.

2.3.3 *Heterogeneous Networks: Coexistence and Interference*

Spread spectrum, in the form applicable in the nineties[210], was the first big promise of spectrum abundance we had. It was not the only method proposed to distribute the signal over a wide bandwidth with the consequence of lowering the concentrated power and allowing coexistence in bands: ultra-wideband (UWB) communications did it without a carrier signal[211]. Combining spread spectrum and UWB resulted in exciting novel designs[212] as the market was getting ready for FCC allocating the 3.1–10.6 GHz band for the UWB.

Another concept that uses the possibility of switching frequencies is CR. So far, we observed CR looking for completely unused white spaces to jump in. However, it does not have to operate exclusively on completely unused white spaces. If the CR users operate on low-power devices and short ranges, they can coexist with an active PU: this is the underlay model and the spectrum portions in which this operation occurs are the grey spaces[213]. In order to allow the CR user to find a vacant band of either white or grey space to operate in, CR has to have a mechanism of spectrum sensing, and a multitude of methods has been proposed for this task.[214] The environmental awareness of a CR user comes at a cost, no matter which approach is used: geo-location database, beacons or local sensing on their own. This cost in the context of local sensing is expressed through hardware, algorithm and time complexity and can be shared between several CR users to alleviate the effects.[215] Another reason to use cooperative spectrum sensing is to avoid the common issue of hidden primary nodes, not visible to a single CR user because of their location and causing serious interference[216]. Once spectrum sensing is implemented, a spectrum sharing scheme building on it is straightforward and efficient[217].

With the opportunity to (1) share spectrum in the white, unused space, (2) use automated database enabled geo-location management and (3) exploit the concept of a primary and secondary user in spectrum sharing system which have priorities to access spectrum and to be protected from harmful interference, emerging sharing

[210] To an extent, the concept was known a century ago:
Zenneck, J.A.W., 1915. Wireless telegraphy. McGraw-Hill Book Company, inc..

[211] UWB technology describes the use of low power communications, short in range and of high bandwidth, over a larger block of spectrum.

[212] Win, M.Z. and Scholtz, R.A., 2000. Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications. IEEE Transactions on communications, 48(4), pp.679-689.

[213] Macaluso, I., Forde, T.K., DaSilva, L. and Doyle, L., 2012. Impact of cognitive radio: Recognition and informed exploitation of grey spectrum opportunities. IEEE Vehicular Technology Magazine, 7(2), pp.85-90.

[214] Yucek, T. and Arslan, H., 2009. A survey of spectrum sensing algorithms for cognitive radio applications. IEEE communications surveys & tutorials, 11(1), pp.116-130.

[215] Fazeli-Dehkordy, S., Plataniotis, K.N. and Pasupathy, S., 2011. Wide-band collaborative spectrum search strategy for cognitive radio networks. IEEE Transactions on Signal Processing, 59(8), pp.3903-3914.

[216] Ganesan, G. and Li, Y., 2005, November. Cooperative spectrum sensing in cognitive radio networks. In New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on (pp. 137-143). IEEE.

[217] Kang, X., Liang, Y.C., Garg, H.K. and Zhang, L., 2009. Sensing-based spectrum sharing in cognitive radio networks. IEEE Transactions on Vehicular Technology, 58(8), pp.4649-4654.

models have the basis to provide us a way for coexistence of systems of extremely different nature, e.g., military and commercial users. The technology is available.

The two trends observed here are densification and heterogeneity of users sharing the same space, time and frequency.

How can we accommodate heterogeneous users in close proximity? One approach includes Massive MIMO (Multiple Input Multiple Output), a proposed concept of large scale antenna arrays at the base station side where the effects of interference disappear and spectral efficiency and capacity grow with the increase of the number of antennas (much larger than the number of users)[218]. Massive MIMO is considered to be one of the underlying technologies for the coming 5G[219] and it quickly went from a theoretical concept to a practically implemented one[220]. While most of the implementations of Massive MIMO have been based on its co-located version where all antenna elements are placed in a single panel, the idea of distributing Massive MIMO antennas over a larger space allows for multiplexing user data streams using their spatial signatures[221]. This is highly relevant to spectrum sharing as well, as it adds the spatial component to it. It also allows an operation of Massive MIMO system in the unlicensed band (Massive MIMO unlicensed, mMIMO-U)[222] where the multitude of antennas at the base station is used both to multiplex the users and to suppress interference at neighbouring devices through spatial nulling.

If we combine Massive Distributed MIMO and the C-RAN we mentioned before, it adds improved spectrum efficiency and network capacity and enables a choice of renting more antennas or more spectrum for the market players[223] in an extreme sharing environment where sharing on anything in the pool of highly heterogeneous resources is possible[224]. This is where new trade-offs emerge, opening different business models: to meet the expectations of 5G, aggressive sharing is going to be needed[225]. MIMO, C-RAN and sharing models go well together, as they all stem from a sharing-like concept.

[218]Marzetta, T.L., 2010. Noncooperative cellular wireless with unlimited numbers of base station antennas. IEEE Transactions on Wireless Communications, 9(11), pp.3590-3600.

[219]Boccardi, F., Heath, R.W., Lozano, A., Marzetta, T.L. and Popovski, P., 2014. Five disruptive technology directions for 5G. IEEE Communications Magazine, 52(2), pp.74-80.

[220]Shafi, M., Molisch, A.F., Smith, P.J., Haustein, T., Zhu, P., De Silva, P., Tufvesson, F., Benjebbour, A. and Wunder, G., 2017. 5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice. IEEE Journal on Selected Areas in Communications, 35(6), pp.1201-1221.

[221]Ozgur, A., Lque, O. and Tse, D., 2013. Spatial degrees of freedom of large distributed MIMO systems and wireless ad hoc networks. IEEE Journal on Selected Areas in Communications, 31(2), pp.202-214.

[222]Geraci, G., Garcia-Rodriguez, A., L-Pz, D., Bonfante, A., Giordano, L.G. and Claussen, H., 2017. Operating massive MIMO in unlicensed bands for enhanced coexistence and spatial reuse. IEEE Journal on Selected Areas in Communications, 35(6), pp.1282-1293.

[223]Avdic, E., Macaluso, I., Ahmadi, H., Gomez-Miguelez, I., Ingolotti, L., Marchetti, N. and Doyle, L., 2016. LSA-Advanced and C-RAN: A (5G) Romance of Many Dimensions. arXiv preprint arXiv:1606.02142.

[224]Doyle, L., Kibilda, J., Forde, T.K. and DaSilva, L., 2014. Spectrum without bounds, networks without borders. Proceedings of the IEEE, 102(3), pp.351-365.

[225]Mitola, J., Guerci, J., Reed, J., Yao, Y.D., Chen, Y., Clancy, T., Dwyer, J., Li, H., Man, H., McGwier, R. and Guo, Y., 2014. Accelerating 5G QoE via public-private spectrum sharing. IEEE Communications Magazine, 52(5), pp.77-85.

The 5G context is necessarily the context of extreme densification and by default incorporates the idea of small cells[226]. Small cells are a concept existing in the cellular network design for a long time[227] but had to face technological challenges of configuration, optimisation and resource allocation, to name a few[228]. Small cells are both a technological enabler for granular, modular geographic sharing and a venue for the decoupling of infrastructure, spectrum and service, fast spectrum sharing[229] and spatiotemporally aware sharing[230].

2.3.4 *Pre-CBRS Sharing*

The potential of previously discussed technologies for putting spectrum to more efficient use and enabling greater sharing has been recognised by the FCC through the following four regulatory developments: (1) recognition of the role of SDR and CR technologies[231], new and smart frequency agile radios allowing more intensive, dynamic and use-per-need spectrum usage; (2) the role of secondary markets in moving spectrum to more efficient use[232]; (3) introduction of trunking technologies in the VHF and UHF bands where the public land mobile radio service (PLMR) of public safety networks share the channels[233]; (4) expanding the unlicensed spectrum and introducing more flexibility via dynamic frequency selection (DFS) and transmit power control (TPC) techniques in the 5 GHz bands where Unlicensed National Information Infrastructure (U-NII) devices are sharing spectrum with military radars[234,235].

All of these developments in one way or another enable dynamic spectrum sharing policy shift. They give clear ways for decentralised decision making, relying on more localised information in spectrum sharing environments. They enable a way for using

[226] Andrews, J.G., Buzzi, S., Choi, W., Hanly, S.V., Lozano, A., Soong, A.C. and Zhang, J.C., 2014. What will 5G be?. IEEE Journal on selected areas in communications, 32(6), pp.1065-1082.

[227] Davi, G., 2004. Using picocells to build high-throughput 802.11 networks. RF DESIGN, 27(7), pp.16-23.

[228] Hoydis, J. and Debbah, M., 2010. Green, cost-effective, flexible, small cell networks. IEEE Communications Society MMTC, 5(5), pp.23-26.

[229] Berry, R., Honig, M.L. and Vohra, R., 2010. Spectrum markets: motivation, challenges, and implications. IEEE Communications Magazine, 48(11).

[230] Zhou, H., Berry, R., Honig, M.L. and Vohra, R., 2013. Complexity of allocation problems in spectrum markets with interference complementarities. IEEE Journal on Selected Areas in Communications, 31(3), pp.489-499.

[231] Report and Order, In the Matter of Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies, FCC 05-57, ET Docket No. 03-108, at 1 (March 11, 2005)

[232] In the Matter of Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, WT Docket No. 00-230, Memorandum Opinion and Order, 2004

[233] Federal Communications Commission, "Replacement of Part 90 by Part 88 to Revise the Private Land Mobile Radio Services and Modify the Policies Governing Them," PR Docket No. 92-235, Report and Order and Further Notice of Proposed Rulemaking, 10 FCC Rcd 10,076 (1995)

[234] Federal Communications Commission, "Revision of Parts 2 and 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band," Report and Order, ET Docket No. 03-122, 18 FCC Rcd 24484 (2003). Available: `http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-287A1.pdf`.

[235] Federal Communications Commission, "Revision of Parts 2 and 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band," Memorandum Opinion and Order, 21 FCC Rcd 7672 (2006). Available: `http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-06-96A1.pdf`

spectrum as per need, for example pooling the channel for conversation and releasing it after transmission is over without having an exclusive assignment to individual channels. They also give a way of monitoring spectrum use, detecting unused channels and ability to adjust transmit power according to the conditions detected in the sharing environment. We will briefly describe the two precedents for dynamic spectrum sharing in the FCC policy prior to CBRS regulatory developments: land mobile radio sharing and the 5 GHz sharing.

2.3.4.1 *Sharing in Land Mobile Radio (LMR) bands*

Public safety networks are emergency responders users of spectrum such as police, firefighters, medical emergency services. Prior to introduction of the trunking technology, the Private Land Mobile Radio (PLMR) services relied upon conventional technologies until the 1980s. They have been allocated large portions of spectrum for individual use despite the sporadic nature of their spectrum usage. PLMR stations were licensed in various parts of VHF and UHF bands functioning as private dispatch communications, i.e. between a dispatcher and mobile units in the field and they were not connected to public mobile telephone service networks. They operated robust networks (high transmitter power and high antenna sites to achieve wide-area coverage) and thousands of local public safety agencies owned their transmitters. Any signal transmitted from a single fixed antenna was received by all users within its coverage area. Some dispatchers had multiple channel to select from and use for one communication session. As Peha describes[236], if the police officer asks a dispatcher a question all of the responders miles away also receive the answer and they could not simultaneously use the channel for other communications. To avoid interfering with each other, the rules specified using the listen before talk (LBT) protocols. This was a command and control structure where high degree of coordination was needed between the units and spectrum was underutilised and used inefficiently. The fragmented approach of the FCC to public safety spectrum meant that independent local governments would each decide on their own public safety agencies: building large networks and getting individual licenses without the need for it. And as Peha argues as well, this kind of fragmented approach to policy in which every police department can purchase its own infrastructure produced systems that do not interoperate resulting in communications infrastructure that costs more and consumes more spectrum than it should[237].

That changed with the introduction of trunking for PLMR services in the 800 and 900 MHz bands[238] which is essentially a technique of pooling the channel from the

[236]Peha, J.M., 2007. How America's fragmented approach to public safety wastes money and spectrum. Telecommunications Policy, 31(10-11), pp.605-618.

[237]Ibid.

[238]In the Matter of 1998 Biennial Regulatory Review -- 47 C.F.R. Part 90 - Private Land Mobile Radio Services Replacement of Part 90 by Part 88 to Revise the Private Land Mobile Radio Services and Modify the Policies Governing Them and Examination of Exclusivity and Frequency Assignment Policies of the Private Land Mobile Services. WT Docket No. 98-182, PR Docket No. 92-235, Report and Order and Further Notice of Proposed Rulemaking, July 2000.

available set to carry out conversations temporarily and per need and releasing the channel for another use after the message is transmitted. Similarly to cellular technology which divides the region into cells and transmits a message only in the cells where recipients are, reusing the same communication channel while transmitting multiple messages - trunking is spectrally more efficient technology in that it allows public safety networks to dynamically share the channels. This dynamic channel assignment happens either via centralised or decentralised trunking systems. Hatfield and Tenhula[239] provide an elaborate case study of the regulatory developments around land mobile radio as precedent of dynamic spectrum sharing and develop the idea of decentralised trunking further through its connections with CR techniques. Decentralised trunking is characterised with the constant monitoring of channel activity inside and outside the trunked system and transmission happens only when open channel is detected. Instead of storing the information on the pooled channels and having a dedicated channel control in a centralised manner, in decentralised trunking system all radio units continuously scan all of the pooled channels in the system[240].

The PLMR dynamic spectrum sharing precedent is a type of frequency coordinated sharing among equals. A community of public safety networks is very specific and tends to manifest more cooperative spirit than other types of spectrum users. Public safety communications systems need reliable wireless communications as they save lives. And still, they are a proof of concept that dynamic sharing does not have to encounter a problem of tragedy of commons[241]. The users did not claim more spectrum than they needed and the trunked LMR systems reduced the incentives of public safety agencies to hoard on spectrum they do not need. Public safety networks comprise a small community and share this spectrum pool in a repeated game and demonstrate a selfless behaviour. They also genuinely want the other agencies with whom their share spectrum with to succeed[242].

2.3.4.2 *Sharing in Unlicensed bands*

Although unlicensed use happens in other bands to a lesser degree (900 MHz, 24 GHz, 60 GHz), the most popular globally unlicensed bands are 2.4 GHz and 5 GHz bands, with pervasive use applications such as Wi-Fi, Bluetooth, Zigbee with new flavours of Wi-Fi being devised continuously under the IEEE 802.11x standards and protocols[243]. Successful attempt of a common standardisation enabled smooth communication of the different vendors' equipment in the band. This was an incentive

[239] Hatfield, D.N. and Tenhula, P.A., 2007, April. The Potential value of Decentralized trunking as regulatory precedent for the Introduction of Dynamic Spectrum Access technology. In 2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (pp. 597-605). IEEE.

[240] Bernthal, J.B., Brown, T.X., Hatfield, D.N., Sicker, D.C., Tenhula, P.A. and Weiser, P.J., 2007, April. Trends and precedents favoring a regulatory embrace of smart radio technologies. In 2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (pp. 633-648). IEEE.

[241] Hardin, G., 1968. The tragedy of the commons. science, 162(3859), pp.1243-1248.

[242] Peha, J.M., 2009. Sharing spectrum through spectrum policy reform and cognitive radio. Proceedings of the IEEE, 97(4), pp.708-719.

[243] The IEEE 802.11 Working Group is charged with developing standards for wireless local area networking devices. `http://grouper.ieee.org/groups/802/11/#`

for each equipment manufacturer to create devices that do not cause interference to others. The type of dynamic, horizontal sharing that happens in unlicensed bands is characterised by having different operators occupying the same spectrum at different times. The occupancy of spectrum is guided by fair use criteria prescribed by the regulator, like listen-before-talk LBT protocols. The politeness protocols devised by the industry standards bodies can be thought of as machine versions of the human rules which amateur and CB radio operators were expected to use[244].

Due to users having to accept some degree of interference in order to operate, the unlicensed bands are the bands of emerging technologies. It originated with the FCC decision in 1985 to expand the Part 15 rules[245] to allow for unlicensed use for communications in 900 MHz, 2.4 GHz and 5 GHz bands, known as "garbage bands" inhabited only by microwave ovens. These became spread spectrum technology bands[246], due to it enabling more devices to operate in the band with minimum interference.

The significant technology innovations are what marks the explosive success of Wi-Fi bands. One of them is cellular operators integrating Wi-Fi networks within their infrastructure and offloading data traffic on Wi-Fi. The smaller cells of Wi-Fi have proven to reuse the limited spectrum more efficiently and reduce congestion of cellular networks. The spread spectrum bands such as ISM bands (2.4 GHz) had the aggregate spectral efficiency, according to Thanki in 2012[247] at least 30 times greater than the overall efficiency of any cellular band. The majority of all spectrum is exclusively licensed (government and commercial spectrum) and the majority of all traffic is carried by Wi-Fi[248]. The studies that dealt with the estimate of the value of Wi-Fi suggest how highly valuable the Wi-Fi has been for the economy[249,250,251]. The most recent study, comissioned by Wi-Fi Alliance[252]estimates the global economic value of Wi-Fi in 2018 to be nearly $2 trillion, and is expected to grow to almost $3.5 trillion by 2023.

Unlicensed bands started hosting innovative technologies and network deployments (spread spectrum techniques, MIMO, OFDM) earlier than licensed bands started host-

[244]Thanki, R., 2009. The economic value generated by current and future allocations of unlicensed spectrum. Perspective Associates.

[245]Part 15 is the part of Title 47 of the Code of Federal Regulations that governs the deployment of all equipment that radiates radio energy, whether intentional or unintentional. It sets the general requirement for a license, as well as a range of exemptions from licensing. See 47 C.F.R. 15.1 et seq. (2012).

[246]Amendment of Parts 2 and 15 of the Commission's Rules Regarding Spread Spectrum Transmitters, ET Docket No. 96-8 RM-8435, RM-8608, RM-8609
REPORT AND ORDER, Federal Communications Commission, 1997.

[247]Thanki, R., 2012. The economic significance of licence-exempt spectrum to the future of the internet. White Paper.

[248]Ibid.

[249]Thanki, R., 2009. The economic value generated by current and future allocations of unlicensed spectrum. Perspective Associates.

[250]Milgrom, P.R., Levin, J. and Eilat, A., 2011. The case for unlicensed spectrum. Available at SSRN 1948257.

[251]Cooper, M., 2012. Efficiency gains and consumer benefits of unlicensed access to the public airwaves: The dramatic success of combining market principles and shared access. Boulder, CO: University of Colorado. Available at `http://consumerfed.org/pdfs/EFFICIENCYGAINS-1-31.pdf`.

[252]R. Katz and F. Callorda, 2018. The Economic Value of Wi-Fi: A Global View (2018 and 2023).

ing CDMA and TDMA applications of spread spectrum in their cellular networks. As Thanki[253] writes,

> Licence-exempt communications adopted more resistant digital encoding more than five years before cellular technologies and Wi-Fi was the first major communications technology to utilise spread spectrum – originally used by the military for robust undetectable communication. Wi-Fi also pioneered the use of the more robust OFDM modulation method. More recently advanced antenna techniques that allow spatial multiplexing and beamforming have been introduced first into Wi-Fi, enabling greater throughput or more robust links at a given power output.

Compared to cellular exclusive bands, unlicensed bands are less subject to regulatory errors in particular when it comes to packaging and technical requirements of licenses that are auctioned. Once they are auctioned, licenses cannot be revoked and secondary markets have not been effective in transfer of the rights to more efficient spectrum use[254].

The U-NII dynamic spectrum sharing, precedent of CBRS in sharing government spectrum, is a type of uncoordinated sharing among equals and hierarchical sharing. Besides sharing among themselves, the U-NII devices are also sharing spectrum with military radars in 5 GHz bands. When PCAST report recommended to improve spectral efficiency by requiring federal agencies to share their unused spectrum with commercial users, they stated that such proposal builds on the success of Wi-Fi sharing spectrum with military radars in 5 GHz band. What enables U-NII devices to utilise the 5 GHz bands where the military radar is the primary user are the interference avoidance technologies, DFS and TPC. DFS is a CR technology of signal detection and interference avoidance which monitors spectrum and selects free frequency for operation. U-NII devices are defined under Part 15 Rules, among other four types of intentional radiators (low power devices, spread spectrum devices, unlicensed PCS devices, and UWB devices). The U-NII regulations specify power restrictions for each of the 5 GHz bands (5.15–5.25 GHz, 5.25–5.35 GHz, and 5.725–5.825 GHz) and the out-of-band emissions. Apart from that, there are no other restrictions and any device that meets these requirements can enter the band and transmit any time, accepting the interference and not complaining about it. As devices are required to stop the transmission if they do not have to use the spectrum and have no information to transmit, this kind of sharing is a great promise for more efficient spectrum use.

The devices that operate in unlicensed bands sharing the spectrum dynamically in an uncoordinated way, have been intentionally designed to anticipate and cope with the channel noise. Their economic success and significance is due to innovative use of technology, which in turn had a positive outcome for spectrum utilisation efficiency. It is simply because in unlicensed bands users face the competition and have incentives

[253] Thanki, R., 2012. The economic significance of licence-exempt spectrum to the future of the internet. White Paper.

[254] Ibid.

to use more efficient technologies due to constant potential threat of interference, but are not expecting long term guarantees for their services nor investing in those kinds of licenses. They rely on technology completely and therefore develop innovative cooperation and coexistence strategies for their band operations.

2.3.5 *Takeaway points*

The level of development of technologies capable of supporting spectrum sharing speaks volumes against regulatory approach to managing spectrum with the interference protection as a priority over sharing it. Geo-location database technologies, sensing and detection of interference as well as the ability of networks to coexist even in the presence of interference make the building blocks for a sustainable spectrum sharing system in which the accurate spectrum availability and usage information is maintained and monitored in real-time. The radio environment in which diverse technologies coexist in spectrum bands is the one of controlled interference without exclusivity. The exclusivity within the configuration of spectrum rights of use means precluding other users from using the unused, protected spectrum. This is a matter of regulatory approach to a licensing model, dependent on the enabling coexistence technologies.

2.4 REGULATION

In this section, we take a regulation perspective on spectrum. As everything else we have seen so far, sharing has to go through formalisation: regulatory entities have to define the rules of spectrum sharing, frame it through a legal apparatus, approve and communicate to the stakeholders. The stakeholders are a diverse group when it comes to their attitudes about sharing. This story is told from the perspective of academic involvement in regulatory decision process, which we consider important. It can take two paths and in our opinion, the less productive one is levitating without getting our feet wet in the context. We should immerse in the fluid reality of regulatory framework design process, the cumbersome, long back-and-forth journey. Building on the (in this thesis already overused) ocean metaphor, the proper exploration of the Big Blue asks for a proper vessel: this is where the technology, economy and social context come in play to keep us on the surface and not drown in the administrative depths. To fully appreciate this, let us make a brief description of what lurks in the deep.

It's an ecosystem, a complex community of a myriad different bodies, decision making levels, mandates and approvals for sharing to become reality. Robust as it may seem, a lot of the components of this system find themselves on the critical path and in possession of emergency brakes. In any given moment, the administrative process of regulation can be stopped, slowed down and pushed back to the start. Here, the stakeholders are the game changers. The regulator develops the spectrum management strategy, usually on band-by-band basis and opens the consultation asking for the stakeholders' comments. Stakeholders respond to the call for input by submitting their opinions and policy positions in the form of technical and economical comments and proposals. Whether the regulator's reaction to the submitted content is proactive, adequate, timely and concrete depends on several things. Different regulators have different structure for this process. We will illustrate the differences through our own experiences.

2.4.1 *Regulatory Developments Towards Sharing*

The timeline of this thesis matches closely the timeline of the emerging sharing models in EU, UK and US.

Our work started at the same time the Licensed Shared Access (LSA) emerged on the level of ECC mandate about mobile broadband in 2.3GHz[255] in the EU member states, for the 28 CEPT countries. In the earliest days of defining LSA we pushed for the more dynamic solution for sharing arrangements than it was conceived by the regulator. Within the EU project[256], we investigated the regulatory approach to LSA and use case scenarios that could unlock the potential of sharing in a more dynamic way[257,258,259,260] than envisioned.

Ofcom followed suit. They opened two consultations in 2016: publishing their spectrum strategy[261] aiming to assess sharing opportunities and asking for first, comments on more innovative use for 3.8-4.2GHz band[262] and then on improving consumer access in 3.6-3.8GHz band[263]. This opened a window to advocate for sharing and that is what we have done[264,265]. Window is a window though, and not a door, so when it was closed in the 3.6-3.8GHz band, their response showed little intention to share. Ofcom decided to consider an award for this band and make a decision in 2018, but it looks like the 116 MHz available in this band will be treated similarly to the 2.3GHz and

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[255] 2013, European Commission, Draft Mandate to CEPT to develop harmonised technical conditions for the 2300-2400MHz ("2.3GHz") frequency band in the EU for the provision of wireless broadband electronic communications services.

[256] `http://www.fp7-adel.eu`

[257] Gomez-Miguelez, I., Avdic, E., Marchetti, N., Macaluso, I. and Doyle, L., 2014, May. Cloud-RAN platform for LSA in 5G networks—Tradeoff within the infrastructure. In Communications, Control and Signal Processing (ISCCSP), 2014 6th International Symposium on (pp. 522-525). IEEE.

[258] Morgado, A., Gomes, A., Frascolla, V., Ntougias, K., Papadias, C., Slock, D., Avdic, E., Marchetti, N., Haziza, N., Anouar, H. and Yang, Y., 2015, June. Dynamic LSA for 5G networks the ADEL perspective. In Networks and Communications (EuCNC), 2015 European Conference on (pp. 190-194). IEEE.

[259] Avdic, E., Macaluso, I., Ahmadi, H., Gomez-Miguelez, I., Ingolotti, L., Marchetti, N. and Doyle, L., 2016. LSA-Advanced and C-RAN: A (5G) Romance of Many Dimensions. arXiv preprint arXiv:1606.02142.

[260] ADEL FP7 project, 2014. Project Deliverable D3.1: Reference scenarios, network architecture, system and user requirements and business models. Available at: `http://www.fp7-adel.eu/deliverables.html`

[261] `https://www.ofcom.org.uk/__data/assets/pdf_file/0028/68239/statement.pdf`

[262] `https://www.ofcom.org.uk/consultations-and-statements/category-2/opportunities-for-spectrum-sharing-innovation`

[263] `https://www.ofcom.org.uk/__data/assets/pdf_file/0017/103355/3-6-3-8ghz-statement.pdf`

[264] `https://www.ofcom.org.uk/__data/assets/pdf_file/0031/85198/connect_research_centre_for_future_networks_and_communications_trinity.pdf`

[265] `https://www.ofcom.org.uk/__data/assets/pdf_file/0037/96895/CONNECT.pdf`

3.4GHz bands announced to be auctioned[266,267]. For the second band in question, 3.8-4.2GHz, we still do not have responses to comments and the UK government seems very motivated to open this band for sharing within their 5G strategy[268]. However, the details and the real strategy are deferred to later time since they are hesitant to make moves on this band "given the uncertainties around when suitable equipment will be available and when innovative 5G use cases will be developed".

In the third episode, we engage with the FCC. After the turn of the tide caused by the Presidential Council of Advisors on Science and Technology (PCAST) paradigm shifting report in 2012[269], which came as a reaction to the President addressing issues of radio spectrum[270], technology and regulation were drawn closer. It wasn't done by hindering the technology, for a change, but by fostering more progressive regulation. With the Notice of Proposed Rulemaking (NPRM)[271] of 2012, which was the fast response of the FCC to the PCAST initiative, a docket GN 12-354[272] was opened to consult and work out the design of this new, innovative sharing regime, with a focus on 3.5GHz band. This is the case study of the thesis. The consultation process with the FCC we formally experienced in 2017[273], but also implicitly four kilometers and four census tracts away from FCC headquarters, presenting a paper at Globecom 2016, on the shortcomings of the licensing regime in the 3.5GHz band[274].

How do FCC and Ofcom compare then? Speaking from the perspective of a stakeholder engaging in interaction with both, we first note that we *had* this opportunity to engage[275]. Both regulators have an instrument to listen to the stakeholders' views and a culture of using it has been shaped. The general public saw it in the ongoing saga about net neutrality, where the system was hacked revealing its vulnerabilities and strengths, and most importantly its existence. It is akin to calling your Senator or your Member of Parliament, something significant parts of Europe have never had. Of

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[266] https://www.ofcom.org.uk/__data/assets/pdf_file/0022/103819/Statement-Award-of-the-2.3-and-3.4-GHz-spectrum-bands-Competition-issues-and-auction-regulations.pdf
https://www.ofcom.org.uk/about-ofcom/latest/media/media-releases/2017/ofcom-sets-rules-for-mobile-spectrum-auction

[267] Third parties call it an auction, slide 21.
https://www.qualcomm.com/media/documents/files/spectrum-for-4g-and-5g.pdf

[268] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/672118/Next_Generation_Mobile_Technologies__An_Update_to_the_5G_Strategy_for_the_UK_Final_Version_with_Citation.pdf

[269] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf

[270] https://www.gpo.gov/fdsys/pkg/DCPD-201000556/pdf/DCPD-201000556.pdf

[271] Federal Communications Commission, 2012. Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band, Enabling Innovative Small Cell Use In 3.5 GHz Band NPRM & Order. Available at: https://www.fcc.gov/document/enabling-innovative-small-cell-use-35-ghz-band-nprm-order

[272] https://www.fcc.gov/rulemaking/12-354

[273] *See* Comments of Elma Avdic, Irene Macaluso and Linda Doyle, available at: https://ecfsapi.fcc.gov/file/1124135896869/Comments_CBRS_EA_IM_LD.pdf

[274] Avdic, E., Macaluso, I., Marchetti, N. and Doyle, L., 2016, December. Census Tract License Areas: Disincentive for Sharing the 3.5 GHz band?. In Global Communications Conference (GLOBECOM), 2016 IEEE (pp. 1-7). IEEE.

[275] As a stakeholder, you know that you have this instrument for your voice to be heard. It's a game controller which may or may not be plugged in, but makes you feel a bit empowered to act on the issues close to your heart, brain or wallet - depending on the stakeholder category you fall in.

course, it would be naive to ignore lobbying and the "monetary comments" circulating. Maybe because of the sheer size of the market and therefore number of stakeholders, the FCC responds to comments in a more proactive way than the Ofcom. The FCC and Ofcom have a very similar governing structure for the decision making: with the chairman and chiefs of executive board and different technical and advisory committees as part of the whole government regulatory body. Ofcom is modeled after the FCC, according to some accounts[276].

Being involved in EU project that deals with spectrum sharing, one soon becomes famliarised with the EU regulatory structures about spectrum: the EC and the ECC with decisions and the system reference documents, the RSPG advisory group, the RRS and ETSI and NRAs, national regulatory authorities within the CEPT countries[277]. The EC has a system of listening the stakeholders from academia, through involving them in their different working groups, presenting ideas and working together towards technical standards of the solutions proposed.

To an extent, the EU regulatory structure resembles the one seen in national regulatory bodies like FCC and Ofcom[278]. However, the telecommunications world has

[276] Newcomb, H. ed., 2014. Encyclopedia of television. Routledge.

[277] `https://en.wikipedia.org/wiki/ITU_Radio_Regulations`

ITU-R Radio Regulations (RR) and European harmonisation measures provide key references to administrations for their national spectrum management, from a global point of view. The RR allocates frequency bands to Radiocommunication Services, which as a result provides an international regulatory and economic environment that facilitates the development of specific applications. In the area of mobile communication, the identification of specific bands for IMT is generally seen as a key enabler in the development of mobile broadband technologies. ITU issues Recommendation Reports and Radio Regulations.

At regional level, important organisations are CEPT, EC and ETSI.

CEPT, (Confnce Europne des Postes et des Tcommunications): policy makers and regulators from 48 countries across Europe collaborate to harmonize telecommunication, radio spectrum and postal regulations. CEPT issues Decisions, Reports and Recommendations.

EC, the European Commission, which is the Executive Body of the European Union and is composed of various departments or directorate generals (DG). EC issues important Decisions and Recommendations.

ECC, Electronic Communications Committee, expert group within CEPT responsible for developing common policies and regulations in electronic communications and related applications for Europe and harmonising spectrum use

The Radio Spectrum Policy Group (**RSPG**), which is a high-level advisory group, assists the EC in the development of radio spectrum policy.

ETSI, the European Telecommunications Standards Institute, is responsible for most of the European telecommunication standardization activities. Within ETSI, the ETSI Technical Committee (TC) on Reconfigurable Radio Systems (ETSI-RRS) is working on the standardization of SDR (software-defined radio) and CR (cognitive radio) technologies, while the ETSI TC on Electromagnetic Radio Matters (ETSI-ERM) is working on radio-frequency and spectrum-related issues. ETSI is in charge for developing standards and initiating their harmonisation.

CEPT develops further harmonisation of the use of radio frequencies in order to create economies of scale, border coordination and interoperability. In the area of mobile broadband communications, this is illustrated by numerous **ECC Decisions** setting out a single or preferred channel plan for the use of designated bands.

Another standardization group working on this subject is **IEEE DySPAN-SC** which develops supporting standards dealing with new technologies and techniques for next generation radio and advanced spectrum management. Its working group 1900.6 specifies spectrum sensing interfaces and data structures that are useful for LSA. `http://cn.committees.comsoc.org/files/2016/05/ICC16_DySPAN-SC_Update.pdf`

[278] The standardization body in the US is WinnForum, in the EU it is ETSI; the PCAST technical advisory committee resembles the RSPG advisory group reporting to the EC etc. Note that the UK regulation is performed by Ofcom and is a separate regulatory body from the EU regulatory structures.

been nationalised through and through from its birth. The EU institutions and their supra-national character linger between the international organisations like the ITU and national regulatory authorities NRAs as a hybrid: too strong to be ITU, too weak to be the the FCC. The story of CEPT is not unlike the story of EBU, widely seen as the organiser of the Eurovision song contest and the producer of the Vienna Philharmonic New Year concert. The voluntariness principle that EU member states can act upon is no match to the level of autonomy, if any, regions have in nation states. In the US, member states cannot act upon something not aligned with the FCC[279]. If the EU had been introduced after WWI, there is a chance that we would have common allocation throughout the continent, but after decades of entrenched well established allocation tables within national borders finding a common ground without much effort is impossible.

The LSA can serve as an example with diverse incumbents in the 2.3GHz band across the continent.

2.4.2 *LSA in a Nutshell*

The question of why the CBRS model is a case study and not the LSA has an answer that is going to come as a natural one at the end of this section. This is the LSA regulatory review - what LSA is in terms of regulatory framework that defines it[280]. The concept evolved from the Authorised Shared Access (ASA) model, initially proposed by the industry (Qualcomm and NSN)[281]. Following up on the industrial initiative, Radio Spectrum Policy Group (RSPG) published the first report on spectrum sharing models, extending the ASA concept to a more general model, LSA[282].

The LSA is defined as[283]:

> A regulatory approach aiming to facilitate the introduction of radiocommunication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the LSA framework, the additional users are allowed to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorized users, including incumbents, to provide a certain QoS.

[279] `https://arstechnica.com/tech-policy/2017/11/fcc-will-also-order-states-to-scrap-plans-for-their-own-net-neutrality-laws/`

[280] Without diminishing the importance of the enormous effort that researchers made in exploring the possibilities of LSA, this is what is relevant to the rest of the thesis - as a materialistic viewpoint on LSA.

[281] Nokia Siemens Networks, Qualcomm; "Authorised Shared Access - An evolutionary spectrum authorisation scheme for sustainable economic growth and consumer benefit", Input Document FM(11)116 to the 72nd Meeting of the WG FM, Miesbach- Germany, 16 – 20 May 2011.

[282] Radio Spectrum Policy Group, "Report on Collective Use of Spectrum (CUS) and other spectrum sharing approaches", RSPG (11)-392 Final, November 2011.

[283] Radio Spectrum Policy Group, "RSPG Opinion on Licensed Shared Access", RSPG13-538, 12 November 2013

This definition places LSA as a complementary spectrum management regime to the license-exempt approach, meaning that it becomes an individual license authorisation which gives a possibility (to the licensee) to finely manage network deployment and (to the incumbent) to control the sharing arrangement. The licensee is specifically envisioned as an mobile network operator (MNO)[284], which implies that a new player cannot base its business model solely on arrangements in LSA bands. In other words, the LSA spectrum is seen as an additional resource for those already having exclusively licensed spectrum elsewhere. The incumbent is the primary holder of rights in the band and owns the piece of spectrum that is supposed to be shared with an MNO under the LSA rules.

The LSA applicability criteria are outlined and interpreted in brief as follows.

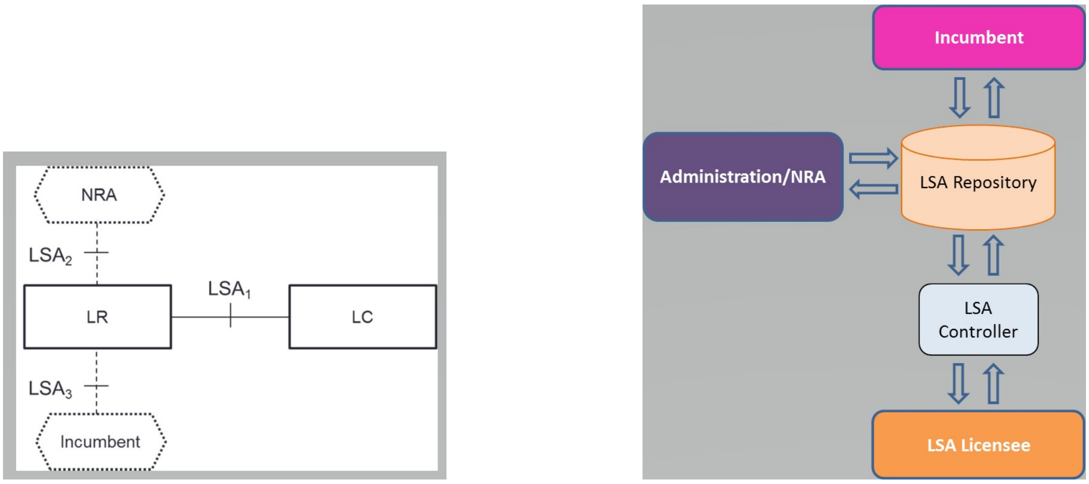
1. The first of the five criteria describing the key conditions for LSA implementation is the *long-term availability* - the incumbent has to inform the LSA licensee of the spectrum availability for the whole duration of the sharing framework, which in legacy timescales could mean decades.

2. The incumbent decides on whether to share or not and under which initial conditions. Sharing is not mandated by the regulator in any way, as the second LSA criteria defined is *voluntariness*.

3. The conditions may or may not include a compensation fee, sort of reward for giving up on parts of spectrum that were not being used anyway. A fair share of incumbents did not pay for the spectrum to get into the bands and they were simply "born" there. This opens a moral question of compensating the incumbents for their birth right but in terms of motivations to share and the incentives, the third criterion asks for dozens of person-years of *discussions* between the incumbent (the proactive volunteer) and the LSA licensee. Of course, this goes through the regulator, just like every other communication between the two interested parties. The document states that "LSA should be based on incentive and market demand" which gives an idea of what the discussions are about. Incumbent gets a compensation, monetary or equivalent (access to new markets through the licensee, or the infrastructure they normally do not have) and the long term security is an incentive strong enough on its own. The licensee gets to build a long term business model with no strings attached in terms of coverage obligations, unlike what they already have in their exclusive licenses. This implies that it is a form of doing business on the side, akin to renting a car to work as an Uber driver in afterhours.

4. The fourth criterion is the *exclusivity* among LSA licensees, which can be interpreted as the exclusive incumbent passing on the exclusive badge to the licensee when and where appropriate. The idea is to make the leased spectrum indistinguishable from an owned one in terms of QoS provision. This is supposed to

[284] ECC, WG FM53, "ECC Report 205 – Licensed Shared Access", February 2014.



(a) (b)

Figure 2.2: Reference architecture model of (a) ETSI, (b) ECC Report 205

assure MNOs to incorporate it as a part of the long-term strategy and business model guaranteeing return on investments. The time is not the only big dimension in this picture: so is the space, the licenses are nation-wide. While theoretically the relationship incumbents find themselves in could be poly-licenseeous, with all the administrative and every other burden required to get on the same page with a single licensee and the NRA it is hard to imagine incumbents pursuing several licensees. This results in an essentially one-to-one relationship. The MNO will avail from spectrum only if incumbent says it is available. The inherent exclusivity on the incumbent side is emphasised with their control over "sharing": it is grounded in their right to protect their spectrum, not the right to share it. This is the epitome of property rights.

5. Finally, the criteria list ends with the idea of LSA having a role in global *harmonisation* of harmonisable bands. For this mission, the EU's own harmonisation in the first LSA bands will be the proof of concept.

To briefly explain what the blocks of an LSA system are and the mechanisms of their interaction, we will look at the reference architecture model[285] and a functional block architecture[286] of the LSA system shown in Fig. 2.2.

The interaction between the incumbent and the NRA goes through a database which is supposed to store incumbent spectrum usage statistics (when, where and how is spectrum being used or not used) in order to identify the spectrum that will be available for sharing under LSA. It was named LSA repository, LR. If the licensee was directly connected to the LR, the NRA would lose the ability to control the sharing and so would the incumbent. And to protect everyone from everybody, a gate and a gatekeeper were installed half-way between the licensee and the LR: the LSA con-

[285] ETSI TS 103 235 (V1.1.1, 2015-10), System architecture and high level procedures for operation of Licensed Shared Access (LSA) in the 2,300 MHz–2,400 MHz band.

[286] ECC Report 205, 2014. Licensed Shared Access.

troller, LC. The database was interfaced toward the NRA, incumbent and controller (as an intermediary to the licensee). The interface protocols are designed and specified in the relevant ETSI documents. As far as the control and management of the database is concerned, ETSI leaves space for the NRA or a higher EU regulator administration, a third party and the incumbent[287]. The prescription is the same for the controller, except it's the licensee who gets a chance to run it. "Gets a chance" might be too mild of a statement, as the controller has been generally perceived to be placed within the MNO network domain. Incumbent has no interaction with the controller, except via the database. The controller gates the OA&M module of an operator's network and processes the information retrieved from the database about the incumbent spectrum. The protocols for inter-block communication, the interfaces and the whole structure of the LSA system elements are put in place to protect and control.

To put the LSA regulatory scheme under the scope of features of dynamic spectrum sharing introduced in Chapter 1 and verified throughout this chapter, the LSA features can be summarised as follows:

- LSA prioritises guaranteeing spectrum access and protecting from the interference over sharing. The NRA does not seem to mandate sharing: use all the spectrum available and all the time. Instead, it will happen only if the incumbent expresses the willingness to do so, which means sharing will be an exception and protection is by default. It is also about creating a new incumbent, the MNO licensee who benefits from some additional LSA spectrum via what comes down to spectrum leasing. And it is about protecting MNOs business interests, ensuring that what they get is what they are used to in their exclusive licenses: QoS guarantee, interference protection, long-term license over the large geographic area (entire country), most likely for forever and all that with the lack of competition.

- Whenever incumbent does not use spectrum, it can submit it to sharing arrangement under LSA. But first, the incumbent needs to communicate the willingness to share to the NRA, in charge of the band in that particular country. The rules then get negotiated through the NRA-incumbent-licensee interaction. This in turn means a huge involvement of the regulator, for even the smallest sharing deals. For an outsider this may seem as a waste of resources, because it is and it also implies how little the LSA diverged from command and control models.

- Competitive bidding is discouraged, both by the explicit statement in ETSI reports and this design which makes the use of auctions not an option, especially the auction designs not recognising NRA as the auctioneer. Neither the incumbent nor the regulator want to go through it. LSA sharing agreement is supposed to happen with a one-on-one sit-down with the NRA.

[287]ETSI TR 103 113 (V1.1.1,07/2013), System Reference Document for LSA: Mobile broadband services in the 2,300 MHz–2,400 MHz frequency band under Licensed Shared Access regime.

- With all of the effort the NRA puts in administering the LSA, monitoring spectrum use has been left out and has no role in LSA system. Efficient spectrum use is not an incentive: there is no efficient spectrum use without competition, diversity and, therefore, innovation. Innovation in technologies, equipment and business models is not enabled by the regulatory design. Network architectures and solutions other than those of traditional licensed carriers are not encouraged and neither is the shared infrastructure, because the regulator does not state: any entity is free to use the LSA spectrum and deploy technology they desire. The rules and technical specifications are set around LTE standards and for a typical MNO network. This closes the door for diversity, together with the requirement for the LSA licensees to be the MNOs.
- There is no guarantee that the licensee will actually use the spectrum of the incumbent. If we had a comprehensive survey of measurement campaigns for the whole Europe in 2.3 GHz band (besides being defined for a specific user, the MNO, the LSA is also set for a specific band) and if the same campaigns were to follow the eventual LSA implementation, it is doubtful if the results would be significantly different. One can imagine a scenario where the licensee is getting a license to share the allocation of the incumbent over the entire country and yet uses it inefficiently in any of the dimensions, spatial (the license areas are huge, nationwide) or temporal (long-term licenses).
- There is no dynamic re-assignment of frequencies. The incumbents' control over the spectrum also means that once they need spectrum back, the licensee has to vacate it and terminate operation.
- The omnipresent and always busy regulator keeps track and decides on a lot, but skips the crucial parts of what should be a proper working sharing model. It has no central place for all users in LSA system, which would guide the sharing by promoting it while controlling the interference and not giving exclusivity: instead it splits the control over spectrum between two players only. The repository-controller axis around which the process revolves is there to make sure the market is closed. The spectrum use will not be monitored once it goes to the MNO, allowing it to be poorly utilised as with the original incumbent.

"L" in LSA might stand for 'leasing', "S" for 'static and "A" for 'assignments'. The way LSA is regulated is a reflection of issuing a license to a single licensee owning and operating particular communication infrastructure, in a dedicated way for a single purpose (application). If this reminds you of a new incumbent replaced by the old one, it is. This is how frequencies get forever reserved for a small number of users. **L**easing **S**tatic **A**llocations might be serving *a* purpose, but not the purpose it originated with.

This discussion aimed to explain one view of LSA and why we are not seeing its wide adoption and implementation[288] across the CEPT countries[289]. General perception in worldwide regulation is that Europe is aggressively going for LSA sharing model, perhaps to make a larger distinction with the wider idea of sharing captured in CBRS sharing model in the US. The reality is that the dynamic sharing with the LSA seems to remain an academic exercise about the regulatory framework that was set, defined and now proceeding with the implementations as crude as it was set from the beginning. Innovation hampered, competition not fostered, dynamic sharing not envisioned by the regulator, the incumbent nor by the licensee.

2.4.3 *CBRS in a Nutshell*

LSA licensed sharing model is two things: traditional and left to the countries' NRAs to deal with. A CBRS model is an attempt to be revolutionary.

To share spectrum under the rules of a spectrum sharing framework, the spectrum users need to be incentivised to share. In any kind of resource use and resource consumption (not necessarily in sharing mode of use), there are incentives to use the resource in a certain way. The use of spectrum resource via sharing puts the question of incentivisation in the focus more, for two reasons. The first reason lies in a general perception of spectrum sharing among the most prominent players on the market - the core belief is that sharing the resource reduces the value (of the resource or more generally, value gained out of the resource utilisation/consumption). The second reason is more specific to spectrum sharing functionality - with sharing, the issues of interference and spectrum rights become more impactful as the network operation of a spectrum user is highly dependent on the neighboring spectrum use so the radio environment changing conditions dictate the functionality of sharing.

Spectrum users get classified by the way they access spectrum: falling under one of the two spectrum management regimes - licensing models. They access spectrum via the rules of exclusively licensed or license-exempt (unlicensed) model. Accessing

[288] `https://cept.org/ecc/topics/lsa-implementation/`

[289] Three years after it has been defined and regulated and trialed (in Finland, CEPT Report 56, approved March 2015. Report B1 from CEPT to the European Commission in response to the Mandate on 'Harmonised technical conditions for the 2300-2400 MHz ('2.3 GHz') frequency band in the EU for the provision of wireless broadband electronic communications services'. Annex 2: Finnish LSA Trial. More information available at: `http://core.willab.fi/`), we are seeing limited, sporadic implementations of the LSA: in Spain, France, Netherlands and Italy:

ECC, Project Team FM PT 52, 2015. LSA Demonstration carried out in the Mobile World Congress, Barcelona;

ANFR, 2015. Rapport d'de de la Commission de Compatibilitectromagnque sur l'utilisation par le service mobile de la bande 2300-2400 MHz en Licensed Shared Access. Available at: `https://www.anfr.fr/fileadmin/mediatheque/documents/etudes/15-04-17_CCE_2015_01_Rapport_LSA_VersionDiffusable.pdf`;

Radiocommunications Agency the Netherlands, G. Petersen, Nov. 2016, Licensed Shared Access pilot in the Netherlands;

Italian Ministry of Economic Development and the Joint Research Centre of the European Commission (JRC), Sept. 2016. LSA pilot Sharing analysis in a live LTE network in the 2.3-2.4 GHz band: Test configuration and results. More information avalable here: `http://www.mise.gov.it/index.php/en/2014-06-27-15-06-15/2033594-licensed-shared-access-lsa-pilot` spectrum in a sharing mode is not classified as a third model of spectrum management - it is believed to encompass users which belong either to exclusively licensed or unlicensed model. What the CBRS framework is introducing through its three-tier access model is a diverse range of users who can belong to both models - via one set of sharing framework rules. Depending on whether they need protection the users can chose to which tier of users to belong: protected one or the one accepting some levels of interference. This is allowed in a dynamic way in CBRS: it enables interchangeability of spectrum users, which is a feature of a dynamic spectrum sharing framework. Based on a demand and supply principle, higher tier user can scale down to lower, and the lower tier can move up and become a higher tier user if aiming for providing services completely protected from interference during operating time. CBRS is a spectrum sharing framework configured as a hybrid licensing model. Whether or not the users are incentivised to belong to one of the licensing models under the spectrum sharing framework is what dictates the success of its implementation.

Therefore, licensing model is the most important way for the regulator to incentivise spectrum users (stakeholders) to use that spectrum under the sharing framework rules. It is a matter of economic, technical and regulatory approach. This work will address the issues of licensing, incentivisation and modalities of regulation by introducing a perspective of culture of sharing to design policies that effectively put spectrum to more efficient use and promote sharing as a predominant way of spectrum usage. As CBRS is our case study, this subsection aimed to briefly introduce the context within the wider perspective on spectrum presented in this chapter.

2.4.4 *Takeaway points*

The regulations in EU, UK and US have been mostly responsive in terms of rulemaking but this type of responsiveness ends with the deliverance of rulemaking results. The responsiveness of regulation when designing spectrum sharing framework in our perspective, asks for the rules to enter a loop to rely on feedback from the ecosystem and the stakeholders.

Despite the feedback mechanism in the rulemaking process, the final rules are still rigid and non-interacting, possible to change only through the same administrative procedure that led to their original creation. What if we had adaptable rules acting on the basis of general principles and able to accommodate new technologies and ways of use as they appear?

2.5 SOCIETY

In this section, we take a social perspective on spectrum sharing to explore what kinds of social norms exist around spectrum sharing behaviour; we observe the norms in spectrum allocation process and in spectrum usage. Despite the lack of its treatment in literature on spectrum, social norms have a larger role to play in spectrum, especially in spectrum sharing. When sharing, spectrum users are highly dependent on neighbouring uses in time, frequency and space; a proper control and coordination to avoid interfering with each other is constantly needed. The efficient use of spectrum is the goal when sharing the spectrum; the potential of the resource can be limited if users engage in disruptive behaviour. And they will if there is no social norm pressure nor legal enforcement. Sustainable spectrum sharing models implemented in the bands ask for cooperation and coexistence, in a dynamic way and in real-time which is today enabled by advanced technology. However, the regulatory and administrative burdens are still not adapted for the new age. As we aimed to show in previous four sections of this chapter, none of the options to change policy came as a result of catching up with the technological change. As spectrum neighbours can operate in close proximity in time, space and frequency, the importance of having a way to predict their behaviour is evident. The mechanism of social norms can help with that. The norms can not only serve as a way to enforce the rules to change the behaviour to a desired outcome, but they can also change the law. Norms are arguably more powerful than the law.

In this section, we draw on publications of norm theorists, economists and legal scholars to: (1) explain the norm and law relationship, (2) make a case for regulating with social meaning for spectrum policy, and (3) to document the existing norms of culture of sharing in wireless context.

2.5.1 *Norms and the Law*

Spectrum policy rules, designed by the regulator, are a law-abiding prescription that shapes the behaviour of spectrum users. Social norms as *consensus sets of beliefs held by people engaged in a collective activity that shapes their behaviour* can have a powerful impact on changing the behaviour in a society. Scholars have explored the impact of norms, providing good overviews[290,291] and exploring the effect of the choice of a regulator, when using norms to send message in order to mobilise action against some social problem. Caldini et al.[292] show that the regulators were more likely to mobilise action on an issue if they communicated the level of others' disapproval to a collective, than the mere descriptions of how others behave. The kind of social pressure that collectives feel has an effect to a desired action. Norm theorist Richard Posner[293] sees norms as "a rule that is neither promulgated by an official source, such as court or legislature, nor enforced by the threat of legal sanctions, yet is regularly complied

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[290] Cialdini, R.B., Demaine, L.J., Sagarin, B.J., Barrett, D.W., Rhoads, K. and Winter, P.L., 2006. Managing social norms for persuasive impact. Social influence, 1(1), pp.3-15.

[291] Ross, L. and Nisbett, R.E., 2011. The person and the situation: Perspectives of social psychology. Pinter & Martin Publishers.

[292] Cialdini, R.B., Demaine, L.J., Sagarin, B.J., Barrett, D.W., Rhoads, K. and Winter, P.L., 2006. Managing social norms for persuasive impact. Social influence, 1(1), pp.3-15.

Caldini et al developed the Focus Theory of Normative Conduct, showing that norms can strongly affect the behaviour when they represented a focused goal.

[293] Posner, R.A., 1997. Social norms and the law: An economic approach. The American economic review, 87(2), pp.365-369.

with (otherwise it would not be a rule)". He also explains social pressure: "some norms are self-enforcing, some norms enforce emotions, some norms are enforced by disapproval, ridicule, ostracism, and some norms are internalized and obeyed out of sense of guilt or shame".

There exists a complex relationship between the law and the norms. Origins of a legal system and governance are within social norms, as first communities were guided by the norms, they had no centralised authority. Besides being "older" than the law, the norms have an interesting effect on the law. When Posner talks about the interaction of law and norms, he states "law both complements and substitutes for norms". Newer scholarship, especially economics literature, has suggested that those who study law should study norms, implying that to change the laws, change of norms is needed[294]. This argument that the effects of formal rules cannot be fully assessed without understanding the informal rules, the norms, which govern individual behaviour was advanced recently, mainly influenced by the work of Nobel laureate Elinor Ostrom on common pool resources (CPR)[295].

As behaviour shapers, law and norms can have a nuanced and dynamic relationship:

- Norms can act on their own, making law irrelevant. The norms of cooperation, for example, can arise without people being obliged by the law to cooperate. A famous example of how norms can govern behaviour making the formal rule irrelevant is given in Ellickson's[296] empirical study showing how property regimes of a legal system had no effect on a community of farmers in Shasta County, CA. Farmers bargained and negotiated amongst themselves to resolve their property disputes. They fixed each others' fences, payed their debts, resolved the cattle trespassing issues and demonstrated an impressive cooperative behaviour, without even understanding what the law is. This example has similarity with the Ostrom's CPR work, showing that the communities can collaborate and cooperate in the production of collective goods when an effective legal regime is absent.

- The law and norms influence behaviour together by acting independently or reinforcing each other. Norm theorists have argued to use the norms to intentionally shape the laws. As McAdams reviews[297], Cooter[298] suggested "decentralisation of the law by incorporating business norms directly into contracts governing the industry in which the norms arise". Sunstein discusses how law can strengthen the norms it embodies or weaken those it condemns[299]. Lessig has called for the regulation of social meaning[300], showing how in a nuanced way law can change

[294] McAdams, R.H., 1997. The origin, development, and regulation of norms. Mich. L. Rev., 96, p.338.
[295] Ostrom, E., 2015. Governing the commons. Cambridge university press.
[296] Ellickson, R.C., 1994. Order without law. Harvard University Press.
[297] McAdams, R.H., 1997. The origin, development, and regulation of norms. Mich. L. Rev., 96, p.338.
[298] Cooter, R.D., 1996. Decentralized law for a complex economy: the structural approach to adjudicating the new law merchant. University of Pennsylvania Law Review, 144(5), pp.1643-1696.
[299] Sunstein, C.R., 1996. On the expressive function of law. University of Pennsylvania law review, 144(5), pp.2021-2053.
[300] Lessig, L., 1995. The regulation of social meaning. The University of Chicago Law Review, 62(3), pp.943-1045.

the norms about certain behaviour in order to change the behaviour (example he gives is how ban on dueling changed the norm of dueling, the norm of honour.). He further argues that without considering the norms you cannot predict the effect of law on a certain behaviour and the state must consider the social meaning of behaviour it seeks to regulate, its interpretative dimension.

In our view, there is a case here for dynamic spectrum sharing systems in wireless context, where cooperation and coexistence are the enablers of a sustainable sharing model. Along the lines of Lessig's "regulating for social meaning", we aim to explore how law can act not just as an enforcer but shaper of the norms to predict behaviours. To predict the sharing behaviour, we need to explore the norms about sharing behaviour: those that have been there, those put forward by the regulator and those that exist in stakeholders' community. The stakeholders' community in spectrum band is small enough to act as a group subject to the norms. Spectrum sharing is a dynamic behaviour, there is a lot of interaction among users, repetitive transactions and it is fairly easy to identify the norm-breakers. As Ellickson argued[301], the norms of cooperation can be powerful without the law in communities where it is easier to identify the norm-breakers. The literature suggests, as Weiser and Hatfield state, that the communities are more likely to cooperate if they know each other[302]. As we will see in chapters to come, stakeholders do "know each other". Their social behaviour in spectrum bands is manifested through them being local neighbours in spectrum space. Being aware of who does and who does not follow a social norm would encourage compliance with the norm. They form alliances and forums, they interact with the regulators frequently through different kinds of instruments: face-to-face meetings[303] and a policy consultation procedure where they express their policy positions on the issues. The dialogue that the regulator hosts is already a norm-shaping element for motivating sharing.

2.5.2 *Initial conditions for Culture of Spectrum Sharing*

Drawing of the definition of norms given in previous section, we define the norms of culture of sharing as *a set of beliefs and behaviours of a community that engages in sharing a resource*. As explained in Introduction, a culture of sharing is a socialised behaviour of the regulators and the stakeholders community: it is their attitudes towards innovation, competition, cooperation, coexistence. The necessary **conditions** that need to

[301] Ellickson, R.C., 1994. Order without law. Harvard University Press.

[302] Weiser, P.J. and Hatfield, D.N., 2005. Policing the spectrum commons. Fordham L. Rev., 74, p.663. "In short, the game theory literature suggests that social norms which address and prevent counterproductive behavior may well arise in repeat games situations, but there are no such guarantees where the parties are not likely to interact with one another on a regular basis."

[303] Ostrom showed how important face-to-face negotiations are to solve the problems of collective action that may arise.

Ostrom, E., 1998. A behavioral approach to the rational choice theory of collective action: Presidential address, American Political Science Association, 1997. American political science review, 92(1), pp.1-22.

exist for the norms of culture of sharing to develop are: (1) a positive perception in a society about the sharing behaviour, and (2) wide adoption of the sharing behaviour. As an evolutionary trait of a community, culture of sharing is also necessarily linked to the resource being shared. Understanding the culture of spectrum sharing involves asking these kinds of questions: (1) What are the examples of culture of sharing developed?; (2) How can we build it for spectrum sharing?; (3) How do we set the initial conditions for its development and what kinds of practices to adopt for a long-term sustainability of a sharing model? The exploration of the third question starts in this section[304] where we aim to establish if the existing climate is suitable for culture of sharing to emerge.

2.5.2.1 *What would the norms of culture of sharing be if they exist?*

Legal, engineering and economic complexities in spectrum policy have been studied, but the literature is lacking studies of norms in telecommunications markets and policy. Despite this gap, the reader should not think that the norms in spectrum policy do not exist. They have always existed but in this section we aim at showing that these are traditional norms which are counterproductive for culture of sharing. For example, the norm of a regulator of over-dimensioning spectrum and allocating it to users which leave it unused only to not be bothered by neighbouring usage in spectrum space is the norm against sharing. The norm that "sharing is bad" is not a good norm for sharing.

We define norms of culture of spectrum sharing as sets of beliefs in spectrum sharing ecosystem that govern the behaviour of the users, that are driving sharing behaviour and affecting the spectrum utilisation efficiency through promoting sharing. If they existed, those would be the norms that build[305]:

- incentives mechanisms so that users feel motivated to share spectrum,
- trust and feedback mechanisms so that users feel at ease to participate in cooperative behaviours while sharing spectrum,
- awareness of importance of productive and reasonable spectrum use,
- transparency.

2.5.2.2 *Examples: Amateur Radio and Wi-Fi bands*

The origins of culture of sharing are in the ham radio community. As De Soto[306] highlights, the amateur radio bands have followed the Ostrom principle of self-monitoring communities. Weisser and Hatfield[307] show how they are a self-enforcing community.

[304] The first question is answered in Chapter 3, and the second question in Chapter 8.

[305] An example of how the existence of culture of sharing would reflect on the rulemaking proceeding and make it look completely different is in the fact that those who would not be "happy to share" would be left outside the inner circle of stakeholders. It is an example of social pressure, discussed earlier.

[306] DeSoto, C.B., 1936. Two hundred meters and down: The story of amateur radio (No. 13). The American Radio Relay League, inc..

[307] Weiser, P.J. and Hatfield, D.N., 2005. Policing the spectrum commons. Fordham L. Rev., 74, p.663.

The HAM operators resolve disputes and issues and act on policy violations without bringing the FCC into it, eliminating the need for public enforcement. The peer pressure in HAM radio operations is taken seriously. There are "voluntary spectrum management leaders" as a supplementary tool for the FCC enforcement process: they police their spectrum community based on social norms by issuing warnings to whoever is violating the norms and the rules. Additionally, there is a form of private enforcement, a group of frequency coordinators monitoring the use of repeaters in HAM radio transmissions and facilitating coordination between users[308]. Buck[309] also highlights the case of HAM radio and acknowledges that social norms are the tool of enforcement and etiquette which practically replace the law. The culture is such that violations of the etiquette means going against the norm of cooperation.

The case of amateur radio is an example of how norms of cooperation can arise without being obliged by the law to cooperate. What makes it work is the social pressure but by the "spectrum managers", they work as a self-enforcing community. The HAM culture demonstrates how norms of resonable and productive spectrum use are effective and significant in regulating their use of spectrum.

Sharing in the unlicensed bands is in many aspects a special case of dynamic spectrum sharing in the way we propose it in the thesis. Wi-Fi bands rely on the ability of technology and owe their success to it; the markets of Wi-Fi as we have seen previously are technology-driven. These bands are also relieved of administrative burden of regulation, as one enabler of putting spectrum to more efficient use.

The norms governing behaviour in Wi-Fi bands are not the norms of fearing the interference or needing guard bands to ensure protection, but instead innovating in technology use to avoid it. They resolve disputes by agreements with the neighbours in spectrum space to tilt their antennas differently. The equipment manufacturers for these bands also have an incentive to minimise interference with others' equipment. Despite the fact that this sharing is uncoordinated, it is based on cooperation and the awareness of the need to coexist with others to operate successfully. The culture of sharing in Wi-Fi bands manifests the norms of:

- cooperative behaviour,
- the openness to innovation.

The Wi-Fi users have also formed strong alliances and forums over the years. The industry cooperation is evident in joint efforts for universal standards. Buck gives examples of collective industrial cooperation in unlicensed bands, such as WAP forum, the Bluetooth project, WECA and BWIF[310]. This kind of collaboration in unlicensed bands between large corporations shows they can successfully bargain and negotiate to resolve the problems common to all of them. These collaborations happen because companies are interdependent: their success depends on willingness of others to cooperate in designing interoperability standards. For a standard to be successful it has

[308] Ibid.
[309] Buck, S., 2002. Replacing spectrum auctions with a spectrum commons. Stan. Tech. L. Rev., p.2.
[310] Ibid.

to be used by many different players in the market, so that end users do not have problems without interconnectivity. This is important for entire wireless spectrum ecosystem.

The culture of sharing in Wi-Fi was not systematically built into their rules by the regulator, was not shaped by the law, and that is what we look for. Although these norms are evidently present in precedent of dynamic sharing such as unlicensed sharing in 5 GHz band discussed earlier, the Wi-Fi markets are niche markets. There are many reasons why Wi-Fi norms are the norms of an incidental example of success and why there needs to be a systematic decision to change policies to embrace culture of sharing as a norm, not the incident. Some of the reasons are: (1) it is something you do behind the closed doors, (2) it did not evolve from a non-sharing system, it started as a sharing one altogether, (3) it was invented by an astronomer, not the person from Motorola, (4) it started as a complementary technology and people are fine with complementary having less guarantees.

2.5.3 *The Norms in Spectrum Allocation and Usage*

As we have seen in this chapter, and we will see further in Parts III and IV of the thesis, important norms in spectrum policy are business norms. The debates reviewed in Section 2.2.3 are academic debates, the participants are not those who generate revenue out of spectrum. As such they only partially shape the traditional norms and affect the mindset of stakeholders (players in the markets) and the regulators (those that make the rules), but not much. Spectrum allocation historiography shows that it took decades to implement Coase ideas, and many other ideas were rejected over the years. What we have also seen in previous sections, the norm was not to make policies that can evolve with technologies, it was the opposite: regulate for a specific service, usage, technology and frequency. The part where the debates do affect their mindsets is where it matters: on the markets. In this sense, we can distinguish pro-market norm of the regulator which guides them to "structure cellular markets and regulations to lower the barriers to entry and increase competition", and the pro-business norm of the dominant stakeholder in spectrum which says that "the big carriers dictate the cellular regulations".

To describe the nuances of this regulator-cellular companies relationship let us look at the regulatory objective. The FCC is a governmental institution that has to take care of "public interest". Regulating with the public interest in mind, the regulator understands that existence of wireless networks is of vital interest for the country. What this produced however, is the norm that **the state control is dictated by the importance of wireless communications**[311]. This norm is the command and control norm by which the government aligns itself with industry in promoting new services,

[311] Ballantyne, L., 1993. Cutting the cord: a telecom solution to the crisis of capitalism (Doctoral dissertation, Carleton University), p.97.

holds exclusive control over the telecommunications sector and at the same time, most of the government spectrum today is still command and control.

But those who make the communication networks, network operators, for them the public interest or a maximal usage of the resource is not a priority. They are not the important part of the society that improves society. Therefore, when asking **"Is X a norm in telco world?**" the question is: Would the CEO of an operator say that everyone in the industry should be guided by that specific principle? Driven by this question, we identify the following norms in the most prevalent spectrum markets, cellular markets.

Cellular companies in particular are aware of their influence over the regulator because there is the norm that says that **cellular companies are important**. This norm is anti-sharing norm which can be seen in the fact that the cellular companies were not invited to the PCAST negotiations, they were deemed too influential and an obstruction for forward-looking ideas of dynamic spectrum sharing outlined in the PCAST report. The PCAST ideas also did not come as an extension of existing norms of sharing of the regulator, but the opposite: the ideas came from the new types of players in the markets seeing business opportunities in dynamic spectrum sharing, such as Google Inc[312].

The norms of culture of sharing do not exist in regulator mindset. As noted, the PCAST ideas did not come from the FCC. The legacy mindset, as we discussed in this chapter already, always reflected the norm that said **incumbent services need to be protected from competition**. Weiser elaborates on how the FCC for years has awarded "the art of spectrum lobbying" which the incumbents practiced effectively[313] and writes:

> "FCC historically minimized the use of spectrum by adopting highly conservative measures to guard against possible interference, the challenge today is to ensure the more efficient uses of spectrum even if that means allowing for the possibility of more interference."

The stakeholders' influence over the regulator is best seen through the norm of lobbying to a desired policy outcome. This norm says that **strong regulation means strong need for lobbying**[314]. In this study, Sutherland identifies lobbying in telecommunications as means of: (1) influencing competition through regulation and policy (precisely because they are heavily regulated), (2) undermining current rivals by raising costs for them, and (3) blocking new entrants. He further develops the Porter's five-forces model to analyse how lobbying and litigation as the norm and widely accepted behaviour can shape the future markets. It is worth noting that this norm is present in unlicensed bands as much as it is in cellular markets where few players dominate

[312]Marshall, P., 2017. Three-Tier Shared Spectrum, Shared Infrastructure, and a Path to 5G. Cambridge University Press.

[313]Weiser, P.J., 2008. The Untapped Promise of Wireless Spectrum.

[314]Sutherland, E., 2014. Lobbying and litigation in telecommunications markets–reapplying Porter's five forces. info, 16(5), pp.1-18.

as telecommunications service providers. Benkler documents this chronologically[315] explaining how lobbying became important in unlicensed markets as well:

> "Since 2002, lobbying around unlicensed spectrum rulemaking has been extensive. As critics have described exhaustively, the designation of 3.65–3.7 GHz for WISP services was rife with lobbying; the White Spaces Order was almost abandoned because of Dolly Parton's microphone;[316] and Cisco, caught flat-footed on TV band devices because of its major investments in 5 GHz, spent 2011 fighting tooth and nail to deny its competitors open access to the TV white spaces.[317]"

The lobbying is used by the traditional market players and prospective entrants to modify and adjust the incentives the players may see in the proposed rules of the regulator. The important incentive of cellular carriers are the license conditions and the configuration of spectrum rights, because their market performance depends on it. The norm here is that **telecommunications are an economies of scale**. As Sutherland describes, the cellular markets have strong monopolistic features because of the investments in network infrastructure and economies of scale[318]. When it comes to monopoly, the norm is that **monopoly is justifiable if achieved through competition and monopoly is natural**[319]. This norm is reflected in the CBRS developments, as we will see, the reduction of competition in CBRS.

The minority of big players impose norms because a majority of small players is indifferent on that certain behaviour. As McAdams explains, consensus does not always include majority[320]. For example, another norm in telco markets is that **everyone should offer bundled services and be the overall provider**[321]. This norm reflects on small companies as they exibit fear in doing just parts of the service providing. In the CBRS example, as we will see, the types of players that go against this norm would be e.g. database operators or local providers of a sliced service. Minority of big players strongly approve this behaviour, and the small players do not have an attitude on this behaviour because they cannot even play in that league. For this behaviour to actually become a norm, all that is needed is that among the big players, the majority of them all have the same opinon. This is just one example of a norm formed by the minority of big players who all have the same opinion.

[315]Benkler, Y., 2012. Open wireless vs. licensed spectrum: Evidence from market adoption. Harv. JL & Tech., 26, p.69.

[316]Matt Richtel, Airwaves Battle Pits Dolly Parton Against Google, N.Y. TIMES, Nov. 4, 2008, at B1, available at http://www.nytimes.com/2008/11/04/technology/internet/04wireless.html.

[317]Harold Feld, My Insanely Long Field Guide to Cisco's War on the TV White Spaces, WETMACHINE (Nov. 15, 2011), http://tales-of-the-sausage-factory.wetmachine.com/myinsanely-long-field-guide-to-ciscos-war-on-the-tv-white-spaces.

[318]Sutherland, E., 2014. Lobbying and litigation in telecommunications markets–reapplying Porter's five forces. info, 16(5), pp.1-18.

[319]Ballantyne, L., 1993. Cutting the cord: a telecom solution to the crisis of capitalism (Doctoral dissertation, Carleton University), p.97.

[320]McAdams, R.H., 1997. The origin, development, and regulation of norms. Mich. L. Rev., 96, p.338.

[321]Sutherland, E., 2014. Lobbying and litigation in telecommunications markets–reapplying Porter's five forces. info, 16(5), pp.1-18.p.7

The norm that shows the dominant stakeholders attitude towards innovation is that **new potentially disruptive technologies could be a useful addition to the existing dominant business plan**[322]. The existing dominant business plan of cellular carriers (in EU the MNOs) is based on exclusively licensed spectrum, long term licenses, which are renewable and provide wide area coverage (sometimes nationwide, since there is only few such market players in the country). Such players see shared access spectrum schemes as additional parking lots[323], as documented in Chapter 6 for the case of CBRS (in EU the case of LSA). Also, the norm that **new potentially disruptive technologies should be blended into the existing model so that they do not gain importance on their own**[324]. We discussed the Wi-Fi offloading traffic from cellular networks. As we will see in the CBRS analysis of stakeholders' in Chapter 6, 3.5 GHz has been seen as an offloading band by the dominant carriers as well.

The market players see the competition through their fear of interference and expect from a regulator to protect them from interference. We discussed the share scare in this chapter and the way interference and scarcity are presented as a twinned scare and a barrier for sharing. In this sense, the norm is that the **competition creates interference and competition takes the scarce resource**[325,326]. When competing in auctions there is the norm to compete in auction to stifle competition[327]. As Buck explains,

> "Some existing regional players may try to buy spectrum in markets where they already operate in hopes of cornering the market. For example, during a previous local multipoint distribution service auction, New York City licenses sold far cheaper than some markets in New Mexico, where existing players were bidding for licenses to keep the competition out. (Nancy Gohring, Auction Block Intrigue: 39 GHz Auction May Yield Some Surprises, TELEPHONY, April 24,2000)."

Another norm that is grounded in the scarcity postulate is that **increased user demand is a threat**[328]. As Ghezzi notes:

> "It is opportune to note that interviewees see the increase in data traffic not only as a driver of business, but also as a technological threat. This is so because mobile bandwidth is a scarce resource that, according to some forecasts, can be saturated in the near future if the pattern of traffic growth intensifies."

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[322] Madjdi, F. and Hsig, S., 2011. The response strategies of incumbent mobile network operators on the disruptive potential of public W-LAN in Germany. Telecommunications Policy, 35(6), pp.555-567.

[323] Ibid. p.563

[324] Ibid. p.564

[325] Sutherland, E., 2014. Lobbying and litigation in telecommunications markets–reapplying Porter's five forces. info, 16(5), pp.1-18.

[326] Ghezzi, A., Cortimiglia, M.N. and Frank, A.G., 2015. Strategy and business model design in dynamic telecommunications industries: A study on Italian mobile network operators. Technological Forecasting and Social Change, 90, pp.346-354.

[327] Buck, S., 2002. Replacing spectrum auctions with a spectrum commons. Stan. Tech. L. Rev., p.2.

[328] Ghezzi, A., Cortimiglia, M.N. and Frank, A.G., 2015. Strategy and business model design in dynamic telecommunications industries: A study on Italian mobile network operators. Technological Forecasting and Social Change, 90, pp.346-354. p.5

The undefined concepts serve to strengthen a norm that users in spectrum bands should be bordered, heavily separated with the walls between them and guard bands to protect them. Here, the norm is that **the interference is this mystical concept which is to be feared; no definition of it**[329] and **everyone is an enemy and everyone wants to cheat (w.r.t. interference)**[330]. This adversary politics is anti-sharing. The norms in cellular bands may be effective for the small number of dominant operators, but they are bad for spectrum sharing ecosystems and efficient use of spectrum, for a society as a whole.

2.6 CHAPTER SUMMARY

So far, we have toured the exciting developments of relations and connections of regulatory designs with the technologies of spectrum sharing. Let us take a step back, and recap the nature of these relations. We told the story of spectrum, its questionable existence, proclaimed scarcity and the attached fear of interference, the means of spectrum management and the divided opinions on its future. Disagreements around the fundamental questions about economy of spectrum, engineering and metaphysics of the resource call for a new philosophy of spectrum sharing. Spectrum sharing calls for a hybrid model of both spectrum worlds together, commons and exclusively licensed spectrum, but with modifications of both in order to build a structure uniquely tailored for sharing the spectrum resource. We told the story of technology and regulatory structure behind spectrum sharing, mechanical miners of the abundant resource and the ways in which we manage the abundance factory of spectrum sharing. Regulations have been much slower than technologies for spectrum sharing. With technology as a vehicle there is a space for the new philosophy of spectrum as the driver, which should in our opinion, come from the culture of sharing. The predispositions for: innovation in business domain, advanced networks enablers for sharing in the technology domain, dynamic regulations and culture of sharing exist. This work aims to bridge the gaps and provide an insight into what happens if spectrum sharing frameworks are configured by using a ubiquitous tool of culture of sharing to motivate (incentivise) users to share spectrum and what effects that has on spectrum utilisation. With this chapter we end the part of introducing the problem and proceed with presenting the methods used for the case study in Part II.

[329]Littman, L. and Revare, B., 2014. New times, new methods: Upgrading spectrum enforcement. Silicon Flatirons Center. p.4

[330]Ibid. p.5

Part II

METHODOLOGY

The Share Scare

"No. It's not rules. Just a few principles.
Say, trust is one."

Audio version at: https://www.youtube.com/watch?v=iu_rrGwz76Y

3 CONCEPTUAL FRAMEWORK: THE NTBRS CHECKLIST FOR SHARING

This chapter develops ideas around the culture of sharing. It sheds light on the richness of a cross disciplinary look at what culture of sharing means in general and in the case of spectrum, and ultimately what this wider perspective has to offer to spectrum sharing. It deals with the thematic examples of sharing economies, where successful sharing models are an evidence of a culture of sharing. One of the key contributions of the chapter is the creation of a conceptual framework which we use to support the thesis. The goal was to (1) devise a framework for the analysis of spectrum sharing by (2) exploring the ways in which the concept of culture of sharing can be extracted from the sharing economies (definitions, thematic examples, success stories).

Outline is the following: We start in Section 3.1 by devising the NTBRS (nature, technology, business, regulation, and society) framework. We call it the checklist, as we are going to use it to check if spectrum sharing fulfills its requirements for a sustainable sharing. After determining its components, *enablers* of sharing, their *interconnections* and the generalised *domains,* in Section 3.2 we show that (1) the NTBRS framework is well suited for spectrum sharing and (2) its cultural component is underdeveloped in spectrum sharing. This motivates the treatise of culture of sharing we give in Section 3.3 which is followed by a summary of the chapter.

3.1 DEVISING THE SHARING ECONOMY CHECKLIST

The scope we take widens with the analysis. We observe the sharing culture as a more general concept than one of sharing economies. And we observe the spectrum sharing concept as the most general one, encompassing both: the sharing economies and the culture of sharing. It is a chain of necessary conditions, as the possibility of spectrum sharing (e.g. having the regulatory rules set for sharing) is necessary for the culture to develop, and the culture is needed for a *sustainable* sharing economy[1].

[1] When observed in the other direction, it is a chain of sufficient conditions: existence of a successful sharing economy would mean the existence of culture of sharing and consequently spectrum sharing as well.

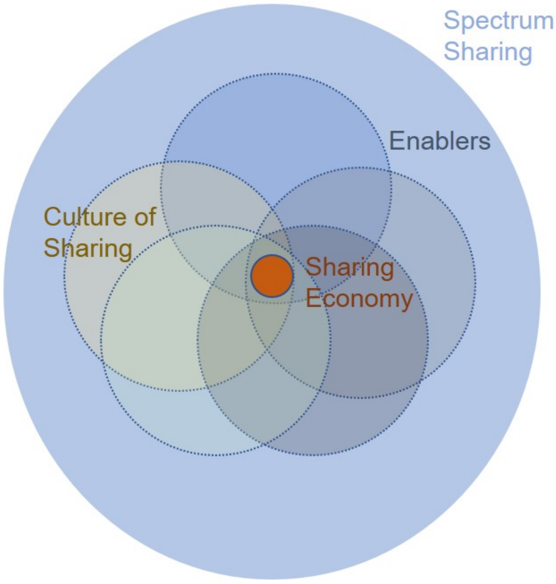

Figure 3.1: Spectrum sharing, culture of sharing and the sharing economy

We aim to establish a framework based on the enablers of sharing economy, which is by definition wider than the sharing economy itself - as a successful sharing economy would be the region in the intersection of all of its enablers (Fig. 3.1). The assumption that the culture of sharing is one of the enablers of a sharing economy will be justified once the checklist is devised: the other circles in the figure will be named as well.

We look for a successful recipe for spectrum sharing within sharing economies to see if all the ingredients (enablers) are there. If not, we have to find a way to make the missing ones. We will search for ingredients in different sharing economy definitions, as there is no unified one. However, we are not taking a resource agnostic position nor performing a comparison of different definitions. Instead we put them in spectrum context to extract relevant features. These features will correspond to *enablers* (ingredients) and *their interconnections*. Once we find the recipe, we look at it once again in Section 3.2 to verify that it is the one we were looking for - a spectrum sharing one.

3.1.1 *Definitions of Sharing Economies*

There is no unified definition of a sharing economy, as it represents an umbrella term for many economic activities built around the Internet platforms that enable digital economies. A range of authors have defined the sharing economy and these definitions are framed as lists of characteristics that each author considers to be a necessary precondition for a successful sharing economy model. The purpose of this section of

One might argue that the Uber sharing business is a counter-example of our claim. That it emerged without, or in competition with, existing regulation; and no culture was needed for the Uber business to succeed, only a market need that was successfully met. But we argue that "sustainable" is the word not to skip here. A company can win the market by blitz, with a brilliant unsustainable idea, despite everything else out there, but it does not mean it will exist the next day. Uber is a good example of this: unless the regulation is what the framework presented here asks it to be, and the culture exists (that we could already say there is a culture of ride sharing), Uber would disappear.

the chapter is to look at the different ways in which the sharing economy is defined and provide a definition/model that will be used in the thesis[2].

We briefly analyse five prominent definitions by explaining the main characteristics of sharing economy that each author sees as the most important ones to map those characteristics to spectrum sharing.

There are many terms used interchangeably for the sharing economy concept[3], such as collaborative consumption, crowd-based networks, mesh economy, peer economy, gig economy, we-economy - and they all reflect the idea of community-based[4] online platforms on which sharing economies exist.

Rachel Botsman[5] uses the term collaborative consumption. She prefers framing a checklist of criteria instead of a definition - to establish if a model is a sharing economy or not. Her five criteria for successful collaborative, sharing-driven businesses are:

1. putting underutilised assets to use - assets with *idling capacity*[6], for financial or non-financial benefits,
2. strategic decisions in a sharing economy company should be *values-driven* (transparency, humanness, authenticity),
3. the *service or resource providers should be valued, respected and empowered*,
4. the customers should see a *clear benefit of access vs. ownership* as they would be able to get goods and services in more efficient ways,
5. *distributed marketplaces and decentralised networks* as platforms which the businesses are built on lead to creation of a community, collective accountability and a sense of belonging[7].

Lisa Gansky[8] uses the term "mesh economy" for a model built around the idea of network mesh topology, in which every node can be linked to any other node in the network in any direction; all nodes are interconnected and they move in tandem. The mesh economy is about:

1. *shareability* of products, services, raw materials which are shareable within a community, market or value chain,

[2]What a sharing economy is for one, might not be for the others, as you may have noticed. In such a situation, I see little sense in going into the tangential discourse of "real sharing economies". The authors of the definitions are settling that among themselves in their field of research.

[3]`https://en.wikipedia.org/wiki/Sharing_economy`

[4]When we use term "community" for sharing economies and for spectrum sharing, we mean all of the stakeholders in both cases.

One of the points this thesis is making is that grouping a population of an ecosystem into a single community does make sense, considering that the common traits, stemming from the nature of the resource that this population is gathered around, - deserves to be studied.

[5]Botsman, R. and Rogers, R., 2010. What's mine is yours. The rise of collaborative consumption.

[6]The period of time when additional value can be extracted from the assets if they are put to use.

[7]R. Botsman has four different boxes to put business models in: collaborative economy, sharing economy (e.g. BlaBlaCar), collaborative consumptions (e.g. ZipCar), and on-demand services (e.g. Uber).

[8]Gansky, L., 2010. The mesh: Why the future of business is sharing. Penguin.

2. relying on *advanced web and mobile data networks* to track goods, aggregate usage, customer and product information,

3. *localised* delivery of services and products: shareable physical goods delivered whenever and wherever,

4. *social media platforms promoting the mesh economy* (its offers, news and recommendations) and replacing the instruments of advertisement used in traditional markets.

5. *global scale and potential*: We live in an unprecedented global network, as she writes:

   > The Mesh is made possible by the way in which we are all increasingly connected to everything else—to other people, businesses, organizations, and things. This is the first time in human history when this kind of far-reaching, always-on, and relatively inexpensive connectivity has existed. Just as our minds are more than a collection of neurons, these Mesh connections have given rise to something more complex and challenging[9].

Alex Stephany[10] prefers the term "sharing economy" but also uses the term "we-economy". He defines sharing economy as:

> The sharing economy is the *value* in taking *underutilized assets* and making them *accessible online* to a *community*, leading to a *reduced need for ownership* of those assets

His definition reflects the cycle of a sharing economy:

1. *value* is the first ingredient for thinking about sharing economy model which is the economic value that the sharing economies create, as he focuses on the business of sharing[11].

2. anything that lies *underutilised* can be turned into an asset to provide a service and generate revenue[12],

3. *online accessibility* of these assets enables a more efficient utilisation: sharing in sharing economy is about making the asset available - via selling, trading, renting, leasing, gifting, swapping[13].

4. importance of *community*: making underutilised assets is not enough as they need to move within a community:

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[9] *Ibid*.

[10] Stephany, A., 2015. The business of sharing: Making it in the new sharing economy. Springer.

[11] He distances from the gift economy for example, as he looks at the revenue generation model which enables people to get paid for doing the work via platform which in turns earns money as well. *Ibid*.

[12] Asset can be anything: time, expertise, bicycles,...any asset with the idling capacity. *Ibid*.

[13] This implies the blurred lines between business model, as an incentive does not have to be monetary - instead, any type of exchange and rewards mechanisms still make this model a business. *Ibid*.

Community means more than just supply and demand. In successful sharing economy businesses, communities of users engage with each other above and beyond their transactional needs. They trust each other. They are values-based and, as we will see, police these values from internal threats and defend them from external ones. Often, these communities are built around interest groups[14].

5. once people can access assets within a community, it leads to a *reduced need to own* them: goods become services - "as-a-service" business model.

Arun Sundararajan[15] uses the terms "crowd-based capitalism" and "peer economy". He lists the following features of a sharing economy:

1. *largely market-based*: the sharing economy creates markets that enable the exchange of goods and the emergence of new services, resulting in potentially higher levels of economic activity,

2. *high-impact capital*: the sharing economy opens new opportunities for everything, from assets and skills to time and money, to be used at levels closer to their full capacity,

3. *crowd-based "networks" rather than centralized institutions or "hierarchies"*: the supply of capital and labor comes from decentralized crowds of individuals rather than corporate or state aggregates; future exchange may be mediated by distributed crowd-based marketplaces rather than by centralized third parties,

4. *blurring lines between the personal and the professional*: the supply of labor and services often commercializes and scales peer-to-peer activities like giving someone a ride or lending someone money, activities which used to be considered "personal",

5. *blurring lines between fully employed and casual labor, between independent and dependent employment, between work and leisure*: many traditionally full-time jobs are supplanted by contract work that features a continuum of levels of time commitment, granularity, economic dependence, and entrepreneurship.

Billee Howard[16] uses the term "we-commerce". She offers her own 5 elements needed for shared economy success:

1. create a new *culture that encourages trust and sharing*: the economy functions on a direct interaction within a community (which is built on trust),

2. successful companies are created by a *leader who inspires passion,*

[14] *Ibid.*

[15] Sundararajan, A., 2016. The sharing economy: The end of employment and the rise of crowd-based capitalism. Mit Press.

[16] Howard, B., 2015. We-Commerce: How to create, collaborate, and succeed in the sharing economy. TarcherPerigee.

Table 3.1: The elements of NTBRS framework

Domain	Enabler of Sharing	Features in the Domain
Nature	Resource	Shareable Underutilised
Technology	Network	Feedback P2P Decentralised
Business	Innovation	Out of comfort zone Creativity Diversity
Regulation	Dynamics	Right to: access, property, protection Less inertia Responsiveness
Society	Culture of sharing	Trust Community

3. recognise that *failure is the new success*: tendency to punish failure leads to denial of real problems (Howard gives an example of Wall Street crash in 2008),

4. honour the anarchists, tinkerers, non-conformists and *encourage creativity and innovation*,

5. *make change a core business competency*: those able to adapt to high pace of markets evolving and changing will succeed, those who not will perish.

The reader may have noticed significant overlaps in these definitions and criteria. It is no wonder, as these authors are inspired by one another and are after all trying to describe a single phenomenon. Our task is to map their observations to spectrum sharing to devise a useful framework for what this thesis is looking for. This task is not just about removing duplicates and merging similar features of the definitions in a single point. It is also about recognising which features are not relevant to the case of our interest, spectrum sharing.

3.1.2 *Enablers of Sharing and the Interconnections*

If plotted in an imagined coordinate system, the features of sharing economies presented in these definitions would cluster around a few central topics corresponding to the *enablers* of successful sharing economies. The statements in definitions represent *features* of the enablers, which are crucial for a sustainable sharing.

In this section, we tell the story about the enablers and how their different aspects are interconnected. The connections represented as blue lines in the Fig. 3.2 stem from the sharing economies definitions and represent the foundation of our framework. However, in the process of tailoring the general framework for spectrum sharing, new

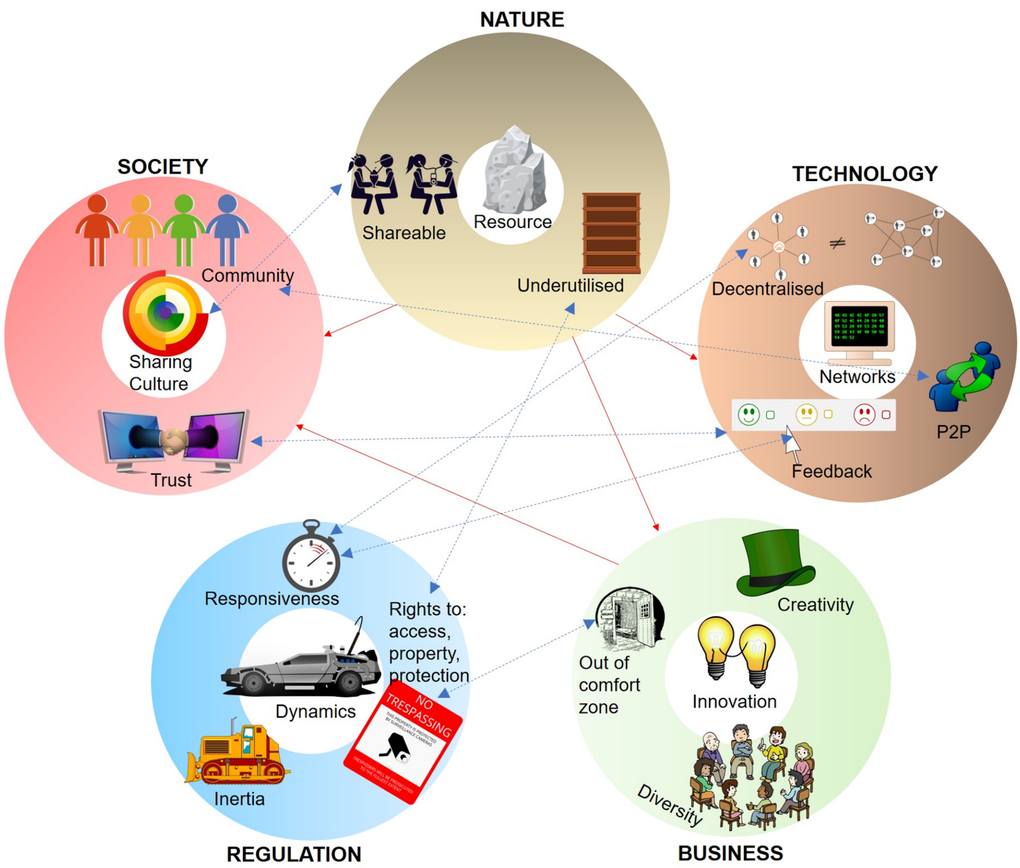

Figure 3.2: Sharing economy based framework for using the tool of culture of sharing in spectrum sharing models

connections emerge: they are represented as red lines. These connections are specific for spectrum resource and they largely follow from the discussions in Chapter 2. They connect *domains*, the generalised realms in which the enablers of sharing exist. The blue line interconnections serve to show how our framework is about sharing and they offer a basis for institutional sharing. The red lines serve to show how NTBRS is about spectrum. This in principle means that another institutionalised sharing researcher could re-interpret red lines to suit their type of resource under analysis and the blue lines would remain the same, as they stem from institutionalised sharing economy.

The domains, the enablers and the aspects form the framework hierarchy. It ranges from the specifics of aspects to the all-encompassing generality of domains. The high-level abstraction of the domains will allow us to make general conclusions later in the thesis and to encompass abstract concepts in the multifaceted challenge of sharing regulation. This is why we dubbed the framework NTBRS, after its domains: **N**ature, **T**echnology, **B**usiness, **R**egulation, **S**ociety. The hierarchy of the framework is illustrated by Fig. 3.2 and represented in Table 3.1.

3.1.2.1 *The Resource, an enabler from Nature*

In one way or the other, the authors we cited recognise that sharing economies would not exist without a shareable resource, one that is relatively easily put on this new market. This makes the Nature, physics and metaphysics of the resource, service, asset in general, one of the defining domains in our framework and the resource is the central point of it, the enabler. While two resources might both be shareable, the way they are used and shared may differ significantly - so the domain is not only about shareability but also about the other properties (features) of the asset in consideration (Gansky (shareability), Botsman (idling capacity), Stephany (underutilised asset), Sundararajan (high-impact capital and everything becomes an asset)). Lyft's John Zimmer explained it to Sundararajan: "Vehicle utilization is about 4%, occupancy in those cars is about 20%. So you basically have about a 1% utilization rate on something that accounts for about 13% of global GDP. I saw that as a big opportunity."[17] Comparing this to single digit percentage usage of spectrum reported worldwide[18] reaffirms the relationship with spectrum in this context.

The community conscious of resources shareability and the advantages that the sharing such resource brings, has a chance of building a culture of sharing from which the sharing economy can then grow (blue line shareable↔sharing culture). In the case of spectrum, the relationship of the resource and the society extends further, as spectrum is the most important medium for information transfer and is a communication enabler (red line nature→society). The underutilisation of the resource can have many different reasons (think of reasons why cars are underutilised), but for the context of spectrum sharing it is the regulation and the restrictive rights policy that causes the underutilisation (administrative scarcity) (blue line underutilised ↔rights to property and protection). Another connection is the one between nature and business. It is logical to tailor business models to match the nature of the resource and it would hold true for any resource. However, the unique nature of spectrum results in a unique business models as well: providing the same service via wired or wireless infrastructure asks for significantly different business priorities. Even though it, in technological sense, means only a difference in the lowest layer of the ISO/OSI model, it is a business game changer (red line nature →business).

3.1.2.2 *The Networks, an enabler from Technology*

When explaining why are the sharing economies blossoming right now, the authors all recognise the support of technology, networks that have enabled fast, global, reliable and direct access to underutilised assets. This makes the Technology our second domain. For Gansky, those are advanced web and mobile data networks, Botsman em-

[17] Sundararajan, A., 2016. The sharing economy: The end of employment and the rise of crowd-based capitalism. Mit Press.

[18] Patil, K., Prasad, R. and Skouby, K., 2011, February. A survey of worldwide spectrum occupancy measurement campaigns for cognitive radio. In Devices and Communications (ICDeCom), 2011 International Conference on (pp. 1-5). IEEE.

phasises the distributed and decentralised topologies. These offer online accessibility, as Stephany puts it and are peer or crowd-based as Sundararajan describes.

The role of technology is emphasised in the spectrum context, as spectrum does not exist until put to use. The enabler here are *the networks* - decentralised, P2P networks, supporting feedback. The world of big networks (and networks of networks[19]) we live in today enables fast (if we do our job with spectrum right, even faster[20]) connection between users and services, nodes of an elaborate graph without a central node. When the control in the network is enabled by a centralised topology, it puts a lot of pressure on the central node and keeps it busy all the time with the demands coming from the nodes near and far. If we distribute the regulatory control over several local networks, the responsiveness increases (blue line decentralised ↔ responsiveness). The peer-to-peer architecture giving us a connection with anyone in a single hop is the ideal vehicle for a sharing economy (blue line P2P ↔ community). Running on social-engineering-aided ideas, the technology provides a feedback tool economy can use: not just the sharing one, but in general. However, it is the sharing economy that is making the most use of it and giving it an important place in the overarching meta-business model. The feedback of trust has also been enabled by the existing networking technology[21], allowing a continuous, multi-iteration interaction between the resource providers and users, building reputation and bi-directional trust.[22],[23] While it has not been perfect due to inherent biases[24] and non-extensiveness, it is not hard to propose better feedback strategies and enhance the proper trust building, aided with the underlying technology[25] (this is the blue line feedback ↔ trust). The feedback is not only about checking if spectrum users are not violating policies and regulatory rules. It is also about checking the accuracy of spectrum availability information, what spectrum is in use, where is it being used, the time of use. This is an important component for a responsive regulator to be able to make informed decisions (blue line feedback ↔ responsiveness).

3.1.2.3 *The Innovation, an enabler from Business*

Not surprisingly, all definitions have business as the core element - it is an economy after all. We make it our third domain and recognise that whenever Business is addressed in these definitions it is accompanied by the words new, innovative, emerg-

[19]Noam, E.M., 2001. Interconnecting the network of networks. MIT Press.

[20]If done right, spectrum management can make this connection faster, more reliable and robust. Accomplishing the goals of 5G would mean more throughput, more connections, lower latency - in long-term only a spectrum reform can keep us hitting the ceiling.

[21]BlaBlaCar's TrustMan (Entering the Trust Age report 2016)

[22]Hawlitschek, F., Teubner, T., Adam, M.T.P., Borchers, N.S., Moehlmann, M. and Weinhardt, C., 2016. Trust in the Sharing Economy: An Experimental Framework.

[23]Abramova, O., Shavanova, T., Fuhrer, A., Krasnova, H. and Buxmann, P., 2015, May. Understanding the Sharing Economy: The Role of Response to Negative Reviews in the Peer-to-peer Accommodation Sharing Network. In ECIS.

[24]Malhotra, A. and Van Alstyne, M., 2014. The dark side of the sharing economy... and how to lighten it. Communications of the ACM, 57(11), pp.24-27.

[25]Stemler, A., 2017. Feedback Loop Failure: Implications for the Self-Regulation of the Sharing Economy. Minn. JL Sci. & Tech., 18, p.673. CULTURE OF REVIEW

ing, dynamic. Spectrum sharing is no different as old business models rely heavily on ownership, exclusivity and property rights. A sharing economy of spectrum would reward those who bravely change their business models, as Howard suggests in her point about "cultivating the mavericks" and encouraging creativity and innovation and her point of change as a core business competency. This is what 5G is about, emerging and new businesses and inclusion of new players on the markets. Some of these new models can be foreseen, some not, but sharing economies are supposed to be flexible and embrace the new, creative uses of the resources. Markets blossom due to emerging uses, new ways to utilise and marketise, as Sundararajan states in his point on dominant market-based character of sharing economies.

Enabler in the domain of business is *the innovation*, it makes new business models and finds new ways of monetising the resource. The innovation can of course reside in any of the fields of the framework depicted, as it is so often seen in science and technology and so desperately needed in regulation. However, we placed it in the business, emphasising the marvel of emerging business models inspired by sharing. The new models push the old incumbent enterprises out of their comfort zone (prison cells of creativity) and increase the sales of creativity hats[26]. The primary holders of spectrum rights (incumbents) are in the comfort zone enabled by the regulator by granting them property rights over spectrum which also give them right to exclude others from their spectrum even when not using it and the right to be protected (blue line out of comfort zone $\leftrightarrow$ rights to property and protection). With new players on the market, coming in different sizes and models, the innovative process has a lot of new bits and pieces to include and play with and what emerges from this diversity are the new types of business models. With respect to uniqueness of spectrum resource, business models that are built on spectrum resource are also unique as they exploit a public good (red line business $\rightarrow$ society).

This is mirrored in CBRS, an emerging spectrum sharing model which we are doing a case study on. The PCAST report (which we elaborate on in Chapter 5) aims to answer how to spur economic growth of the US and uses the word "innovation/innovative" 83 times (on average, every two pages). The report recognises that it is the innovation that drives the better utilisation of the resource, which is what dynamic spectrum sharing is about. The CBRS band is termed the Innovation band, once the FCC initiated the framework design by taking the PCAST ideas and recommendations as the driving motives. The innovation is usually used to reflect technological innovation, but terming the CBRS band as an innovation band is about economic innovation, technological and the regulatory innovation.

3.1.2.4 *The Dynamics, an enabler from Regulation*

Sharing economy scholars we cited here make their definitions from a perspective of business, technology and society and they do not see the regulator as an enabler of a sharing economy, but as a challenge. This aligns with the problems sharing economies

[26] De Bono, E., 1985. Six thinking hats (1st US ed.). Boston: Little Brown.

have with the regulation and licensing[27]. European Commission recognises the regulatory issues as it takes the viewpoint from the other side, the one the regulator and the policy maker, framed in Science for Policy report by the Joint Research Centre (JRC) in 2016[28]. What the authors we cited do want is regulatory burden-free, fluid access to a resource or an asset replacing obligatory ownership rights. Stephany and Botsman emphasise the reduced need for ownership. As Botsman puts it, the customer needs to see the benefit of access vs. ownership.

Enabler in the domain of regulation is *the dynamics*[29] - reflected in the rights to access and not own the resource, high regulatory responsiveness and less inertia from a regulatory side. Regulation, as we have seen in previous chapters, too often acted as a deadweight, pulling the advancement of technology and business down into the past. The regulation of future, Regulation 2.0 and beyond will have to be a DeLorean DMC-12[30] from "Back to the Future" franchise and be the force foreseeing the future. Stripping down the barriers of administration and blocks of retrograde ideas which have aged badly will allow the sharing economies to move the resource they are aiming at using from the underutilised category. In the language of dynamic regulation, resource is 'shared', 'used', and not 'owned'[31]. A dynamical, short time constant regulation allows for a high all-round responsiveness. Resorting to the peer to peer communication blitz and an elaborate feedback, the responsive system's only barrier is inability to read minds. And yet, with artificial intelligence and habits analysis, that might be a soft limit as well. Non-existing red line links reflect the fact that spectrum is managed without addressing its uniqueness, as we will in Chapter 6.

3.1.2.5 *The Culture of Sharing, an enabler from Society*

Sharing is what societies do[32]. Communities share goods but even more fundamentally they share interests and values. This is where all other sharing comes from, where the culture is formed. The authors we cited recognise the role of the society and its deeply rooted principles in sharing economies. This is why Society is the fifth domain.

[27] `https://www.rte.ie/news/business/2017/0628/886287-airbnb-calls-for-regulation-of-home-sharing-in-ireland/`, `https://www.theguardian.com/technology/2017/dec/20/uber-european-court-of-justice-ruling-barcelona-taxi-drivers-ecj-eu`

[28] Codagnone, C., Biagi, F. and Abadie, F., 2016. The passions and the interests: Unpacking the'sharing economy'.

[29] The ability to change a rule locally in time and space, without waiting for years of FCC procedure.

[30] Leirer, C., Speeding Through Time.

[31] This statement may seem naive, considering that the US law uses a particular language implying that spectrum cannot be owned. See Title 47 U.S. Code 301: "It is the purpose of this chapter, among other things, to maintain the control of the United States over all the channels of radio transmission; and to provide for the use of such channels, but not the ownership thereof, by persons for limited periods of time, under licenses granted by Federal authority, and no such license shall be construed to create any right, beyond the terms, conditions, and periods of the license." Looking at the table of allocations it depicts that most spectrum bands are shared by multiple service.

However, the FCC succumbs to using the terms other stakeholders use: owning spectrum is one such term; law and enforcement are not the same thing.

[32] One could argue that sharing is just one thing that societies do and they also provide for private, non-communal ownership. I disagree. Societies form around a common interest, and within it there is necessarily sharing, even if it is just sharing the common interest. Private ownership can come or not come, but later.

Botsman states that the collaborative consumption relies on: enterprises that are value-driven, communities built on trust and collective accountability, the recognition of the one who shares. Howard insists on culture of trust and sharing, passionate leadership and a societal shift in embracing failure as a chance for a new beginning. For her, the sharing economy functions on a direct interaction within a community. Stephany sees community as more than just supply and demand and recognises that the communities trust each other and police their common values. Furthermore, he recognises communities are often built around interest groups.

Enabler in the domain of society is *the culture of sharing*. The society saw economy emerging within itself, going through a continuum of models in which, as Belk suggests "commodity exchange lies at one end and sharing at the other"[33]. It has seen the wax and wane of sharing and hosted the revival of it in the age of internet. The natural course of society evolution is both the course of sharing and the course of division and borders, cultural universals being both generocity and territoriality[34]. A cultural emancipation of sharing is therefore an imperative for the sharing economies, drawing its inspiration from sharing, to succeed. Here we found the missing ingredient, as the culture of sharing is nowhere to be found in Chapter 2 where we introduced spectrum in its whole. This is why we dedicate the rest of the chapter and the thesis to bringing culture of sharing into spectrum sharing, where the NTBRS conceptual framework serves the purpose.

3.2 VALIDITY OF THE NTBRS FRAMEWORK

A sign of successful sharing is a sustainable sharing economy, as it is able to marketise the sharing. Sharing economy of the resource is one realisation of a concept of sharing that resource. The NTBRS framework defines the recipe for a successful sharing economy - all the necessary ingredients to build a successful model of it.

In a general case, the case of sharing a generic resource, sharing economy would be only a sufficient sign of a successful sharing and not a necessary one. There might be resource sharing that is not marketisable either because of its nature or because the goal of sharing that resource is not to get it on the markets. Second reason is in the context of stakeholders: the stakeholder community may have a characteristic of a non-market oriented one. Example for this is trivial: sharing pavement with other pedestrians. That kind of sharing works but it is like sharing the air, there is no market around it nor the stakeholders (us, the pedestrians and the civil authorities are not market oriented for this kind of sharing). Then there is a case of stakeholders who share a monetisable resource but reject to make it a market, usually because of their culture. The example for this is ham spirit, the culture of radio amateurs. And finally, there is the case where the resource is monetisable, and the regulatory goal is to get it on the market as it spurs the country's economic growth for example, and also

[33]Belk, R., 2007. Why not share rather than own?. The Annals of the American Academy of Political and Social Science, 611(1), pp.126-140.

[34]Brown, D.E., 1991. Human universals (p. 118). New York: McGraw-Hill.

the stakeholders community around sharing the resource is highly interested to make profit out of it - to keep it an economy. And this is the case of spectrum sharing.

This thesis is trying to reform the spectrum markets (by promoting spectrum sharing as a predominant way of using spectrum). Spectrum sharing economy would therefore be a proof of spectrum sharing success. This means that instead of observing the very general notion of spectrum sharing, we can observe the sharing economy of it. There can be economy for spectrum sharing, which is not a spectrum sharing economy. But the reason we are interested in the sharing economy image of spectrum sharing is because sharing economies have something that spectrum sharing does not have and that is culture of sharing[35]. And for any kind of economy around spectrum sharing to happen, there first needs to be willingness to share - motivations to share. This is a necessary ingredient for a culture of sharing to exist. We will explore further in the thesis whether these motivations exist while we search for answers of how to build the culture of sharing.

This motivates the thesis, as it gives us the target and the means of reaching it. At this point, it is important to justify these preliminary conclusions by showing that the NTBRS framework is indeed relevant to spectrum sharing. This is necessary because: (1) the NTBRS framework has been devised from sharing economy definitions relating to existing examples and shared resources (the authors of definitions did not have spectrum in mind), (2) the used definitions place individuals in the role of peers, while spectrum sharing is necessarily about enterprises[36]. The following subsections offer arguments in favour of NTBRS validity.

3.2.1 *Individual vs. Institutionalised Sharing*

Sharing has always been a part of the economy. The word itself in multitude of languages including English means division (of land in particular)[37]. In 16th century, the word sharing meant to "cut into parts", to divide and distribute. Throughout the evolution of human culture, the word sharing gained a more positive meaning[38]. In spectrum world, as we have seen, that is not the case. In 21st century we have reached a point where sharing becomes a focal point of a new economy and various new business models revolving around it. In this section we will discuss the peculiarities of this economy, necessary conditions for it and the relationship between the sharing economi(es) and the culture(s) of sharing.

[35]One could argue that there is no culture of sharing in e.g. Lyft or eBay, which seem to be sharing economy businesses. This observation did not come from author's imagination; it was extrapolated from the field and from the working definitions of sharing economy scholars. There is a culture of sharing in these examples. If I look at my unused yoga mat or car and first thought is going to eBay or Lyft (or if I need a yoga mat of a ride, and think of them first), and if I consider those communities something positive and if I feel safe in those environments... we are getting to a culture.

[36]This thesis is about CBRS and other commercial bands

[37]Jiang, J., 2016, June. The Challenges and Opportunities of Sharing Economy-a New Wrapping for Doing Business Online?. In PACIS (p. 111).

[38]John, N.A., 2016. The age of sharing. John Wiley & Sons.

We argue that it's a natural transition to ground culture of sharing in the institutional, systematic type of sharing in spectrum world while drawing the experiences from the individual, peer to peer kinds of sharing we see in sharing economies thematic examples. The prerequisites for such a transition are there already and the experiences from incentive modeling for individuals[39],[40],[41] can readily be used. The point we aim to make is that the groups can share like individuals for two reasons: technology and humanisation that comes with it (e.g. personification of the enterprise)[42].

How are individuals sharing? Technological enablers have increased exposure and interaction, and there is no choice for an individual to be offline, to not be a part of a community. This makes you interact; and every communication in the digital networked world you have is sharing[43]. We are exposed to sharing more than we have ever been because of the network centric world we live in. If you tell me something I did not know before, you are sharing information with me. If you do that online, the concept of broadcast that the Internet is built on makes it possible for the whole world to see it, so you are sharing in a wide sense. When you are consuming an online content (reading a text, watching a video), once you are finished it gives you two options: to share it or to comment on it - and it is again a broadcast to the planet. By the technology you are using, you are trained to recognise the icon for sharing (on your Android or iOS phone). With the smartphone revolution, sharing has became a trend, that was not evident in the older Internet days, the age of computers.

That is how individual in the information age is sharing, but what about enterprises/institutions? Enterprises are not just a sum of people who work for them, but there are points at which we can observe enterprise/institutions as people: (1) the attitudes of countries are observed as attitudes of their leaders because of the governance structure, (2) general public has anthropomorphic perception of company's actions and behaviour (at least as a first approximation) and it is mostly about company's ethics and morals, (3) the media and the companies themselves either portrait their CEOs as the identification of the company ("our CEO represents our values the best...") or they build a presence of an anthropomorphic company that does not have the CEO face but a corporate profile that is turned into a mascot (when companies tweet as humans). Economic theories and practices have scaled down to a human level, personifying the enterprises with the people who run them, especially in tech world. In some cases, CEOs of big corporations became household names.

[39]Hamari, J., Sjklint, M. and Ukkonen, A., 2016. The sharing economy: Why people participate in collaborative consumption. Journal of the Association for Information Science and Technology, 67(9), pp.2047-2059.

[40]Bucher, E., Fieseler, C. and Lutz, C., 2016. What's mine is yours (for a nominal fee)–Exploring the spectrum of utilitarian to altruistic motives for Internet-mediated sharing. Computers in Human Behavior, 62, pp.316-326.

[41]Hawlitschek, F., Teubner, T. and Gimpel, H., 2016, January. Understanding the Sharing Economy--Drivers and Impediments for Participation in Peer-to-Peer Rental. In System Sciences (HICSS), 2016 49th Hawaii International Conference on (pp. 4782-4791). IEEE.

[42]Ashman, I. and Winstanley, D., 2007. For or against corporate identity? Personification and the problem of moral agency. Journal of Business Ethics, 76(1), pp.83-95.

[43]Kennedy, J., 2016. Sharing in networked culture: Imagination, labour and desire.

Halfway between the individuals and the big corporations are the emerging players on the market and the small companies which stem from start-up culture in which sharing has been recognised as an important way to do business. The incubators are a representative example, as 5-6 companies share the same space in the incubator. What this culture is showing is that the sharing behaviour has been nurtured and it is not an incidental phenomena. The start-up culture is inherently collaborative[44]. It is a cooperative culture where space, time and resources are shared. In this ecosystem, the actions of the companies are perceived as the actions of the CEOs they have been augmented with. It's humans all the way down.

Sharing behavior of big companies does not follow from sharing behaviour of individuals, we recognise that it is not that simple, but there are mechanisms of sharing economies (e.g. how Wikipedia, Airbnb users learned to trust one another) that are readily employable and their mapping to the big corporations world is convenient. This is the world we want to see sharing projected in, especially when it comes to spectrum sharing. In the meantime, the world of emerging sharing economies in which cars, real estate and information is shared in an exponential pace is the world in which these economies are going to reach 335 billion USD revenue by 2025[45] according to PWC predictions[46]. And "[a]s P2P gives rise to the emergence of a third mode of production, a third mode of governance, and a third mode of property, it is poised to overhaul our political economy in unprecedented ways"[47].This is exactly what we are seeking for in the polarised debate court: a third way. Later in this thesis one such way will be presented. It is important to say that the sharing economies were mentioned before in the context of spectrum sharing: in Wi-Fi auction design[48], cooperative sharing in heterogeneous networks[49], and CBRS.[50]

3.2.2 *Spectrum, Sharing and Spectrum Sharing*

In Chapter 2 we told a story about wealths of spectrum in its multiple dimensions and interpretations - resource nature interpretation, technological, economical and regulatory interpretations. These are the four components of the NTBRS framework - nature, technology, business and regulation. The one component is missing in the story, the society, and this is not accidental. We have seen how spectrum is perceived and in-

44 Dolgin, E., 2013. Thanks for sharing: co-working spaces in which many entrepreneurs share a common environment have been a hallmark of the computer startup industry for decades. Now, the life sciences sector is beginning to do the same. Nature Medicine, 19(12), pp.1557-1560.

45 While it may seem as trivially small amount (for example it is 1.6% of current US GDP of $20 trillion), it is still more than the revenue of any single company in the world.

46 PWC, Consumer Intelligence Series: The Sharing Economy 9 (2015), `http://www.pwc.com/us/en/industry/entertainment-media/publications/consumer-intelligence-series/assets/pwc-cis-sharing-economy.pdf`

47 Bauwens, M., 2005. The political economy of peer production. CTheory, pp.12-1.

48 Qiu, L., Rui, H. and Whinston, A., 2017. Optimal Auction Design for WiFi Procurement. Sharing Economy goes to Spectrum

49 Chang, H.B. and Chen, K.C., 2011, December. Cooperative spectrum sharing economy for heterogeneous wireless networks. In GLOBECOM Workshops (GC Wkshps), 2011 IEEE (pp. 458-463). IEEE.

50 Tarazi, I. 2016 What the Sharing Economy Means for the Wireless Industry. Wireless Week's Show Daily, 10/08/2016, CTIA, 8.

stitutionalised as an economic good. But spectrum is a social good as well (even the regulator recognises that the use of spectrum needs to serve public interest). While we have mentioned that spectrum issue is a social issue, we did not offer discussion on how society provided solution for it as there is no evidence of the existence of such a solution. Chapter 2 is a complete unit as it describes the whole story about contemporary spectrum and yet it never mentions culture[51]. In this chapter we are adding a component to spectrum wealth to reflect its importance to society. And we use sharing economies to add this component. Why? As we said, unlike in sharing economies, the culture of spectrum sharing does not exist. NTBRS gives a chance to spectrum sharing to succeed by adding a necessary ingredient overlooked in contemporary discussions.

The NTBRS framework components are obviously universal in the sense that they can be applied to the analysis of any kind of resource consumption, any kind of service or application. But the power it has in the sharing perspective lies in the interconnections which we defined, because they are all characteristic to sharing, and not to general resource consumption, service providing or showcasing an application. Another mode of spectrum use could have different interconnections. It is context-sensitive. If we would ask any policy maker or spectrum scholar of the command and control era what is the relationship between the technology and trust, they would not recognise the same interconnection that we have here. The odds are that they would not recognise the importance of trust at all, as command and control does not rely on it. But a spectrum sharing scholar should be able to see importance of trust and how the technological mechanisms of feedback help building it. This is why NTBRS, as formulated, is about sharing.

How is it about spectrum? It is the way we devised it, with spectrum in mind. This is the cornerstone of our framework synthesis, the context of spectrum. If we were context-free, everything mentioned in the definitions provided would go verbatim into the framework, but the spectrum perspective led us into modifications and reductions, tailoring it to the resource.

The final confirmation of NTBRS as a natural and realistic framework for spectrum sharing will, however, come a posteriori, from its application. Chapters 6, 7, 9 are the example of this: the framework shows its full potential once the stage is set.

3.3 CULTURE OF SHARING: THE EMPTY CHECKBOX

When searching for references connecting a sharing economy and the culture of sharing, the most often found adjective is *emerging.* A natural question to ask is whether the culture of sharing is emerging with the rise of the sharing economies from scratch, or has it always been there. The second question is how is culture of sharing perceived - as something general or something localised, community based.

[51] While it may seem that the current spectrum practice has a very deep and old culture, until we can speak of culture of T-Mobile or Verizon, we cannot speak of any culture. Fringe examples do not help the case. We are talking about commercial entities, Chapter 6 is all about them.

Kurtki and Wilenius define the culture of sharing as "an ancient phenomenon revitalised by the possibilities of the digital age, which has helped turn an age-old community practice into a profitable business model."[52] In this definition, culture is monetised and its existence leads to the emergence of sharing economies through the technology-enabled networking. It exists on the level of the civilisation, it is general.

Light and Miskelly succinctly describe a sharing culture through the result of interviewing local change-makers changing their world "out of passion, rather than following formal design approaches"[53] from Brockley, Lewisham (London).

> "Significantly, people are all aware of each other; no one is working in isolation. Borrowing goes on between projects and the effort to find materials, support and funds is often shared (...) the area has developed a character that includes such support, so no one is surprised when another initiative takes root locally. Importantly for those doing the initiating, others are willing to help. Not only are there many communal assets; there is the local relational asset of having a rich culture to draw on and to use for support. This might be called a 'sharing culture'."[54]

We cite their work because of the interpretation of sharing cultures (note the plural) they offer, unique pieces of norms and principles within small creative communities. The question of *the* culture of sharing versus *a* culture of sharing is straightforward: different philosophies and driving forces may formulate different instances of sharing cultures. Different contexts can have specific flavours of sharing cultures and within a narrow field and a compact community, different *cultures* may exist as seen in the examples from makers communities such as 3D printing[55]. Different people may all claim to be sharing, but the way they do it is different, and so are the licenses under which they share their work[56]. Each one of them has *a culture*, while the general culture of sharing just provides a wide frame. The diverse cultures may all be sharing in name, but may differ significantly, on both individual and institutional level, as we will see.

The culture of sharing, as we mentioned before, is about engaging all the stakeholders in the community, creating epistemic communities, interest groups around sharing the resource. In other words, the stakeholders inclusion is an important building block for culture of sharing. Two thematic examples of sharing economies can serve here to illustrate how different approaches towards stakeholders may exist. Uber has focused on technology and ignored the three human components of the structure (customers,

[52] Kurki, S. and Wilenius, M., 2015. Organisations and the sixth wave: Are ethics transforming our economies in the coming decades?. Futures, 71, pp.146-158.

[53] Light, A. and Miskelly, C., 2009. Brokering between Heads and Hearts: an analysis of designing for social change.

[54] Light, A. and Miskelly, C., 2015. Sharing economy vs sharing cultures? Designing for social, economic and environmental good. Interaction Design and Architecture (s), 24, pp.49-62.

[55] Moilanen, J., Daly, A., Lobato, R. and Allen, D.W., 2014. Cultures of sharing in 3D printing: What can we learn from the licence choices of Thingiverse users?.

[56] Creative Commons licenses (CC) allow formalisation of a wide range of sharing preferences, from allowing re-distribution of the work and its derivatives without reference to the original author, over allowing commercial use, to demanding attribution and preventing derivatives to be made from the original work.

drivers/providers and employees) directly and the general public indirectly. Together with the established service providers in a given domain, the four groups listed constitute all the stakeholders of a sharing economy model[57]. The opposite example to Uber is Airbnb, keeping the humans in scope at all times. The culture of Airbnb platform is focused on community and connectedness, removing the borders between platform and the providers and blurring the line between the institution and the individual. The difference in the approach to people does not stem from the difference in the shared resource in case of Uber and Airbnb, as Lyft shows how cars can be shared with a human-centric model.[58] John Zimmer, the founder of Lyft says:

> "I think people are craving real human interaction—it's like an instinct. We now have the opportunity to use technology to help us get there." [59]

If this "social-building" priority Lyft goes with is not properly rewarded in the market, as opposed to their competitors (Uber), the reason might be simple: the culture of sharing and the institution of trust in fellow humans may be missing in action (data shows that even though we do not trust humans much[60], we might still prefer humans over machines[61]). It is not a reason to lose hope, though: the success stories of sharing are the stories of building a new norm by value-driven groups extending their principles in a wide circle of users.

Two mutually very different examples of Airbnb and Wikipedia can be identified to argue that culture of sharing can be built: from something completely unacceptable in the society to becoming a norm. It started with a lot of skepticism and the lack of trust: you might be murdered in bed if letting a stranger share your house or the information found on a free, online encyclopedia written by anonymous collaborators with their own biases is not a valid source. How can a responsibility of an individual to share the knowledge voluntary be compared to the protected, licensed establishment behind the Britannica?

> So is it possible to replicate Wikipedia's success? What's the key that made it work?
>
> Unfortunately, this question hasn't gotten the attention it deserves. For the most part, people have simply assumed that Wikipedia is as simple as the name suggests: install some wiki software, say that it's for writing an encyclopedia, and voila! — problem solved. But as pretty much everyone who has tried has discovered, it isn't as simple as that.[62]

[57]Codagnone, C., Biagi, F. and Abadie, F., 2016. The passions and the interests: Unpacking the'sharing economy'.

[58]Sundararajan, A., 2014. What Airbnb gets about culture that Uber doesn't. Harvard Business Review.

[59]Sundararajan, A., 2014. What Airbnb gets about culture that Uber doesn't. Harvard Business Review.

[60]`http://surveys.ap.org/data/GfK/AP-GfK%20October%202013%20Poll%20Topline%20Final_TRUST.pdf`

[61]Trang, S.T.N., Busse, S., Schmidt, J., Falk, T. and Marrone, M., 2015, May. The Danger of Replacing Human Interaction in IS-driven Collaborative Consumption Services. In ECIS.

[62]`http://www.aaronsw.com/weblog/morewikipedias`

Aaron Swartz wrote the above quote in 2006 and went on with investigating the distinctive property of the Wikipedia community[63]:

> Wikipedia's real innovation was much more than simply starting a community to build an encyclopedia or using wiki software to do it. Wikipedia's real innovation was the idea of radical collaboration. Instead of having a small group of people work together, it invited the entire world to take part. Instead of assigning tasks, it let anyone work on whatever they wanted, whenever they felt like it. Instead of having someone be in charge, it let people sort things out for themselves. And yet it did all this towards creating a very specific product.

The radical collaboration is a culture: the first adopters went on evangelising it to those who came to this day. So it was not (just) the wiki platform, which has hosted many other attempts to build a community and a product. The technology, the platform itself allows different interpretations, as a model testimony from a workplace use of a wiki platform shows:

> Part of the problem is that they [the leadership team] just don't get it. The worst example is that when they started that wiki, it was called the culture of sharing... the first thing they did after setting up that wiki.... the first thing they did was lock down their attachments, in the culture of sharing.[64]

The cooperative system was built gradually, starting from small to building a global database: thanks to the mechanism of feedback which resulted in trust building. The sample space is large enough for everyone to get a feedback; given enough time everyone will get the mark they deserve. Someone will leave you a message about the content you were editing or writing, or improve your edit, or revert your changes, or suggest higher level changes, additional references and content and someone might even say "thanks!".

Wikipedia was not the first collaborative encyclopaedia - the story of encyclopedia writing is one of collaboration from the very beginning. But the models of other online encyclopaedias[65] were substantially different[66] from Wikipedia. What Wikipedia

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[63] One could argue that Wikipedia had to empower super-editors to solve the problems that arose in the wild and that there are problems in paradise, e.g. "the number of articles continues to grow rapidly, ... while the number of dedicated editors has been in decline" (http://time.com/4180414/wikipedia-15th-anniversary/); "Wikipedia Is Basically a Corporate Bureaucracy, According to a New Study" (https://gizmodo.com/wikipedia-is-basically-a-corporate-bureaucracy-accordi-1746955234)

However, the "insider" experience of Wikipedia would be that every day on Wikipedia is a display of democracy at work, and with all the problems in paradise, it is improving by the day. Wikipedia from this perspective is the best thing to happen in 21st century culture.

[64] Grudin, J. and Poole, E.S., 2010, July. Wikis at work: success factors and challenges for sustainability of enterprise Wikis. In Proceedings of the 6th international symposium on Wikis and open collaboration (p. 5). ACM.

[65] e.g. GNUpedia `https://en.wikipedia.org/wiki/GNE_(encyclopedia)`, Interpedia `https://en.wikipedia.org/wiki/Interpedia`, Everything 2 `https://everything2.com/`, H2g2 `https://en.wikipedia.org/wiki/H2g2`

[66] `http://www.niemanlab.org/2011/10/the-contribution-conundrum-why-did-wikipedia-succeed-while-other-encyclopedias-failed/`

was guided by was: substance over form. Being based on a simple technology of wiki allowed the platform to be focused on the content. Other online encyclopaedians focused on building their custom technological solutions, neglecting the reason why encyclopaedia as a specific form of organising information works: the content. Another reason why Wikipedia works as a collaborative effort and as a sharing economy model is the decreased ownership over the resource, the information and knowledge shared through the platform. Another trick is the timely component: decentralisation of sharing economies follows very small time constant. You see the effects of what you're doing instantaneously. Sharing economies being based on new, advanced, fast, global networks are very responsive.

Wikipedia is a non-market peer to peer project, Airbnb is not: Airbnb define themselves as a community market place. We do not use them as examples of business models, but examples of culture of sharing and sharing models with the focus on community (stakeholders) involvement.

Observing sharing economy examples from the social viewpoint is quite natural. When Airbnb is observed through this lens, it can be viewed as a social boon[67]: a source of additional income for the citizens and a socially-aware resource for emergency situations such as natural disasters[68]. The answer to the question of why Airbnb was first to succeed with its marketplace model is trust and simplicity. The idea of "replacing policy with principles" as they put it in Airbnb[69] allows an easy operation. So easy that it sometimes takes time to adjust, coming from the corporate havoc of the conventional economy. Airbnb builds a culture of sharing through the market it generates[70]. As a normalizing practice in "Learning with the market" framework[71], it sets a social norm.

Wikipedia educated the society: not just about the planets and wild animals, but about the character of information as well. Wikipedia manages knowledge and facts, and through its principles it conveyed the message that the facts on it are verifiable (through sources) and instantaneously editable (through a simple interface). This meta-knowledge Wikipedia provided to its users helped build trust and a culture of both using and building Wikipedia.

An important question is the supremacy of culture over the notion of economy, when it comes to sharing. Light and Miskelly doubt in existence of sharing economy and call for cultures replacing the emerging economies:

> "Do the tasks of Taskrabbit, the car-sharing of Zipcar and the taxi-ing of Uber have much in common with these local pursuits? Not really. Do they promote this culture? No. We have argued that there is a huge, hybridized

[67] McNamara, B., 2015. Airbnb: A not-so-safe resting place. J. on Telecomm. & High Tech. L., 13, p.149.

[68] `https://www.airbnb.ie/welcome/evacuees`

[69] Zak, P.J., 2017. Trust Factor: The Science of Creating High-Performance Companies. AMACOM Div American Mgmt Assn.

[70] Sigala, M., 2018. Market Formation in the Sharing Economy: Findings and Implications from the Sub-economies of Airbnb. In Social Dynamics in a Systems Perspective (pp. 159-174). Springer, Cham.

[71] Storbacka, K. and Nenonen, S., 2011. Scripting markets: From value propositions to market propositions. Industrial Marketing Management, 40(2), pp.255-266.

> space appearing at the moment, which includes networked services that are dis-intermediated (or re-intermediated with new broker-owners), thus allowing for new peer-to-peer provision. But there is no sharing economy and a belief in one is potentially detrimental to community activity. An understanding of sharing as collective – on some level – brings different kinds of interaction into scope. These promote the social case but have limited immediate economic scalability. Nonetheless, replicating the ideas and values evident in this rich soup and enhancing them with digital tools that support further growth could provide a sharing culture that is, we argue, more sustainable of life generally. And the interrelationship between environmental, social and economic well-being suggests that sharing, while no panacea, offers most when it speaks to all three."[72]

We do not go that far, as we acknowledge the existing peer-to-peer marketplaces as sharing economies, but agree about the importance of the culture and making the social case. In the case of spectrum, successful sharing means sharing as collective. So, what we need is not necessarily sharing economy, but definitely the culture of sharing. The culture can't afford to lose the human perspective, as spectrum is as social as it is a technical concept. Let us not forget the story of the public interest, and the unique red lines of spectrum connecting the resource with the society. At the end of each hertz is a human, even if it is a device-to-device communication (it serves a social role nevertheless).

Where did the technical culture of sharing come from?

3.3.1 *Hackers, the People of the Culture*

> "[Shareable founder, Neal] Gorenflo tracks the trajectory for the sharing culture from the MIT computer science enthusiasts in the 1950s. Their seminal idea was that better results can be obtained through sharing, and individuals should have free access to the tools they need to make things (the original hackers at MIT, for instance, picked locks to be able to keep the lights on at their lab in order to be able to keep on programming after hours). Gorenflo sees a direct lineage from these values to the sharing movement, flowing through several evolutionary steps: The Internet was built with hacker values by some of the same people, and the same values guided MIT alumni Richard Stallman to create open-source software. The next step was opening contents to be used as material for creating by the Creative Commons license. Social media brought these values of sharing and creating to the masses. From there, the next logical step is extending the culture of sharing into the physical world."[73]

[72] Light, A. and Miskelly, C., 2015. Sharing economy vs sharing cultures? Designing for social, economic and environmental good. Interaction Design and Architecture (s), 24, pp.49-62.

[73] Kurki, S. and Wilenius, M., 2015. Organisations and the sixth wave: Are ethics transforming our economies in the coming decades?. Futures, 71, pp.146-158.

As stated in this quote, the hackers had it first - the modern era culture of sharing. For us, the term hacker means "exploring the limits of what is possible, in a spirit of playful cleverness" as formulated by Richard Stallman.[74] This captures perfectly the efforts made in radio spectrum utilisation from the very beginning, and it was the spectrum hackers who enabled its widespread use.[75] The (amateur) radio community hacking the hardware and hacking into the available spectrum was the first hacking[76] and DIY (do it yourself) community of the modern era.[77]

Even if we take the cybersecurity-unfriendly definition of hacking as our working premise, it is again the wireless radio enthusiasts who engaged in it first, with the infamous telegraph hacking of 1903 (when Nevil Maskelyne sabotaged Marconi's demonstration[78]) being an early example.[79]

What happens with the criticism of hacking when we observe it from the radio spectrum perspective? Some of the philosophical arguments of the 20th century may be of interest, namely Adorno's and Derrida's.[80] When Adorno introduces his example of a ham operator[81], while cartoonised, it does show an important quality of a radio enthusiast: they aim to squeeze their signal in there, in a spectrum niche. Adorno (intentionally) fails to see the effect of this, but we do not: we see where low power and high imagination has taken us in the century of radio[82]. On the other hand, when Gunkel[83] continues with Derrida's idea of parasitism[84] to note that hacking wouldn't exist without a system to draw its strength from, we can again reflect on the airwaves hacking and note that even in the most anarchical of arrangements hacking of spectrum would still exist, as it hacks the natural entity spectrum is.

Returning to the quote from the beginning of this subsection, extending the culture of sharing into the physical world in case of spectrum means bringing the culture of sharing home.

[74] On Hacking - Richard Stallman - Stallman.org, 2002. Available at `https://stallman.org/articles/on-hacking.html`

[75] Barnouw, E., 1966. A tower in Babel. Oxford University Press.

[76] Galloway, A., Brucker-Cohen, J., Gaye, L., Goodman, E. and Hill, D., 2004, August. Design for hackability. In Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques (pp. 363-366). ACM.

[77] Kuznetsov, S. and Paulos, E., 2010, October. Rise of the expert amateur: DIY projects, communities, and cultures. In Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries (pp. 295-304). ACM.

[78] Maskelyne hacked a presentation of Marconi's wireless telegraph in London by causing powerful interference with the system and sending his own message to the crowd in the room: "RATS RATS RATS, There was a young fellow of Italy, who diddled the public quite prettily".

[79] Fell, J., 2017. Cyber crime-History: Hacking through history. Engineering & Technology, 12(3), pp.30-31.

[80] Taylor, P.A., 2005. From hackers to hacktivists: speed bumps on the global superhighway?. New Media & Society, 7(5), pp.625-646.

[81] Adorno, T.W., 1991. On the fetish character in music and the regression of listening. The essential Frankfurt school reader, pp.270-99.

[82] A good example is the QRP operation of amateur radio enthusiasts, where they seek the maximal range with a minimal power (i.e. 5W and less).

[83] Gunkel, D.J., 2000. Hacking cyberspace. Jac, pp.797-823.

[84] Derrida, J., 1977. Limited inc (Vol. 10). Northwestern University Press.

3.4 CHAPTER SUMMARY

After reviewing the world of spectrum in Chapter 2, this chapter gave a vision of the spectrum world through the lens of sharing cultures and economies. In this chapter, we united several existing definitions of sharing economies to devise a framework suitable in the context of spectrum sharing. We explained why thinking in sharing economies terms is useful for spectrum. We related this point to the societal role of spectrum resource, as this thesis aims to answer the question of how culture of spectrum sharing can be built. To serve this purpose, we devised a conceptual framework called NTBRS - which consists of five components (nature, technology, business, regulation and society) and their interconnections. The interconnections, as we will see throughout this thesis, are inseparable from the context in which spectrum sharing needs to happen and they determine the future direction of spectrum sharing. Chapter 2 covered the first four of NTBRS components, but it's the lack of the fifth one that introduces imbalance in regulatory design of a spectrum sharing model and prevents spectrum sharing from becoming prevalent mode of spectrum use. The fifth component (the one of society) is where the culture of sharing needs to develop and it is by no means detached from the other four. The interconnections of the other components towards the societal one and the culture of sharing are going to play a massive role in building it.

As our exploration was motivated by the lack of culture of spectrum sharing, we first showed what we mean by culture of sharing from the field where it exists, the sharing economies. To find the answers we need to observe the whole spectrum ecosystem through the lens of the NTBRS framework components, but not to do a strict separation of them, not to make borders or dissect them - but to recognise the interconnections and mechanisms that could lead to a balance in a regulatory design. For sustainable spectrum sharing models, the culture of sharing needs to come naturally as an evolutionary phenomenon. By the approach we are taking, we aim to show that the evolutionary solution is a robust one as opposed to an imposed, designed complex solution. Building the culture of spectrum sharing is a gradual, evolutionary process which requires an effort and the policies that work to enable culture of sharing can be designed.

4

INTERDISCIPLINARY RESEARCH DESIGN

Spectrum, as has been shown in the last few chapters, is a multidimensional and complex entity. The research problem of culture of spectrum sharing is interdisciplinary, it reflects the multidimensionality and complexity of spectrum and is in the mix of technical, regulatory, economic and social disciplines. To answer the main question and its sub-questions introduced in Chapter 1, we base the research design on a range of methods. The interdisciplinarity of research methodology is dictated by the diversity of domains identified in the conceptual NTBRS framework and the interconnections between them. If there were no interconnections between the domains, the research could be independently conducted in each of the domains (i.e., multidisciplinary). In our case, the methods are intertwined, the results of analysis within one discipline feed into the other to provide meaningful conclusions. Therefore, the methods are selected to address the questions of the NTBRS concepts and domains because the NTBRS framework captures the spectrum sharing context of the thesis.

The organisation of the chapter mirrors this motivation. We first describe the development of a conceptual framework in Section 4.1, in order to outline the set of heterogenous methods in corresponding subsections within Section 4.2.

4.1 DEVELOPING A CONCEPTUAL FRAMEWORK

A conceptual framework is a researcher's method to organise the key identified concepts in a study and propose their relationships. It reflects a researcher's position to the problem addressed, builds the context for interpreting the study findings, for explaining observations and it aims to encourage theory development that is useful in practice. This is a standard procedure of analysis and synthesis and such frameworks have been devised in number of studies[1].

A necessity for proper conceptual frameworks in spectrum policy has been recognised long before sharing was feasible[2]. The authors took a market-based perspective on spectrum policy and suggested several domains in which the regulator should frame its policy objectives. This work is an example of mutidimensional outlook on spectrum. We need a multidimensional view on spectrum sharing. The regulatory frameworks have not demonstrated yet the broad context which includes all of the

[1] One example of a conceptual framework for a successful sharing comes from a different field, but it is a highly influential work on knowledge sharing. There, the author formulates a model based on the factors that influence and contribute to knowledge sharing, following the general scheme of framework design.

Ipe, M., 2003. Knowledge sharing in organizations: A conceptual framework. Human resource development review, 2(4), pp.337-359..

[2] Rosston, G.L. and Steinberg, J.S., 1997. Using market-based spectrum policy to promote the public interest. Fed. Comm. LJ, 50, p.87.

aspects of sharing reflected through the rules they adopt. There is no a unified framework to serve as a guide for policy design which would connect the rules of sharing through the interplay of economics, technology, law and politics. The interplay is embedded in the rules and the connection between the rules is real. Sometimes a rule comes out of an extensive modification of another rule, as a consequence, but is seen as a standalone point in the framework when it comes to its implementation. The context of their development is lost and with that, the opportunities to incentivise sharing as well. These opportunities come with recognising the different domains in which improvements are possible. Improvements would result in a more effective rule, one which promotes spectrum efficient use. This is a generalised example whose specific instances we will encounter in chapters to come. With the conceptual framework from Chapter 3, we proposed one way to fill this contextual gap.

Spectrum sharing is introduced in this work as a multifaceted problem in background Chapter 2, but in order to really find meaningful answers we needed to define exactly what the facets are and how are they interconnected.

Devising the conceptual framework required a chapter because: (1) it is not a theoretical framework built from the existing theories, so the observations it is built from had to be detailed out, (2) sharing economy perspectives are diverse and require a dedicated discussion, (3) not all of the domains of the framework appeared in detailed background chapter on spectrum issues, the missing one (society, with its enabler, the culture of sharing) had to be presented alongside the framework in Chapter 3.

Through varying level of abstraction, we studied the enablers of sharing and their aspects to arrive to the general concepts, the domains in which we need to look for answers: nature, technology, business, regulation and society. The first four domains were revealed in Chapter 2 where we discussed physical, technical, economical and legal aspects of spectrum policy. The last domain (society) revealed itself in Chapter 3. These are the five domains that build the conceptual framework. We identify the relationships between the key concepts (domains, enablers) from a perspective of what dynamic spectrum sharing could be while identifying the enablers of dynamic sharing in sharing economies. The relationships arise from manifestations seen in sharing economy definitions and the specific properties of spectrum and its ecosystem. With this we are able to give meaning to the research findings, give a starting point for the context building throughout the thesis and propose solutions. In other words, when we say nature, the NTBRS framework ensures that we know in which domain we are primarily moving.

The identification of concepts and connections is coupled with the choice of methods. The role of the framework does not stop there, as it returns to interpret the results that the methods deliver.

4.2 METHODS

To illustrate where and when the methods come into play, we present Fig.4.1 which maps the methods to the chapters. It also shows the interconnection of the chapters.

The main research question of how to build the culture of spectrum sharing is contextualised within the NTBRS conceptual framework. Research sub-questions are answered gradually, chapter by chapter by applying the methods in the following way..

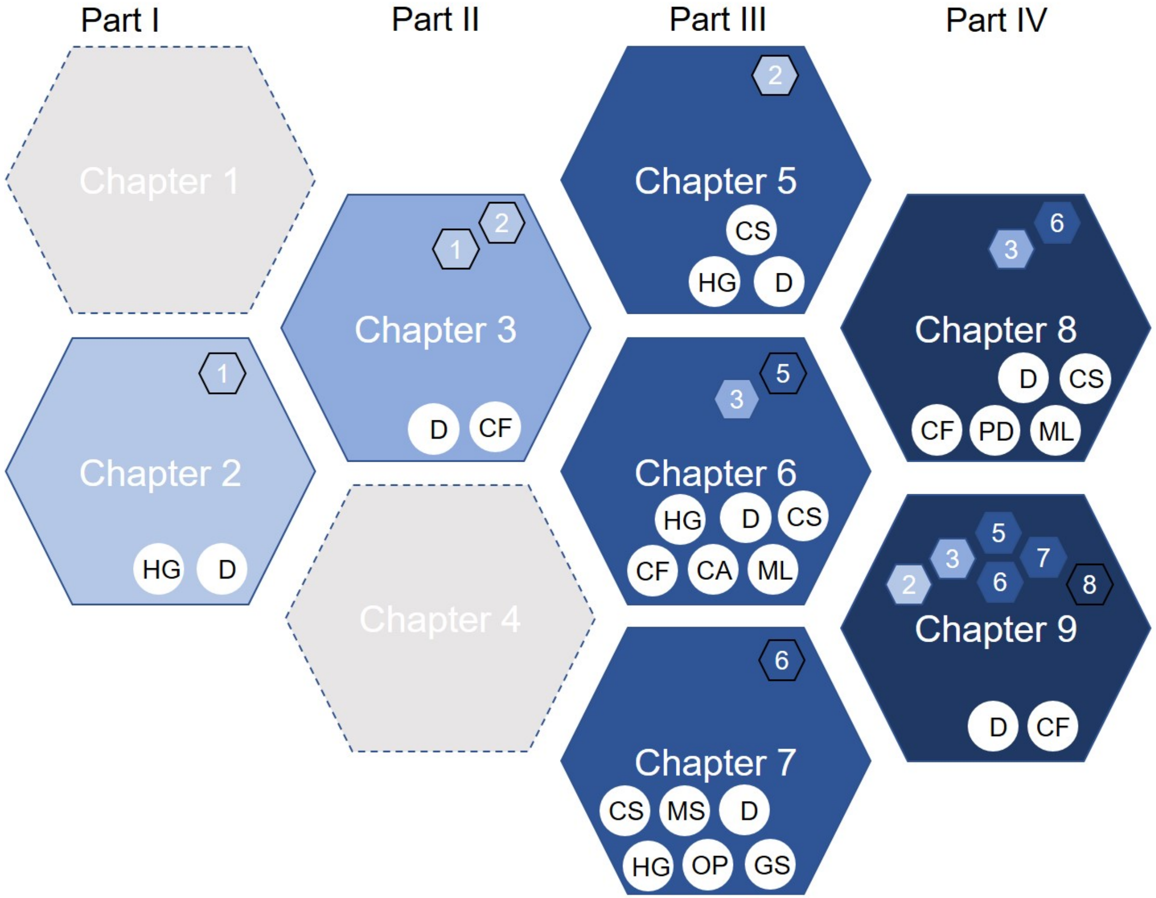
To answer *What is spectrum and what is spectrum sharing?* in Chapter 2, we performed literature review by applying the historiographic approach to scholarly literature. The material is synthesised and presented as a form of policy analysis and historiographic record of spectrum policy development. Elements of policy analysis give us a general view on policy and theories of regulation. They are present in every chapter where we speak of concrete spectrum sharing theory and practice because it is an inherently policy topic.

To answer *Where does the culture of sharing fit in spectrum sharing?* in Chapter 3, we devised the NTBRS conceptual framework as an approach to the analysis, in order to synthesise sharing economies and spectrum sharing through the perspective on culture of sharing.

To answer *What is the right methodology for the problem exploration?* in this chapter, we apply general guidelines for interdisciplinary research and invoke the devised conceptual framework.

To answer *What are the initial conditions for sharing?* in Chapter 5, we begin the case study on an example of a spectrum sharing model, the CBRS sharing framework . We use historiography method, the choice of primary and secondary sources enables us to describe the state of US policy before the CBRS, the origins of the CBRS idea in spectrum policy reports and the structure of regulation in the first part of the CBRS behind the scenes story. The material presented as a form of a documentary is built on the important elements of historiography: timeline, critical interpretation, the use of the sources and the most important element, the context.

To answer *What differentiates the CBRS band from traditional bands?* in Chapter 6, we use few methods from social science and engineering. The content analysis is performed on a primary historiographic source within the CBRS case study. The NTBRS framework is used again and machine learning helps to reveal patterns and answer the chapter question. The material is turned from unstructured documents into a visualised and tabulated structured insights about policy design and can serve as a record of useful information about the CBRS model and a reference for future policy design.



Abbr.	Method
CA	Content Analysis
CF	Conceptual Framework
CS	Case Study
D	Dialogue
GS	Geospatial Analysis
HG	Historiography
ML	Machine Learning
MS	Modelling and Simulation
OP	Optimisation
PD	Pathetic Dot Theory

Figure 4.1: Research design

To answer *How to design a licensing scheme for geographic spectrum sharing?* in Chapter 7, we again use the mix of methods; geospatial analysis, optimisation, simulation are applied on the insights gained from case study analysis combined with historiographic approach. The material is presented in a chronological narrative and through visualising the results in the form of maps. We use the govermental sources of data again, extending the primary source of CBRS proceeding with the US census data for the policy and geospatial analysis.

To answer *How to regulate sharing behaviour to build the culture of sharing?* in Chapter 8, we employ Lessig's pathetic dot theory and the data from the case study, combined with contextual insights and the experience from the case study. With the help of pattern recognition we find the interconnections between the modalities of regulation and reveal the link between our conceptual framework and the pathetic dot theory of regulation. The material is presented in a generalised timeline: from the rulemaking past we arrive to the present state and discuss the future evolution of the CBRS within the perspective of building the culture of sharing through the modalities of regulation.

To answer *How to design future spectrum sharing policy?* in Chapter 9, we use the NTBRS framework as its important purpose is to encourage new theory of spectrum sharing development.

The dialogues as a form of scientific writing are created to serve as introductory material for each chapter. Using the dialogues as a method of exposition of the issues and ideas discussed in each chapter we also mirror the actual process of the FCC rulemaking in spectrum policy design, as the regulator engages in a dialogue with the stakeholders to create policies on sharing. The content of the chapters and the coded language or rulemaking is mirrored in an enstranged interaction of archetypal characters.The dialogues are compiled into a mini radio-drama *"Eight Bits of Frank and Laura"* to accompany the reading of each chapter. Their audio recordings are stored online and the links are provided in the introduction section of the chapters. These features make the dialogues an important element of the thesis as they reveal the context in its bare form.

In summary, the research methodology is designed with a focus on the crucial aspect of policy making which is the context. The context keeps the parts of the thesis together and sustains multidimensional nature of the problems and solutions this work provides. Such interpretation of context also encompasses its philosophical nature.

4.2.1 *Introducing the Case Study*

This thesis is about dynamic spectrum sharing and how the culture of sharing can be built into it. The question cannot be answered in abstract form, so we perform a case study on an emerging example of a spectrum sharing model which is supposed to be the most dynamic and innovative one that we have today. Recognising the vital potential of spectrum sharing for the national economy, the PCAST report "Report to the President: Realizing the Full Potential of Government-held Spectrum to Spur Economic Growth" set the goals for the US policy future of spectrum in 2012[3]. The PCAST Report has called for innovation in spectrum sharing by mapping the technology and regulatory enablers and advancing them both so that *sharing becomes a norm*. One of the many inspiring messages of the PCAST report was that commercial wireless users will get to share military spectrum. To embed this promising sharing diversity into the set of effective and clear regulatory rules of operation, the FCC has put a stamp of approval on such message by first - creating an entirely new class of services for the band[4], and second - adopting the technical rules of CBRS operation[5].

What is the CBRS sharing model about? The broad range of future usage is suggested in the title itself, Citizens Broadband Radio Service. The type of usage and the classes of services under the CBRS name, as depicted in Fig.4.2, range from licensed carrier cells, fixed wireless broadband to advanced home networking and any other uses. The multi-tiered access model defined settles three tiers of users in the band via CBRS rules of spectrum sharing: Incumbent Access (IA) users (Tier 1), Priority Access (PA) users (Tier 2) and General Authorized Access (GAA) users (Tier 3).

IA users, as primary holders of spectrum rights have the highest priority to access the spectrum. Accommodated in the Tier 1, they also have a highest priority to receive protection from harmful interference that commercial users in lower tiers would generate; moreover they are not required to mitigate interference they generate to lower tiers. To protect them, defined are the exclusion zones and protection zones in which the lower tiers cannot operate in case IA users are using their spectrum. For the 3.5 GHz band, the IA users are federal users (military high-powered radars on ship platforms across the coastline) and grandfathered fixed satellite services (FSS). Federal incumbent use is a matter of national security and therefore such users need continuous protection from interference. However, national defense missions are usually executed in shorter times and in limited geographic areas, therefore unused portions of spectrum in space, time and frequency can be reallocated to other users.

PA users need to be issued with a license to access spectrum through a geographic licensing scheme. This is a tier that gets to buy a protection from interference, which comes with the QoS and coverage guarantees. The licenses will be auctioned and the competitive operators are expected to bid for the available PALs (priority access licenses) in 3.5 GHz band.

GAA users do not need to get a license as they access spectrum opportunistically, similarly to an unlicensed mode of operation with the difference of being licensed-by-rule in the framework. This means that GAA devices have to be FCC technically certified (ability to tune to given frequencies or having embedded sensing capabilities in the device) and will be assigned in the band dynamically, based on the demand - whenever and wherever spectrum is free from the PA use. In other words, GAA users do not get to buy protection but have to fit in the band by accepting the reasonable

[3] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf

[4] https://www.fcc.gov/document/enabling-innovative-small-cell-use-35-ghz-band-nprm-order

[5] https://docs.fcc.gov/public/attachments/FCC-15-47A1.pdf

levels of interference caused to their networks, while making sure their networks are not interfering with the tiers that do have higher priority to access spectrum and get protection.

The tiers of diverse users will be managed by the Spectrum Access System (SAS) - a technologically sophisticated system of multiple databases, set in a complex spectrum sharing environment of the 3.5GHz band. As depicted in Fig.4.2, the SAS is in charge of PA and GAA assignments and authorization, tiers coordination and management of interference due to tier-interactions. The types of interference that may occur in tier interactions are: (1) *co-channel interference* (from PA and GAA to IA, between two adjacent PA users, between nearby GAAs, between PA and GAA users) and (2) *adjacent channel interference* (from PA and GAA to IA, between PA users across adjacent license areas, between PA users within a license area, between PA and GAA users and between nearby GAAs). The SAS needs to coordinate the users in the band dynamically and potentially across multiple bands, so it also needs an embedded mechanism for monitoring spectrum usage and many other functionalities to ensure smooth operation in the band.

The sharing framework for 3.5 GHz band accommodates diversity of users, envisions a range of different technologies to be used and supports many different applications to enable efficient sharing. The CBRS system is a subject of our case study and all of its peculiarities will be elaborated on in the rest of the thesis. For now, we note that this is a spectrum sharing model most recently emerged in regulatory landscape and we will explore how advanced it is and if it can be improved.

We focused on the US policy and the CBRS model in our quest for culture of sharing as it provided grounds for an academic work with potential of impact. As a qualitative social science research method, the purpose of a case study is to generalise the findings from specific case studied to produce a grounded theory (built from ground up) about all other similar cases. As noted, CBRS is an example of an emerging dynamic spectrum sharing model. The case study of CBRS, if done thoroughly, could provide us with a theory about dynamic spectrum sharing models. Based on the information we have about the CBRS we are able to observe all the nuances of the model, by applying different methods and techniques presented in this chapter.

The nature of the CBRS data and information is ideal for a case study like this, because: (1) it is complete, without hidden or classified details, (2) it is big enough to accommodate opinions of all stakeholders and to build a full profile of each one of them, (3) it is small enough to be accessible to a human, without skipping, sampling or relying on any other kind of help from the machines, (4) for the first time in history of radio regulations, such an extensive public record on a spectrum sharing model is created, giving a unique opportunity for making a documentary, a historiographic analysis, analysing policy and regulatory approaches, getting an insight into little known stakeholders sub-culture and making inferences about the future, of both CBRS and dynamic spectrum sharing in general.

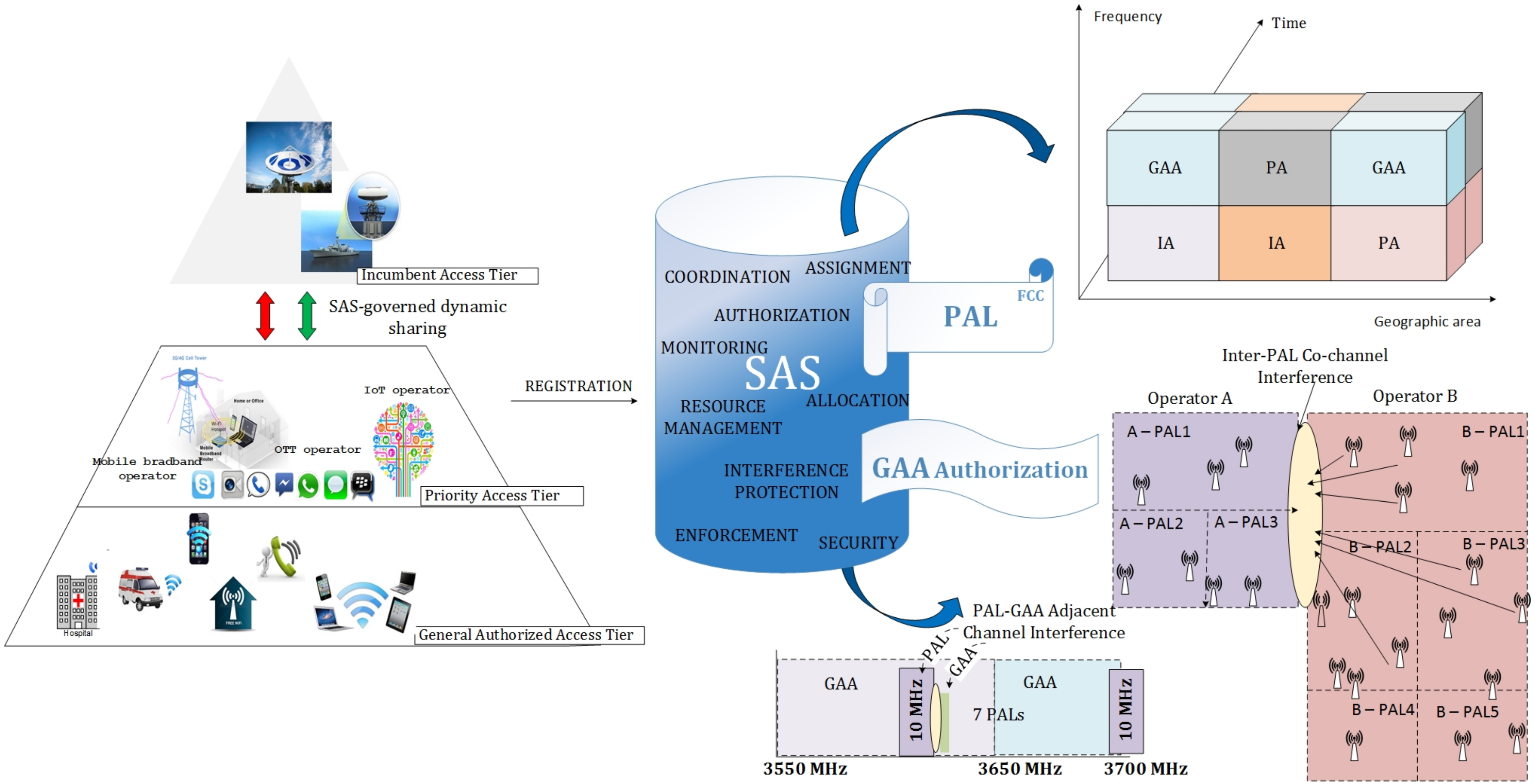


Figure 4.2: Tiers of SAS and SAS functionalities: The 3.5GHz band becomes open to licensed and opportunistic use, accommodating critical operations facilities (hospitals, public safety networks), business and residential users alongside with federal users and fixed satellite stations which encumber the band.

4.2.2 *Carrying out Historiography*

Historiography is classified as a qualitative methodology in social science research, but it is a methods toolbox on its own as well. Historiography is an umbrella term for: the *context*, *timeline and chronology*, *critical interpretation* and the use of *vast amount of sources*.

The documenting goal of historiography may be fulfilled through telling a story chronologically and using the tool of timeline to emphasize periods in which certain events happened, that are of interest for the research questions posed ahead. Critical interpretation means that the researcher needs to put the findings and information collected to the scrutiny of critical theory in order to interpret what the particular events and actions of policy process mean for the research performed.

For the historiography to be reliable, a vast amount of sources was needed to be put under scrutiny of critical theory. In digital age of today, there are no lost documents of these events[6]. The classifications of the material as primary and secondary sources of information is therefore important. The *primary source* (for the technical and regulatory analysis of the framework) is the FCC 3.5GHz proceeding database, docket GN. 12-354 - official record of the CBRS framework development. These are legal documents of different structures (public notices, reports and orders, calls for reconsideration, filings of stakeholders: ex parte letters, comments, replies to comments etc.) and their analysis enables us to devise a timeline and follow its chronological development. It is an extensive evidence of all the events that shaped the policy for this band. In order to understand the CBRS background story and the narrative of the CBRS saga as seen from the general public perspective, a range of *secondary sources* is necessary as well: from media coverage, science and technology blogs and web portals, official press releases, to white papers, different reports, analysis and studies, prototype descriptions and industry white papers.

Motivation for historiographic research method for building the context vital for any serious policy review and/or outlook to the future, is a straightforward one: legacy in regulatory approaches still governs spectrum. Considering the alternatives to historiography, experimentation comes as a default one. We do our share of experiments in this thesis, but the experiments that would single-handedly and undoubtedly give the answers we want are not possible. Benkler called for them:

> At present, however, the lack of clear empirical evidence in favor of one or the other of the two radical critiques of the prevailing licensing regime cautions against any kind of "Big Bang" approach that will preempt future policy making. What we need is a relatively large-scale experiment in both markets[7].

[6]Our interest being the FCC's relationship with commercial stakeholders, not the communications between federal government (NTIA and FCC for example) which do not have to be inserted into the public record.

[7]Benkler, Y., 2002. Some economics of wireless communications. Harv. JL & Tech., 16, p.25.

However, as our historiographic evidence shows we haven't seen these, nor will we in the foreseeable future[8]. As of today, nothing is set in stone when it comes to this story. The events happening as we write require constant documenting, updates and reviews of the works and trends. This is the historiography of yesterday and earlier today.

Learning from the past is an important feature of applied historiography - it is not just studying the past to do justice to the past. The goals set in research design were to produce a documentary (the history) and a manifesto (our ideas inspired by history)[9]. Each chapter that has a documentary character is structured so that the reader can see wider effects on present and future time and not only observe the problems as if they are solely for one country, at one time period, in one specific spectrum band (Chapters 2, 5, 6, 7, 8).

Chapter 9 is a manifesto of SPECTRUMISM, a philosophy of a spectrum sharing economy. It does not come suddenly though. Chapters of the case study (5-8) have been concrete in giving answers to the parts of our research question, and their timeline was open-ended as Chapter 8 opened a discussion on the future. Documentary ends with the Chapter 8 and then in Chapter 9 we deal with the future.

4.2.3 *Performing Content Analysis*

The much needed systematic approach to extensive data we have (which also puts to use the overall context) is provided by application of content analysis method. The data and context are put to use by content analysis through reconstructing the reality from the material snapshots. We adopt Krippendorff's[10] definition of content analysis and his framework for performing it, as he is a pioneer of a rigorously framed content analysis method.

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[8] As we can see from the CBRS status in 2018, the tendency is to go back to traditionally governed bands approach, which is not promising on the possibility to do extensive experimentation in CBRS band.

[9] Umberto Eco recognises these two parts (documentary and a manifesto) in a historiographic thesis:

> "Let us hypothesize that the student believes he has understood an important problem. Since nothing is born from nothing, the student must have developed his thoughts under a particular author's influence. In this case, he should transform his theoretical thesis into a historiographic thesis. In other words, he should not discuss the problem of being, the notion of freedom, or the concept of social action; but develop a topic such as "The Question of Being in Early Heidegger," "The Notion of Freedom in Kant," or "The Concept of Social Action in Parsons." His original ideas will emerge as he grapples with his author's ideas, as it is possible to say new things about freedom while studying an author's work on the concept. If he is ambitious, he can transform the theoretical thesis that he originally conceived into the final chapter of his historiographic thesis. Consequently, readers will understand his original ideas in the context of a previous thinker, and the concepts he proposes will gain support from their proper frame of reference."

(Eco, U., 2015. How to write a thesis. MIT Press (first edition in English, originally published in Italy in 1977.).)

[10] Krippendorf, K., 1980. Quantitative content analysis: An introduction to its method. Beverly Hill: Sage publications. and the 2003 edition under the title Content analysis: An introduction to its methodology

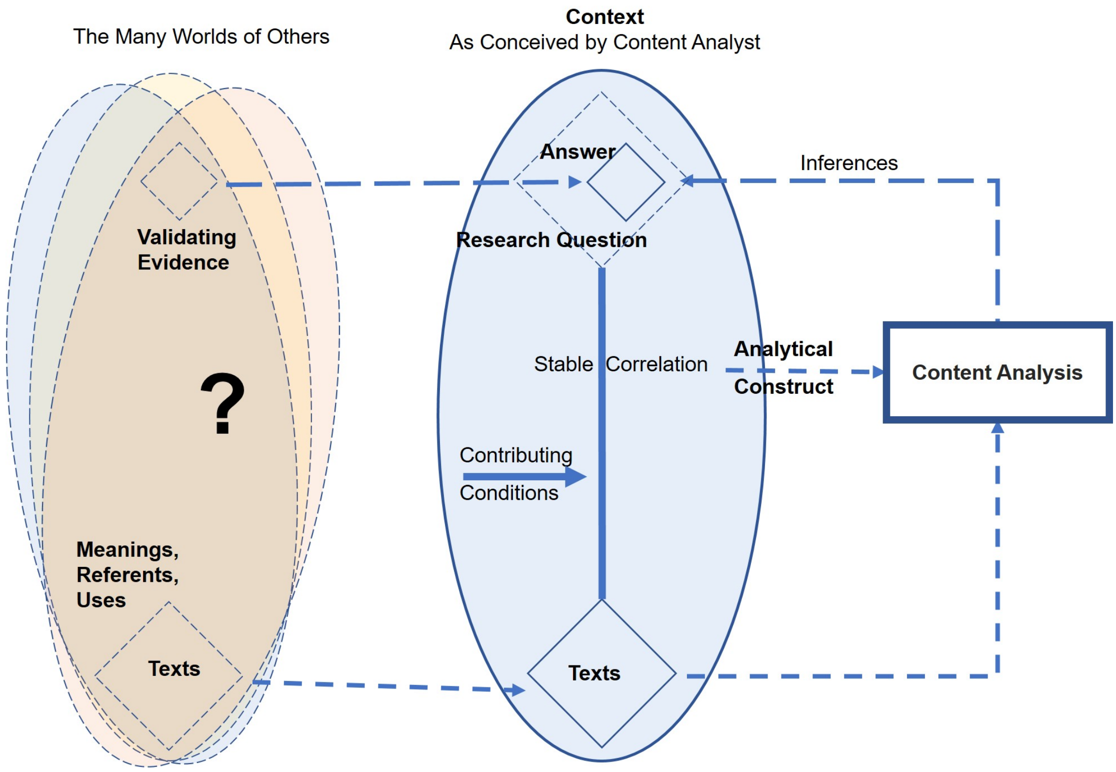

Figure 4.3: A framework for content analysis

> Content analysis is a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use.

This definition is formulated broadly, as it is a result of Krippendorff's systematic review of existing definitions and a finding: there are three wide types of content analysis definitions, depending on the relationship between the text and content ((1) content is in text, (2) content is in the source of text and (3) content is emerging from the process of analysis and the context). In that classification, his definition is one of a third kind as it takes content to "emerge in the process of a researcher analysing a text relative to a particular context"[11]. This resonates with our approach elsewhere in the thesis, as we insist on the interpretation within the context.

Krippendorff's framework for content analysis is shown in Fig. 4.3.

There are six components of the framework: (1) **texts** (data) to analyse, (2) **research questions** to answer by analysing texts, (3) **context** to make sense of the text, (4) **analytical construct** built around what the analyst knows about the context, (5) **inferences** that serve to answer research question, (6) **evidence which validates** the analysis.

The texts constitute the object of content analysis, projection of the real world into a set of documents. Research question is posed about what the analyst suspects can be answered by extracting information from the texts. In other words, it is a question about the real world but answered through the content found in the texts. The context is the crucial part of content analysis as it depends on research question asked by the

[11] *Ibid.*, Chapter 2, p.19-21

analyst and world the analyst chooses to construct. It is defined by the analyst and it aims to describe the circumstances of the real world in which the documents were created and their relation to the real world. The figure represents context as a single ellipse, while the real world consists of multiple ellipses, illustrating how important it is for an analyst to explicitly state what the context for the analysis is so that its results can be understood by scientific peers (which we will do in corresponding chapter). An analytical construct is a formalisation of context created to ensure that what is known about the relationship of the real world and the texts is used to answer the research question. Inferences answer research question, informed by the analytical construct applied on texts. Once the answers are found, they should match the situation in the real world. There needs to be evidence in the real world which can confirm the results of the analysis.

The motivation for the choice of method to be applied on the CBRS proceeding docket is the following:

1. In order to get to know the rules of CBRS and how were they shaped through the multilogue with the stakeholders we have to go through the whole process of rulemaking. Recall what we said in the section on conceptual framework: interconnections will be lost if we just observe the final product. This means that this requires an analysis.

2. FCC's rulemaking process has defined the CBRS proceeding docket 12-354 as the source of rulemaking. That also makes it the source of our analysis.

3. The expression of opinions in the proceeding is not filling out a form - it has nuances, unique language use, explicitly stated motivations and also the latent ones. This requires an informed analyst.

4. The content of the proceeding cannot be observed outside the context of the market, technology, previous law making, society and politics. This implies that the analysis is more than just counting, as there are many worlds and contexts to account for.

4.2.4 *Applying Pattern Recognition to Spectrum Policy*

To find the principles governing the dynamics of the interaction of stakeholders (Chapter 6) and rules (Chapter 8) in the CBRS ecosystem, we use the techniques from pattern recognition. As we look for patterns to observe in a wider sense where something belongs to, the principles that affect and shape the interactions (between stakeholders, between the rules, between the stakeholders and the rules) will help in putting together similarities and forming clusters. Even though pattern recognition existed before the machine learning enabled a fast manipulation of large, high-dimensional data[12], it is almost synonymous with machine learning today. We use the machine

[12] Fisher, R.A., 1936. The use of multiple measurements in taxonomic problems. Annals of human genetics, 7(2), pp.179-188.

learning aided pattern recognition to handle relatively large data sets (in human perception) in high dimensional feature space and to cluster them. While we do have a personal insight into what the clusters may be, the effort is made not to place bias on the clustering algorithms used: the clusters have to emerge from the features of the data and nothing else.

We use EM algorithm[13] for clustering, in order to have the algorithm "fill in the blanks" and extrapolate data points implied by the stakeholders but not expressed in their statements. In Chapter 6, we use it to discover how are the stakeholders grouped in terms of their policy positions, while in Chapter 8 we discover what do different CBRS rules do to the CBRS ecosystem depending on the group they belong to. We also use attribute ranking[14] to handle highly correlated data present in issue lists and to extract representative issues with the highest information content.

The use of machine learning and pattern recognition in this thesis has a deeper message to convey as well: as we reveal at the end of the thesis, data is a crucial dimension of spectrum and handling it efficiently is the key to successful spectrum sharing. Machine learning and big data analytics will have to be a part of the spectrum sharing toolbox.

4.2.5 *Combining Optimisation and Geo-spatial Analysis*

In the theory and practice of wireless communications, modeling of space is an important and difficult task[15], as the spatial dimensions of the communication are somewhat different from the time and frequency. When it comes to the outdoor, long distance scenarios, these models use the geospatial data from open and proprietary sources[16]. Computer data of this kind has been collected since the advent of digital computers, making the area of Geographical Information Systems (GIS) more than half a century old[17]. The public availability of this data coincides with the proliferation of internet and with the first mention of Virtual Earth, the idea of a completely digitised all-encompassing system geo-referencing planet Earth which came in the nineties from the US Vice President, Al Gore[18]. A use case of this futuristic vision is modelling and simulation[19], and we aim at using available data to analyse CBRS spatial licensing dimension, the US Census Tracts.

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[13]Dempster, A.P., Laird, N.M. and Rubin, D.B., 1977. Maximum likelihood from incomplete data via the EM algorithm. Journal of the Royal Statistical Society. Series B (methodological), pp.1-38.

[14]Hall, M.A., 1999. Correlation-based feature selection for machine learning.

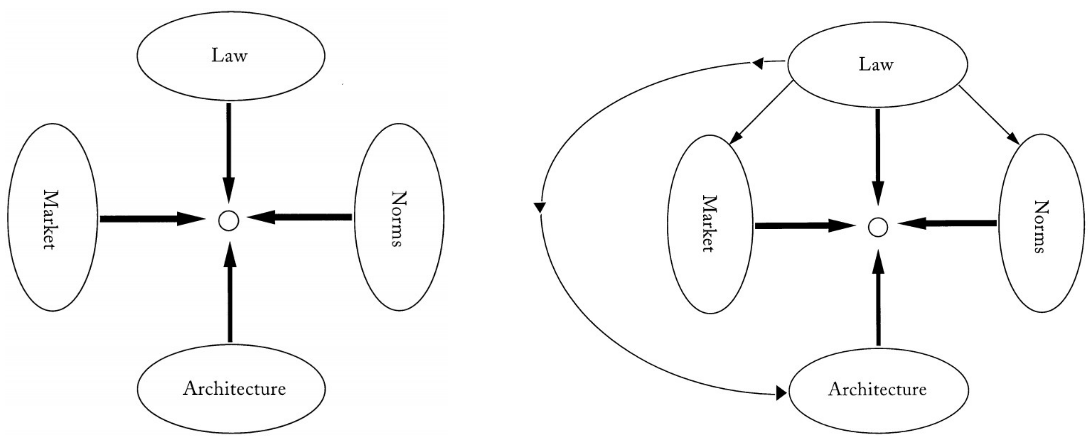
[15]Andrews, J.G., Ganti, R.K., Haenggi, M., Jindal, N. and Weber, S., 2010. A primer on spatial modeling and analysis in wireless networks. IEEE Communications Magazine, 48(11).

[16]Karnadi, F.K., Mo, Z.H. and Lan, K.C., 2007, March. Rapid generation of realistic mobility models for VANET. In Wireless communications and networking conference, 2007. WCNC 2007. IEEE (pp. 2506-2511). IEEE.

[17]Coppock, J.T. and Rhind, D.W., 1991. The history of GIS. Geographical information systems: Principles and applications, 1(1), pp.21-43.

[18]"The Digital Earth - Al Gore". digitalearth-isde.org. 1998-01-31. http://www.digitalearth-isde.org/userfiles/The_Digital_Earth_Understanding_our_planet_in_the_21st_Century.doc

[19]Goodchild, M.F., 2008. The use cases of digital earth. International Journal of Digital Earth, 1(1), pp.31-42.



(a) Pathetic Dot Theory of Regulation, Source: Lessig

(b) Modified PD theory - Law force, Source: Lessig

Figure 4.4: Lessig's Pathetic Dot Theory

In our work, we use the US census database for cartographic data and CBRS rules to examine the areas left precluded from service and assess the justifiability and appropriateness of the rules set up for census tracts using Area Loss Percentage (ALP)[20] and our novel metric, Population of Census Tract with Access to Spectrum (PCTAS). The computations on the non-convex polygons representing census tracts in the model required optimisation for area computation, and the optimisation task was conducted using a series of quadratic programming problems.

4.2.6 *Regulating with Pathetic Dot Theory*

Pathetic dot theory of Lawrence Lessig is a socio-economic theory of regulation, proposed in his 1998 paper The New Chicago School[21], as a rebuttal on the Chicago school of economic theory of regulation. It gives us a way to approach holistically to the modalities of regulation applied to the tiers of users in CBRS sharing model. We examine the balance of the forces acting on the players to learn more about the effectiveness of the modalities of regulation put in place for the CBRS model. The forces are four modalities of regulation: law, social norms, market and the architecture, as shown in Fig. 4.4.

> In the center is a regulated entity—the entity feeling or suffering the constraints being described. Each of the four ellipses represents one modality of constraint. The net is the sum of these different modalities. Change any one, and you change the constraint that it presents. Change any one, and you change its "regulation." More laws, less norms, different architecture, lower prices: Each changes the constraint on that regulated entity,

[20] In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz, GN Docket No. 12-354, Comments of Google Inc. on The Proposed Revised Framework , Dec 5, 2013.

[21] Lessig, L., 1998. The new Chicago school. The Journal of Legal Studies, 27(S2), pp.661-691.

> and changing each constraint changes the behavior of that entity being regulated.
>
> [...]
>
> Now obviously, these four modalities do not regulate to the same degree—in some contexts, the most significant constraint may be law (an appeals court); in others, it is plainly not (a squash court). Nor do they regulate in the same way—law and norms, for example, typically regulate after the fact, while the market or architecture regulates more directly. The modalities differ both among themselves and within any particular modality. But however they differ, we can view them from this common perspective—from a single view from which we might account for (1) the different constraints that regulate an individual and (2) the substitutions among these constraints that might be possible[22].

The old Chicago school promotes neo-classical microeconomic approach to regulation, based on free market principles and advocates for removing the state from the regulation: out with the law. The new school does not displace law, but advocates for state to do more. The law force in Lessig's theory not only regulates behavior directly, but also indirectly, through the other three forces.

The exploration of what kind of regulation is possible is about the balance of the forces[23] and different weighs they have on the "thing being regulated", the pathetic dot. The effects of any mix of the forces for achieving a regulatory objective is to be assessed, qualitatively and quantitatively. We will explain in the corresponding chapter how and why we apply this theory to the CBRS sharing model, detailing the very meaning of the forces and all the ways in which they can affect the dot in the CBRS model. The analysis is based on the *documentary* of the FCC regulatory process for CBRS.

4.2.7 *Writing (in) Dialogues*

The fact that the policy change is formulated as a goal, objective, as something neutral, and framed within the legal or scientific language puts all of the emphasis on its rationality. This hides the political nature of the policy by using the technical language, pointing to rationality and objectivity. The term 'political technology' was first used by Foucault[24] to explain this concept. To not have responsibility for the policy decision outcome, this masking of the political behind the neutrality principle creates a distance between a policy maker and those who will use the policy, stakeholders.

[22] Lessig, L., 1998. The new Chicago school. The Journal of Legal Studies, 27(S2), pp.661-691.

[23] Basham, M.J., Stader, D.L. and Bishop, H.N., 2009. How "pathetic" is your hiring process? An application of the Lessig "pathetic dot" model to educational hiring practices. Community College Journal of Research and Practice, 33(3-4), pp.363-385.

[24] Foucault, M., 1988. Technologies of the self. In Technologies of the self: A seminar with Michel Foucault (pp. 16-49).

Regulatory documents that govern the spectrum usage point to the notion of power games on spectrum. It is like a stage play in which the stakeholder can take part, to advocate for its own policy interest. This involvement can sometimes look like an emotionally impulsive story, where stakeholders have their expectations and hopes but there is a gap between them and the reality.

The estrangement is excluding the stakeholders from this emotional story to force them to reconsider the automatic use of language and review the concepts in question in a new way. When Shklovsky speaks of how "by 'enstranging' objects and complicating form, the device of art makes perception long and laborious"[25], he is giving us a recipe how to reset a view, how to see new details in old concepts. This may be a way to reconsider all the legacy components left in the spectrum world in the last 100 years. We are alienating our stakeholder the same way Brecht alienated his plays' audience[26]:

> "....when that which used to appear natural suddenly appears historical, when that which was thought of as timeless and eternal is seen as deliberately caused and altered across time. Its purpose is political because it aims to overturn the paralysing sense that things have always been 'this way' and therefore that there is nothing that can be done to change them."

Our tool of choice are Platonic/Socratic dialogues[27], as a scientific form of laying out the counter arguments[28].The dialogues feed of conflict and culture, and, according to Bakhtin[29], it is the differences in views that generate the estrangement we look for. To devise the dialogues we use the moments of conflicts and controversies, identified in the analysis of the regulatory documents that govern spectrum sharing as well as subtle references to pop culture to construct the characters. The characters of the radio-drama *Eight Bits of Frank and Laura* are: Franklin Charles Cambridge (the personification of the regulator, Federal Communications Commission), Laura Lustig (alter-

[25]Shklovsky, V., 1991. Theory of prose. Dalkey Archive Press.

[26]`http://www.oxfordreference.com/view/10.1093/oi/authority.20110803095758798`

[27]The form of dialogue has a tradition in scientific writing (from Galileo to Hofstadter), and serves to reflect the contradiction of ideas between the imaginary characters. In the following quote from Dialogue *Pacidius Philalethi*, written in 1676, Leibniz captures the point of using the dialogues in scientific writing.

> When I was with some distinguished men recently, I asserted that the Socratic method of discussion, as expressed in the Platonic dialogues, seemed to me outstanding. For not only are minds imbued with truth through familiar conversation, but one can even see the order of meditation itself, which proceeds from the known to the unknown, provided each person replies for himself when asked an appropriate question, with no one suggesting the right answers. When I had made this claim, they asked me to try to revive so very useful a thing by producing a specimen, which, by that very experiment, would show minds to be endowed with the seeds of all knowledge. I excused myself at length, confessing that this matter was more difficult than might be believed. For it is easy to write dialogues, just as it is easy to speak rashly and in no particular order; but to compose a speech in such a way that truth itself might gradually shine out of the darkness, and knowledge might grow spontaneously in the mind, this is really only possible for someone who has himself gone into the reasons very carefully on his own, before taking it on himself to teach others.

[28]Hofstadter, D.R., Gdel, Escher, Bach: An Eternal Golden Braid. Basic Books. 1979

[29]Bakhtin, M.M., 1981. The dialogic imagination: Four essays by mm bakhtin (m. holquist, ed.; c. emerson & m. holquist, trans.).

ego of the author, hat tip to Lawrence Lessig) and Anon Black (character inspired by Aaron Swartz). The character of the regulator is estranged from the rulemaking process in our dialogues and placed in different situations, but has the same mindset and vocabulary seen in historical policy analysis. While empowering this method of exposure through making strange and showing what is hidden in policy process, by using the moments and critical events throughout the chapters we devise the dialogues to get behind the scenes and understand the context of a policy decision. Policy-making must be understood as a political process as much as an analytical or problem solving one, and political processes scream *dialogue!*

4.3 CHAPTER SUMMARY

In this chapter we discussed the research design and the process. First stage of designing methodology was marked with constructing a conceptual framework, wide enough to encompass the problems to explore and granular enough to infer meaningful insights into the solutions. The NTBRS framework is presented in the previous chapter and repeated here with its general overview. Remainder of the chapter presents the compact set of interdisciplinary methods designed to serve for problem exploration to answer research questions. Methodology combines engineering and social science research methods with elements of philosophy in narration and exposition. The nature of the study necessarily includes understanding of theories of regulation and policy process. We introduced the case study of CBRS in the beginning of this chapter and we perform it in the next part of the thesis.

Part III

THE CBRS BEHIND THE SCENES

The King has Changed, Don't Change the King!

"But yes, I was backed by the law from that point onward.
You know how much I love law."

Audio version at: `https://www.youtube.com/watch?v=cOPJ59lI0Mw`

5 THE CBRS INITIAL CONDITIONS

In this chapter, we begin the case study of the CBRS sharing model. While Chapter 2 told the story of spectrum from (meta)physical, technological and academic point of view, the regulatory history is a universe of its own. The reader should keep in mind the events and the timeline of the ideas in Chapter 2, even if only to see how slow regulation is to catch up with the novelty in other universes. This chapter zooms into allocation and assignment approaches of the US spectrum management of the 20th century to bring together the context from the Chapter 2 and the deeply coded language in spectrum management to show what do we mean by legacy. The 21st century brought the paradigm shift and a policy change. This is shown by using two representative reports: the Aspen conference report from 2004[1] and the PCAST report from 2012[2]. To paint the picture of context fully, the chapter then explains what process of bringing a policy change is about and who will implement the change.

In Section 5.2, a historiographic analysis of the critical events that determined the approaches to spectrum in the US before 2012 is presented. In 2012, the PCAST report announced the critical shift in policy, calling for the new ways we approach to spectrum in regulations and we describe the main messages of PCAST in Section 5.3. What follows in Section 5.4 is a closer look at the organizational structure behind the CBRS rules for sharing, we explain who are the main players on the regulatory side and the stakeholders community that participated in the rulemaking process.

5.1 HISTORIOGRAPHIC ANALYSIS OF THE CBRS INITIAL CONDITIONS

The approach we take for the case study of CBRS rulemaking is inherently historiographic in nature. We go to the primary sources and assemble them in a mosaic to

[1] Firestone, C.M. and Entman, R.M., 2004. A Report from the Aspen Institute Roundtable on Spectrum Policy, *Challenging the Theology of Spectrum: Policy Reformation Ahead*.

[2] 2012, "Report to the President: Realizing the Full Potential of Government-held Spectrum to Spur Economic Growth" submitted by the President's Council of Advisors on Science and. Technology (PCAST)
`https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf`

reconstruct the course of the proceeding. However, starting with the historiographic approach only from the day the first CBRS document, the NPRM, was published leaves the whole analysis context-free: we need to know the roots of the FCC's ideas in the new 3.5GHz band. Backtracking on the primary sources leads us to the PCAST report and to the opinions of the leading scholars and professionals at the turn of the century assembled in the Aspen report. But what about the century of radio before that? It also deserves coverage to figure out the entire context.

This is a hundred years of non-sharing history of the radio spectrum, and this period has been extensively documented to date. Volumes have been written using primary sources, and we can stand on the shoulders of their authors to extract the thread of history we need. Why is it necessary, since we could point the reader to these volumes? What we offer to the reader with our own re-telling of the relevant parts of this century from Marconi to Aspen is *coherence*. The story has no dead ends and it takes us from the first attempt at regulation to the advent of the paradigm shift, with the technological triggers that have stimulated the changes. It is not less historiographic if it does not use primary resources: the story we tell is a reductionist take on the timeline US regulation[3].

This treatment of the past is necessary: we have repeatedly emphasised the importance of legacy in spectrum regulation, and we have to see the legacy's origins in order to study its effects. Historiographic approach and timeline storytelling is important for another reason: it reveals the motives, strategy and influence behind decisions and regulatory acts. This is why Chapter 6 will go into the history of CBRS rulemaking to determine the factors that resulted in the final rules, and why Chapter 8 goes to both past and the future to determine the effects of these rules.

We all exist within some form of government structure, and a system of regulation and rules, protections and processes. When it comes to resources, one of the roles of a society is to define and enforce the rights to use the resource and it is common for governments to fill this role. The use of spectrum resource in communications is defined and enforced by the government in majority of societies and it is built on the assumption that the government owns the spectrum resource. In the context of the chapters to come and their treatment of rulemaking, this chapter also introduces the rulemaking process and the US institutions involved in spectrum regulation to prepare

[3] This approach is echoed in Umberto Eco's quote below:

> Even the brightest young writer will find it difficult to work in a vacuum and establish an argument *ab initio*. He must find a foothold in past scholarship, especially for questions as vague as the notions of being and freedom. Even if someone is a genius, and especially if someone is a genius, he will never be diminished by starting from another author's work. Building on a previous author's work does not mean a student must fetishize, adore, or swear by that author, and in fact the student can demonstrate the author's errors and limits. Medieval writers saw themselves as "dwarves" compared to the "giant" ancients they revered, and yet they could see further than the ancients because they were "dwarves standing on the shoulders of giants."

(Eco, U., 2015. How to write a thesis. MIT Press (first edition in English, originally published in Italy in 1977.).)

the reader for what follows. Again, the historical context helps in understanding the role of various institutions and their organisation.

5.2 US SPECTRUM POLICY IN THE 20TH CENTURY

The initial idea behind spectrum allocation we can trace a hundred years back. In comparison to other resources, it is a short time, but the century was long enough for a vast amount of legacy issues to accumulate. We start the story from the moment when Titanic hit an iceberg. Marconi radios were used to call for help, but the ether was not occupied only by Marconi's devices. The nearby ship, the Californian, had attempted to warn the Titanic of the presence of an iceberg, but its signal was dismissed by the Titanic radio operator as Marconi company had proprietary closed standards on radios. The Californian radio operator went off duty and did not hear Titanic's distress call later. The signal was picked up by many different Marconi radio stations, across the coast. It turned into a massive miscommunication, with everyone overpowering each other. The ship that ultimately rescued more than 700 of the Titanic's passengers, the Carpathia, had difficulty maintaining communications with shore stations because of the interference from other vessels. Seven hundred lives were saved, because Marconi radios existed, but the tragedy that happened spurred the Congress to pass the **Radio Act of 1912**[4] which marks the beginning of radio regulations[5]. This story shows the initial idea behind spectrum allocation: the spectrum needs to be managed based on priorities, type of usage and planning in order to fight harmful interference and avoid tragedies.

The imperative of regulating out of fear from harmful interference led the regulator to *separate and classify transmissions*. This was done by dedicating bandwidths to: government, private, coastal and amateur use. There were not many users of spectrum at that time, so spectrum was not licensed through the defined assignment process. An exception of this rule were maritime and foreign communications services, which, in order to operate, needed to be licensed by the US government. Wireless radio was the only reliable means of long distance communications on the sea, therefore maritime communications had to be regulated more heavily as they represented the unknown. The question of US-based transmitters seemed to be solved by dedicating bandwidths, but the foreign communications as another unknown needed to be licensed also by the US government. The Secretary of Commerce and Labor would specify who could go on air, where and when[6]. The Radio Act of 1912 also introduced the notion of hierarchy in spectrum, specifying the levels of priority to access spectrum. Government users would get bandwidths they prefer and did not need to follow the restrictions imposed on non-government stations. This marks the beginning of a spectrum man-

[4]The Radio Act of 1912, Pub. L. No. 62-264, 37 Stat. 302 (1912).

[5]Hoolihan, D.D., Titanic, Marconi's "Wireless telegraphers" and the US radio act of 1912. IEEE Electromagnetic Compatibility Magazine, 5(1), pp.35-37.

[6]Minasian, J.R., 1969. The Political Economy of Broadcasting in the 1920's. The Journal of Law and Economics, 12(2), pp.391-403.

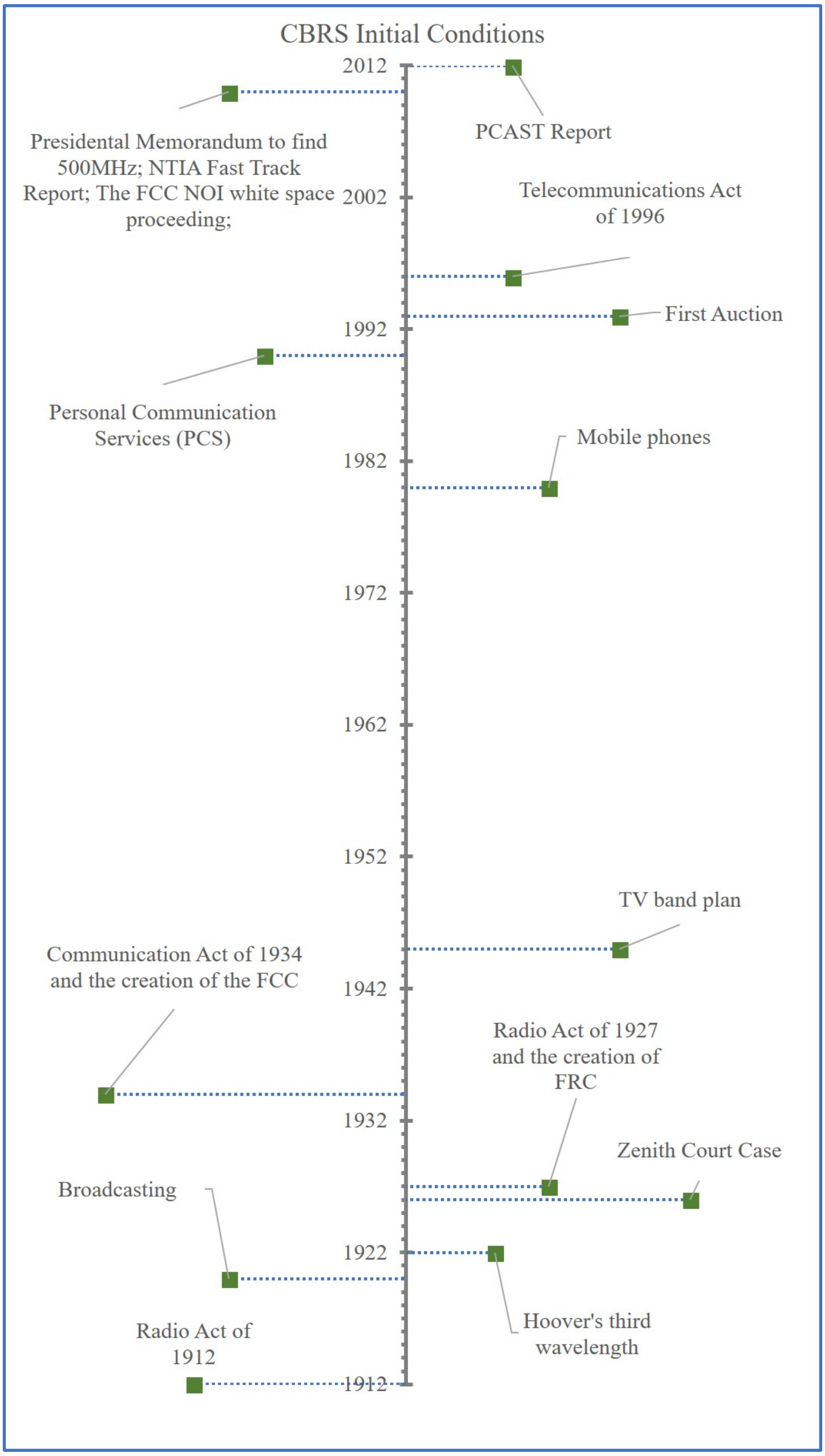


Figure 5.1: Timeline

agement approach that later became known as *command and control*. It was more than simply defining the rights and enforcing them if conflicts happen. It meant that the government specifies which services should operate where, which services should get priority over others and who would be licensed to operate[7].

In the early 1920s, technology enters the scene: it is when the exponential growth in commercial broadcasting starts happening. The broadcast, one-to-many mode of communication took over the dominant role in radio with hundreds of licensed stations emerging in a few years at the beginning of the decade. Such a boom was not bearable by the structures operating under the Radio Act of 1912 and the Secretary of Commerce stepped in to act. The future US President, engineer Herbert Hoover approached the problem by attempting to create a *band plan* to assign licenses. The broadcasters were given two wavelengths to operate on (in 1922 the third was added)[8]. The pace of technology and the broadcasters was not matched by this rationing and Hoover initiated a radio conference for the new band plan[9]. This is when bands started becoming divided: the 550-1350 kHz range was dissected into 10 kHz segments. Stations were assigned specific frequencies and they were carefully separated by frequency when they operated in the same geographic area to avoid interference.

Hoover's role in playing with spectrum was very controversial as it seemed to be a self-proclaimed one. The authority given to the Secretary of Commerce through the Radio Act of 1912 was dubious and while assigning licenses would be part of the job, assigning them by dictating certain stations to operate at certain frequencies in a certain time of the day and to transmit at a certain power level was not. Furthermore, creating the band plan was not a right given to the Secretary either. The subjective course of the license assignment process was not in the spirit of the Radio Act of 1912, as the Secretary Hoover would conclude that a band was occupied beyond capacity and deny stations the right to use those frequencies[10].

This course of events ended up in court in 1926, as the Department of Commerce sued a radio station, Zenith Radio Corporation, for jumping its frequency[11]. The Chicago-based radio station was assigned two hours of air time by Hoover, and their decision to choose their own frequency was backed by the court. Looking for another opinion, Hoover found one in the office of the Attorney General. It was again a negative one for the Secretary, as it conclusively determined he had no right by the Radio Act of 1912 to restrict the frequency, time or power of transmission for a station. Once

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[7]More specifically, it usually means that government specifies not only applications but all which technologies should be used (e.g. TV rules; contrast with cellular and unlicensed where service does not limit application or technology). Service priority and assignment (licensing) are orthogonal to command-and-control. Cf. Spectrum Policy Task Force definition, "allowable spectrum uses are limited based on regulatory judgments."

[8]Aitken, H.G., 1994. Allocating the spectrum: The origins of radio regulation. Technology and Culture, pp.686-716.

[9]Arbuckle, M.R., 2002. Herbert Hoover's national radio conferences and the origin of public interest content regulation of United States broadcasting: 1922--1925.

[10]Hazlett, T.W., 1990. The rationality of US regulation of the broadcast spectrum. The Journal of Law and Economics, 33(1), pp.133-175.

[11]United States vs. Zenith Radio Corporation, 1926. `https://www.leagle.com/decision/192662612f2d6141382`

this was recognised as the abuse of power, stations nationwide began jumping their wavelengths and "The result was confusion and chaos. With everybody on the air, nobody could be heard."[12] as the Supreme Court would put it in a later case.

The Congress recognised that the power Hoover abused had to be given to an authority in a legal manner to stop the chaos. With the new **Radio Act of 1927**[13], the lawmakers formalised the long and powerful arm of government's management and supervision over spectrum, legalising the prior unlawful acts of Secretary Hoover. The five-member Federal Radio Commission (FRC) was created with the task of frequency band allocation for particular services and assigning frequency, time and power level to a radio station. The list of key novelties the Act of 1927 brought started with the official introduction of command and control management regime. Furthermore, the act precluded private ownership, favouring three year licensing instead. Then it introduced a new regime for the government use, giving the President the authority to assign frequencies to governmental users of spectrum. The key premise of the 1927 Act was that the government while controlling uses of the radio spectrum, should ensure that licensee's were rendering appropriate service to the public. This is also where the notion of serving *public interest* by using spectrum started[14]. Under this band plan, the FRC returned the broadcasters to the status before the Attorney General's opinion.

The FRC merged with the regulators of telegraph and telephone to form the new regulatory body, the Federal Communications Commission (FCC). This was one of the effects of a new act: the **Communications Act of 1934**[15]. The Congress passed this converged act of control over multiple means of nationwide communications and put them under the single five-member body. The exception to the Commission's control was still the government use of the radio spectrum which remained under the control of the President. The President delegated this authority, first to the Office of Telecommunications policy and then to the Secretary of Commerce and the National Telecommunications and Information Administration (NTIA)[16]. Everything else considering spectrum was inherited from the Radio Act of 1927.

Now, the FCC era starts. The new one-to-many broadcasting medium was quick to emerge: the television and the FCC had to act on it. In the early 40s, the FCC licensed TV stations on an experimental basis before rolling out a detailed band plan for television in 1945[17]. They relocated FM radio stations to accommodate TV stations in their 12 new very high frequency (VHF) channels (Ch. 2-13). The TV stations were subject to same geographic separation as the radio stations before. Some broadcasters

[12]National Broadcasting Co. v. U.S., 319 U.S. 190 (1943)

[13]The Radio Act of 1927, Pub. L. No. 69-632, 44 Stat. 1162, 1166 (1927)

[14]One of the key Congressional architects of the 1927 Act, Senator Clarence Dill, put it this way: *Of one thing I'm absolutely certain. Uncle Sam should not only police this new beat, he should see to it that no one uses it, who has not promised to be good and well behaved.* In Clarence Dill, "A Traffic Cop for the Air," Review of Reviews, February 1927, pp. 183–184.

[15]Communications Act of 1934, Pub. L. No. 73-416, 48 Stat. 1064

[16]Mayher, R.J. and Wentland, F., 1990, August. Spectrum management structure and regulations in the US-do we need a change in the 21st century?. In Electromagnetic Compatibility, 1990. Symposium Record., 1990 IEEE International Symposium on (pp. 380-385). IEEE.

[17]Noll, R.G., Peck, M.J. and McGowan, J.J., 1973. Economic aspects of television regulation. Brookings Inst Pr.

insisted on using ultra high frequency (UHF) spectrum to support colour or high definition TV which required large chunks of this spectrum, but the FCC rejected that. This is how the regulator ignored the advancement of technology once again. The post-war increase in demands for TV caught the regulator off guard: allocation with the huge geographic separation between users was wasteful. These guard bands in the air remained vacant, while many stations were not able to get a license. Then, the need to expand the available spectrum for broadcast TV led the FCC to freeze the assignment for four years until they figured out the new TV band plan[18]. 70 UHF channels (Ch. 14-83) were added to the initial 12 VHF channels. It looked good on paper. However, the combination of VHF and UHF stations affected the markets and did not result in the expected increase in UHF TV channel programmes for the viewers. The VHF market has been well established and backed by the widely available TV sets, while the UHF newcomers had to struggle with both the question of the viewers' TV sets and the firm geographic restrictions. The TV sets capable of receiving both VHF and UHF signal were just entering the market. The multitude of broadcasters unable to use the spectrum efficiently, locked it up in the practical sense. The point is that the FCC decisions hindered the competition in the market. Technology does change fast, but the regulator has to have a broad vision and a way to anticipate major changes.

The sixties and the seventies saw the calls for a reform of FCC's spectrum approach, as we have seen in the discussion of Coase and post-Coase trends in Chapter 2. However, in practice not much happened. The early 1980s were another pivot point: the focus of the spectrum regulation was moving back to one-to-one communications with the advent of mobile phones. It happened in the midst of FCC's struggle to provide more spectrum for the broadcasters. The idea of the phone moving from the wire to air did not sit well with the FCC as they initially refused to allocate spectrum for it, discarding it as an experiment with little use. The FCC's defiance of support for mobile telephony spanned through more than two decades[19]. The early 1980s turned the tide with FCC's initial allocations. The resource pool they drew from was the UHF channel lot from Ch. 70 to 83[20].Like Hoover's three wavelengths for the nation, FCC's 14 channels were a tight belt for the emerging first generation of cellular telephony. The first FCC's idea of mobile telephony competition was assigning one license to the local incumbent telephone provider and one to the independent provider - the total of two licenses per local market area. Its failure asked for another approach: the one that will turn out to be a success story.

Before the decade-long fast forward to the new FCC's management approach, let us discuss for a moment the assignment methods as they are not separated from the allocation process. The early 1980s (1982 to be precise) saw a shift there as well, turning

[18] Brinson, S.L., 2000. Missed opportunities: FCC Commissioner Frieda Hennock and the UHF debacle. Journal of Broadcasting & Electronic Media, 44(2), pp.248-267.

[19] T. Hazlett "We Could Have Had Cellphones Four Decades Earlier", Reason, July 2017. `http://reason.com/archives/2017/06/11/we-could-have-had-cellphones-f/1`

[20] West, J., 2000. Institutional constraints in the initial deployment of cellular telephone service on three continents. In Information technology standards and standardization: A global perspective (pp. 198-221). IGI Global.

from merit-based hearings to lottery[21]. It does not take much to understand why a merit-based hearings approach to measure how well the spectrum user serves public interest does not work well with the introduction of completely new services. While it had a mechanism for the broadcasters, deciding on who is going to provide the best mobile phone service asked for a different approach. The broadcasting case had a dominant programme content component, but the mobile communications networks were all about the technology. It's easier to discuss a TV show than the SNR at a merit-based hearing, and there can be more differing opinions on the political and social topics than the measurable technical points. Taking into consideration the fact the new wireless technologies were starting to develop, the Congress replaced the merit-based hearings as assignment methods with *lotteries*. It was not free of controversies: (1) the number of applications was unimaginable for the FCC: it exceeded the capacity of their application storage facilities by far, (2) the lottery winners would get a windfall immediately after being awarded the license by selling it at a very high price[22].

As promised, we continue with the success story of the new mobile phone service termed Personal Communications Services (PCS), technically suitable to be located below 3 GHz. With the UHF TV broadcasting under 1 GHz, the FCC opted for the 1-3 GHz range to allocate PCS. That demanded a reallocation of fixed microwave operations to higher frequencies which vacated 220 MHz of spectrum for PCS in place of those services[23]. The reallocation was a lengthy process of transition. Unlike in Hoover's time, in 1990s the FCC had to open a public rulemaking proceeding, accept comments from stakeholders and reply to them in a final decision. As with all changes, there were eager adopters and fierce opponents: the incumbent users were reluctant to move. To appease them and start the transition process, the FCC offered 10 to 15 year grace periods in which they could continue operating in the old bands on a co-primary basis. Furthermore, they allowed negotiations between the players in the bands to enable a continuation of such use past the grace period. The FCC served as a catalyst and the communication medium between the incumbents and the new licensees and offered different means of transition of the bands: the new licensees could pay for the old spectrum holders to leave the bands faster or agree on continued coexistence, given that the old users solve all interference issues with the new ones[24].

Again, the allocation changes motivated by the mobile communications went hand in hand with a change in assignment. In 1993 the Congress authorised the FCC to assign some licenses via government-sponsored *auctions*. PCS license was the first candidate[25]. And then, after the initial success of the mobile phone spectrum auctions in

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[21]Sharp, S.A., 1983. Lotteries at the FCC: The Prelude to Experience. Administrative Law Review, pp.45-52.

[22]McMillan, J., 1994. Selling spectrum rights. Journal of Economic Perspectives, 8(3), pp.145-162.

[23]Carter, K.R., 2006. Policy Lessons from Personal Communications Services: Licensed vs. Unlicensed Spectrum Access. CommLaw Conspectus, 15, p.93.

[24]Barrett, A.C. and Marchant, B.F., 1993. Emerging Techologies and Personal Communications Services: Regulatory Issues. CommLaw Conspectus, 1, p.3.

[25]Cramton, P.C., 1995. Money out of thin air: The nationwide narrowband PCS auction. Journal of Economics & Management Strategy, 4(2), pp.267-343.

the mid-1990s bringing $7 billion of income[26], the Congress ordered the FCC in 1997 to go with the auctions for all spectrum use rights except digital television, the new phase of television to which the transition just started. The case of the digital television would not stay immune to the auctions either: after noting that the government may have allocated too much spectrum to existing broadcasters in the decade of transition, FCC turned to the idea of incentive auctions allowing broadcasters to participate in the revenue originating from reallocation and reassignment of their spectrum[27]. We will shed more light on this when the time comes, once our chronology reaches the revolutionary 2012. First came the slow, evolutionary 1996 with its **Telecommunications Act**, the first major revision of the 1934 Communications Act. This legislative, however, contained little about the Internet or the mobile wireless communications. While being the most recent top communications act, its update was long due[28].

5.2.1 *Reflections on the Twentieth Century*

This is where the new millennium found the US spectrum: divided between two regulatory bodies, managed by a highly fragmented and complex band plan dictated by the fear of interference and scarcity, with administratively burdensome regulation and lengthy and costly transitions in terms of allocations and assignments. The division of regulation between the FCC and NTIA exists since the Communications Act of 1934. NTIA regulates the government use of spectrum which comprises 60% of all spectrum, according to most of the regulatory documents[29], while the FCC is in charge of the commercial use regulation. We will see the regulatory organisational structure behind spectrum in one of the sections to come, and how complex the coordination between the different boards and offices is. The bigger problem in terms of efficiency of using the spectrum, which this section aims to make a point about is the fact that spectrum bands encumbered by government agencies are not being utilised[30].

The rationales of regulation are scarcity and interference, as we have seen in Chapter 2, are both controversial and subject to dispute over the years. In a 2002 speech the former FCC Chairman Powell revisits these fundamentals of the whole century of regulation:

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[26]Salmon, T.C., 2004. Spectrum auctions by the United States federal communications commission. Auctioning public assets: analysis and alternatives, pp.147-76.

[27]Gomez-Barquero, D. and Caldwell, M.W., 2015. Broadcast television spectrum incentive auctions in the US: Trends, challenges, and opportunities. IEEE Communications Magazine, 53(7), pp.50-56.

[28]R. Adler, Will the Telecommunications Act get a much-needed update as it turns 21? Recode, 08/02/2017. `https://www.recode.net/2017/2/8/14500978/telecommunications-act-1996-regulation-update-telecom-policy`

[29]Federal users have access to 57% below 3700 MHz, but most of it is shared with non-federal users. Using `http://data.fcc.gov/api/spectrum-view/services/advancedSearch/getSpectrumBands?frequencyFrom=255&frequencyTo=3700`, one can calculate the federal-only allocations comprise only 293 MHz of the 3465 MHz in the range 255–3700 MHz (8.4%), while mixed fed/non-fed is 1680 MHz (48%). Non-fed only is 1492 MHz (43%).

[30]We will discuss, at the appropriate time in our chronology, the studies done by the NTIA to examine the option for clearing or reallocating their bands, identified as majorly underutilised. At this point, we note these are the problems.

> ...[W]e are still living under a spectrum "management" regime that is 90 years old. It needs a hard look, and in my opinion, a new direction. Historically, I believe there have been four core assumptions underlying spectrum policy: (1) unregulated radio interference will lead to chaos; (2) spectrum is scarce; (3) government command and control of the scarce spectrum resource is the only way chaos can be avoided; and (4) the public interest centers on government choosing the highest and best use of the spectrum.
>
> Today's environment has strained these assumptions to the breaking point. Modern technology has fundamentally changed the nature and extent of spectrum use. So the real question is, how do we fundamentally alter our spectrum policy to adapt to this reality? The good news is that while the proliferation of technology strains the old paradigm, it is also technology that will ultimately free spectrum from its former shackles.

The ninety years Chairman Powell speaks of have resulted in a band plan whose complexity grew incrementally. The imposed constraints made proper allocation an art form. The world that was built is sliced like a Mondrian painting, and we don't just mean the allocation chart[31] in Figure 5.2. Examine the geographic distribution and see the same sharp borders and strict separation, like in Mondrian's art form of spatial illusion. Everything is already occupied, fully packed and scarce, says the illusion here. Each of these little boxes, where some are bigger than the others, is framed to represent one spectrum license for one spectrum use, for one application for one service to a one specific type of network or service provider. Looking for the ineffable balance which is not easily achieved, the regulator artists devised a way to separate these services so they don't interfere with each other. The nature of the services, however, converged in the digital age. Now it's mostly all bits: video, voice, data. And yet, the governing principles of the allocation chart have remained the same as in the pre-transistor era. The division and separation by services is a matter of command and control legacy.

Writing about the Acts, we noted few times that they regulated transmission powers (assigning frequency within a particular geographic area with limitations on power) and that is simply because they never thought of regulating receivers. This is one of the legacies from the old days, because the receivers were 'dumb' and always considered innocent victims of the interference created by the transmitters. Because the FCC does not regulate receivers, claims that a service will cause harmful interference sometimes arise not because the transmitter sends a signal outside of its designated band, but because the poor quality of a receiver allows it to pick up signals from frequencies other than the ones it's designed to receive.

We are not alone in these reflections: various stakeholders' panels at the turn of the century discussed the situation and gave their pointers for the years to come. To exemplify this, let us turn to the 2004 Aspen Conference on Telecommunications Policy report[32].

[31] `https://www.ntia.doc.gov/files/ntia/publications/2003-allochrt.pdf`

[32] Firestone, C.M. and Entman, R.M., 2004. A Report from the Aspen Institute Roundtable on Spectrum Policy, *Challenging the Theology of Spectrum: Policy Reformation Ahead*.

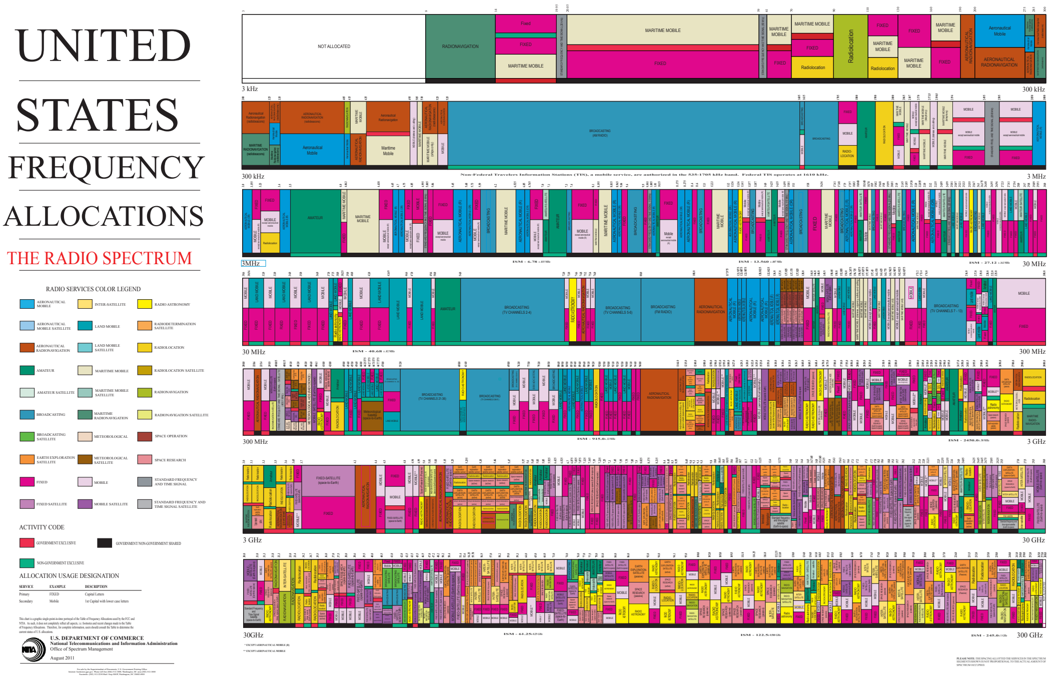

Figure 5.2: FCC Allocation Chart (Source: NTIA)

This conference was framed as a challenge to the theology of spectrum and in accordance with that theme they discussed 9 broadly stated *articles of faith* that were arguably challenged by new technological, market and policy developments. These beliefs were recognised as important concepts to be discussed by the policy scholars gathered at the conference - as important factors that shaped the policy. The starting point of the discussion is the fact that the frequencies can be shared rather than being licensed to exclusive rights holders and that ensuring interference-free environment by regulating the devices rather than regulating frequencies is a better approach. The conclusions of the discussion on all nine topics are listed in Table 5.1 but we proceed by grouping them according to the three topics they resonate with: physics and engineering, economy and governance of spectrum[33].

The physics and engineering of spectrum need a rewrite of the governing code of law (the FCC rules, the Telecommunications Act). The legacy of frequencies as the fundamental units of spectrum is a matter of precedence in time, not in physical importance. If the code division multiple access (CDMA) technology had been known before the frequency oscillators, we would think about spectrum in terms of codes, time, space - rather than frequencies. Using frequencies as the representation of the notion of spectrum led to observing it as an invisible piece of land or space, subject to physical rules added by analogy.

Among others, attendees included Yochai Benkler, Michael Calabrese, Thomas Hazlett, Eli Noam, Kevin Werbach, William Webb, several FCC and NTIA representatives as well the industry represented by Qualcomm, Cisco, Walt Disney, Intel, Verizon and several universities.

[33]This grouping we make again resonates with the first four aspects of NTBRS discussed on Chapter 2.

What do we mean by this, exactly? The spectrum, if it exists[34], is not limited by the worldly impossibility of two objects occupying the same space at the same time. The scarcity of it is a projection from the badly managed allocation chart and can be mitigated by digital technology. Devices subject to the advancement of technology have evolved to operate even in the presence of interference and to share frequencies without an effect on one another. Not all interference is harmful. Closely related to this question is the one of the receivers requiring regulation: putting all the burden on the regulation of transmitters is a counterproductive waste of resources.

The conference participants' views on the enterprise were not dealing with the economics of spectrum in the way we discussed it before. They made it more of a view on the attitude of government with respect to business models. The only relevant role of the government here is the one of a policy maker. They aimed to challenge the old assumption by which government protects businesses whose business models rely on the existing policy and gives up on progressive policy changes as they would endanger the old models and make them adapt. Another protected species, the public investment in their equipment (e.g. old TV sets) has to have their privileges reconsidered, the conference attendees concluded. The fear of reducing the value of users' investments by enforcing new standards and technology changes does not have to cripple the advancement of technology, as the imminent profit of the new, more efficient technological solutions could be shared with the population. The treatise on the relationship between the government and the businesses is one of many fears, and another one tackled was the fear of windfalls as the "political poison". They can be embraced as elements of a win-win situation, or even safely ignored, suggested the conference participants.

The last two points raised address the issue of government's inefficiency. First, the government governing the government's use of spectrum through a channel separate from the commercial side of the allocation chart is shown to be inefficient (the logical advice is to subject it to the same conditions the spectrum on the market is exposed to). And then there is also the red veto button at the every seat in the Congress and the Senate, threatening to block progressive motions, possibly under the influence of lobbying groups: the participants of the conference suggested the need for the presidential leadership on this. Spectrum was deemed vital for the national economy and too important to be left to the House floor.

5.3 THE PCAST PARADIGM SHIFT OF THE 21ST CENTURY

The official national statement on the future of spectrum came in less than a decade. Recognising the same vital potential for the national economy, the PCAST report set the goals for the future of spectrum in 2012[35].

[34] Recall the discussion in Chapter 2.

[35] `https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf`

Table 5.1: Aspen Report - Policy change initiative in 2004.

No.	Old assumption	New perspective
1.	Spectrum is measured strictly as "frequencies" that can only have one licensed occupant.	The essence of spectrum is not "frequencies.
2.	Spectrum is a scarce thing.	Digital technology may vanquish spectrum scarcity and even call into question the very notion of "spectrum" as a distinct entity.
3.	All interference is harmful interference.	Frequencies can be shared without harmful interference; interference can be reduced to acceptable, non-disruptive levels.
4.	Transmitter technology is more important— and more important to regulate—than receiver technology.	Receivers are more important, and setting standards and regulating receivers may be the proper emphasis.
5.	Any business model premised on a government policy has a preemptive right to veto any policy change that interferes with its original business model.	It is not the government's business to protect business models, even those premised on longstanding policy, when changing circumstances demand policy change.
6.	The public's investment in consumer premises equipment (CPE) needs to be protected, and any attempt to reduce the value of CPE may create massive political backlash.	Public fears can be handled readily by using a small fraction of the efficiency gains from policy change for subsidies.
7.	Grants to licensed incumbents are "windfalls," and windfalls are political poison and may be per se undesirable.	Fears of political backlash against windfalls to incumbents may be exaggerated
8.	Government use of spectrum must be considered separately and handled differently from private uses of spectrum.	Government uses of spectrum should become more subject to market-like efficiency standards
9.	Individual senators or House members with key committee positions have the right to veto rational telecommunications policy changes.	Powerful individual senators and House members should not be allowed to block change for idiosyncratic reasons merely because spectrum is a technical area that is off the media's and public's radar screens.

One of the points to take from PCAST report right away is that the way in which we continue to regulate spectrum on service-by-service and band-by-band basis is not a recipe for the future. The wireless revolution is an imperative, as the spectrum ecosystem in which businesses are built needs to satisfy the skyrocketing demand for wireless services (as the PCAST news statement described it[36]).

The PCAST report proposed how to revolutionise spectrum management. New spectrum management can transform scarcity into abundance, it can regulate receivers, it can be cloud-based and replace human-based spectrum management, it can adopt new spectrum management architecture, it calls for greater White House involvement in spectrum management through the formation of a new spectrum management team (SMT) to work with the NTIA and the FCC, advocates for the kind of spectrum management that will increase and maximize spectrum efficiency, changes the approach to allocation by removing the notion of precluding from the exclusivity, intends to make sharing a norm instead of an incident, bases the new spectrum management model on a continued stream of revenue instead of one-time auction returns. This sentence is big on purpose, as it reflects the abundance of progressive ideas for contemporary spectrum management.

If PCAST report provided anything, it provided a wider context to think about spectrum in a different way, to deal with the diagnosed issues with spectrum management and get ahead of the exponential curve of growing demand for spectrum. And yet, all of the literature on the current hot topic of spectrum sharing impeccably dissects it by reducing it to: the SAS and the three-tiers the SAS needs to deal with, i.e. categorised types of users. PCAST wanted us to think about spectrum differently - not simply as a tool we use for radios: spectrum is more than what it can do for our radio so there is more to it than a technology perspective only. The report wanted to get us out of the loop of technology-spectrum dependency and think about...Well, about the title of PCAST report: Realizing the Full Potential of Government-held Spectrum to Spur the Economic Growth.

The Internet is an example of a success story in terms of building an ecosystem, which would not happen if it was thought as being spectrum dependent. Think about new ecosystem dependent on spectrum, but with a focus on other elements that it is comprised of: you have an ecosystem when there is a relationship between its elements, when changes in one causes reaction in others. As discussed in Chapters 2 and 3, the matter of spectrum is an interplay of law, economics, technology, politics and policy. The elements of the spectrum ecosystem are: a wireless network, different types of markets that are born out of it, regulatory framework that prescribes the rules to use the spectrum, culture that comes with using it for communication, diverse effects on society of the connectedness and information sharing, ... That's much more than the SAS and the three-tiers of the SAS. As we will see in this section, PCAST offered the idea of mixing the spectrum rights in the band so that the market decides which model is better. No one ever says that the idea of PCAST is to have a protected

[36] `https://obamawhitehouse.archives.gov/blog/2012/07/20/making-most-wireless-spectrum`

tier competing with the unprotected tier. The definition of *better model* changes with PCAST as well: it used to be necessarily the one providing more revenue, but now it is innovation and potential first, revenue second.

The exposition on PCAST here has a multifold role. Firstly, it lays down the context for the chapters to come, focusing on what we argue is the most important landmark in the spectrum sharing timeline so far. Secondly, it documents PCAST faithfully by reproducing the recommendations, but gives our view of it and describes what PCAST means to us and to this thesis. It also aims at clearing up some misunderstandings coming from narrow interpretations of the report existing in the academic and technological discourse.

5.3.1 *The PCAST Concepts of Spectrum Regulation*

The tools for thinking about the PCAST messages are built on the concepts it proposed: (1) sharing becoming a norm, (2) spectrum superhighways, (3) three-tier model and spectrum access system, (4) hybrid licensing model, (5) spectrum currency, (6) receiver regulation, (7) new spectrum effectiveness metrics, (8) test cities and test services. We explain the concepts and PCAST recommendations using the phrasing and imagery of the report[37].

5.3.1.1 *Sharing as a Norm*

The *sharing as a norm* concept transforms spectrum scarcity into abundance, static preallocations and assignments into dynamic ones and exclusive use into shared use. What will enable spectrum sharing to become a norm, instead of an incident, is the concept of spectrum superhighways and the replacement of static allocation methods with the new dynamic sharing model through which the federal users have to share their spectrum with commercial users. This ambitious goal is achievable because of the technological innovations and the new sharing architecture governing the sharing. This system is called Spectrum Access System (SAS) and it will implement the fundamental principle that underutilised spectrum should be used or shared to the greatest possible extent. The reference architecture for new spectrum management approach is shown in Fig. 5.3. Federal spectrum should be divided into larger frequency blocks spanning over several hundred MHz instead of small, dedicated ones as it is at present.

5.3.1.2 *Spectrum Superhighways*

Spectrum superhighways are an equivalent of the road system in which federal and commercial vehicles share the same highways, with government users having priority over commercial uses for the cases of medical emergency or matters of national security and public safety. Spectrum highways are proposed to be large swaths of

[37] All of the diagrams in this section are taken from the PCAST report

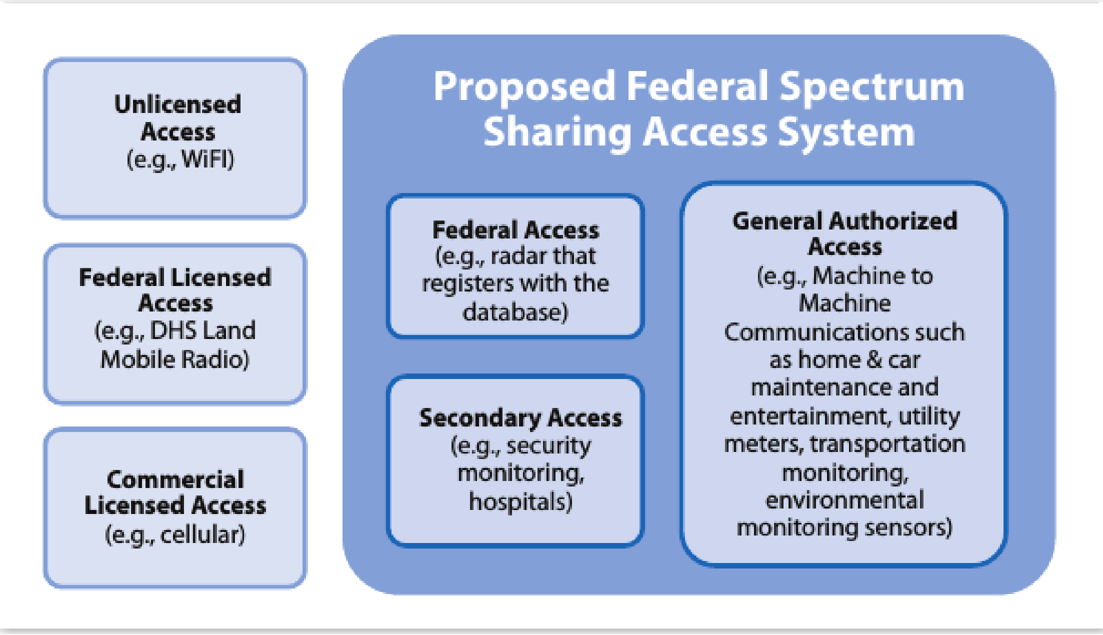

Figure 5.3: Reference architecture: Additional spectrum management proposals with the existing ones, Source: PCAST report

spectrum for lots of different types of wireless services to share, just as vehicles share a highway by moving from one lane to another. Signals, sensors and the wireless equivalents of stop lights would be used to enable coexistence without collisions. This concept assumes technology and service neutrality, to leave the assignment process to the technology which is why PCAST proposed to immediately form 1000 MHz of spectrum into one band in which all new models of communication can be designed to coexist. In wide bands everyone would need to cooperate and the framework would be globally applicable as a multi-band framework. Regulations traditionally zoned the spectrum into a collection of narrow roads, with the unlicensed spectrum zones showing somewhat different phenomenon of sharing a bit wider spectrum road. Highways of spectrum in which new sharing architecture is implemented were proposed to promote a principle of non-identical users sharing the resource while coexisting in the spectrum rather than being isolated. The new architecture will oversee the spectrum in real time, engineer the traffic and the users, preventing and controlling the potential collisions[38].

[38]The *Recommendation 1.1* is based on three findings: (1) spectrum is the driver of US technological and economic leadership, (2) clearing and reallocation of federal spectrum is costly, lengthy process but sharing this spectrum would give benefits for entire society, (3) fragmenting federal spectrum leads to artificial scarcity, inefficiency and constraints future spectrum use.

With the *Recommendation 1.1*, the PCAST calls for an urgent action of the President to declare the new policy approach of spectrum use is sharing the federal spectrum which is not being utilised. Considering the dual structure of spectrum governance in the US, PCAST calls for the NTIA to find that spectrum, 1000MHz of it, and the FCC to create large swaths of spectrum to accommodate diverse usage envisioned. It also asked for an end of the legacy way of spectrum allocation: fragmentation and allocation on a service- and band-basis. Superhighways are needed in which technologies can coexist and spectrum is not issued for specific uses anymore. A wider consequence of this recommendation leads to the paradigm shift called *sharing as a norm*: the approach in which sharing becomes a norm and not an incident. It also paves the way for implementing a different mode of usage which is *share it or lose it*, and this principle is enabled by the architecture and the licensing model that PCAST envisioned for sharing. Another

5.3.1.3 *Multi-tiered Access to Spectrum and the SAS*

The *three-tier model and Spectrum Access System (SAS)* is the crucial component of PCAST-envisioned sharing, concept depicted in Fig. 5.3. Users were envisioned to access spectrum and be protected from interference in a three-tier hierarchy manner. Federal users that now encumber the bands get the highest priority in access and priority to not be interfered from bottom tier users. This model does not exclude their expansion in the band and they do not have to vacate the band. Second tier users get to be assigned with spectrum rights through a licensing scheme which gives them some guarantee of QoS. Possibly in exchange for fees, the second tier users protect the incumbents from interference and can cause interference to the tier below them. This tier needs to register to the SAS database to get assigned and access spectrum. The General Authorised Access tier is the newcomer in the spectrum and operates similarly to unlicensed WiFi services. The users in this tier cannot cause interference to upper tiers and do not receive any protection from interference from them. They need to register with the SAS database to access spectrum opportunistically, whenever it is free, coordinated by the SAS. This means that SAS would take over the regulatory role and serve as a frequency coordinator and manager in the spectrum superhighways. SAS will provide interference protection to federal systems and other users according

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consequence and another meaning of this recommendation is that sharing frameworks should be multi-band and global, as explained earlier.

Recommendation 5.1: PCAST recommends that the White House Chief Technology Officer (CTO) with senior officials at an equivalent level from the National Security Staff (NSS), the Office of Management and Budget (OMB), and the National Economic Council (NEC) formalize a Spectrum Management Team (SMT) to work with the National Telecommunications and Information Administration (NTIA), the Federal Communications Commission (FCC), and the major Federal agencies that use spectrum to carry out the President's directive.

Recommendation 5.2: PCAST recommends that the NTIA, working with the SMT and Federal agencies, reexamine the partitioning of Federal spectrum usage in light of current and emerging technology.

With the *Recommendation 5.2* PCAST recommended NTIA to re-examine the quantitative assessment of spectrum usage, and recommended presidential memorandum to direct NTIA to create a framework to assess spectrum actual usage - as to free up spectrum, it first needs to be identified. The NTIA is starting with the bands already identified as more amenable to commercial use, they are analysing temporal and geographic components and taking a closer look into the bands to see what kind of commercial use can be available. This is what NTIA would normally do, but now they are required to add more information on how they are using the band and do a pilot program for the actual monitoring in the field to measure spectrum usage. Idea of having agencies report individually is complementary to having real world pilot programme listening and monitoring.

Recommendation 5.2: PCAST recommends that the NTIA, working with the SMT and Federal agencies, reexamine the partitioning of Federal spectrum usage in light of current and emerging technology.

Recommendation 5.6: PCAST recommends that the President appoint an advisory committee of industry executives (e.g. CEOs), to be known as the Spectrum Sharing Partnership Steering Committee (SSP), to advise the SMT on a policy framework to maximize commercial success, centered on a public private partnership for sharing Federally-held spectrum, and implementation milestones that lay the groundwork for the first spectrum superhighways.

Recommendation 5.7: The United States, represented by the Department of State with advice from NTIA and the FCC, should make international harmonization of spectrum allocations to wireless broadband, particularly in bands used or planned to be used for mobile broadband applications in the United States, a key element of the U.S. position at the 2015 World Radiocommunication Conference (WRC-15) and in bilateral and regional discussions with its own neighbors, Mexico and Canada.

The seven recommendations within recommendation 5 are based on three findings: (1) there is no incentive system for federal government agencies to use spectrum efficiently, (2) a public private partnership (PPP) is the best mechanism to ensure the optimal use, (3) international harmonisation of spectrum is essential to product innovation, interoperability and roaming, spectrum efficiency and cross-border frequency coordination.

to the hierarchical priorities and for the spectrum not currently in use by Federal systems. With the new sharing architecture, more granular sharing is possible. Such approach should become a norm, and replace the exclusivity of use which leaves spectrum to lie fallow.

This sharing should rely on cognitive radio, sensing, signal beacons and geolocation databases on the technological side, and the band-by-band access rules given by the regulator. Of course, the very existence of these rules is enabled by these technologies working in real time and detecting available spectrum.

In such a model, Fig. 5.4, the Legacy Federal users have the Federal Primary Access, the one of highest priority, followed by Secondary Access given to users registered in the database and by General Authorized Access. The high power transmission and high quality of service of Secondary Access may or may not be paid for by the users (depending on the public policy), and the low power transmission of the General Authorized Access would not be charged (and the participation can be either through individual sensing of open spectrum or registration in the database, again depending on the policy). The database we keep on referring to is the essence of SAS, and it contains information about spatio-temporal occupancy of spectrum; transmission parameters; geographic constraints; spectrum access price. While improving spectrum efficiency, The Radio Access Coordination and Management and Optimization function provides frequency assignments and authorizations and ensure the priority of Federal Primary Access[39].

5.3.1.4 *Hybrid Licensing Model*

The idea of a *hybrid licensing model* is grounded in the emerging economies of new applications and services. PCAST built this proposal through arguing that the crucial element of a new spectrum policy is its ability to create a vibrant marketplace in which there is room for any type of user. The spectrum ecosystem so far has offered room only for exclusive use with long-term, automatically renewable licenses which are also nationwide or for shared unlicensed use with no protection against interference. As examples of novel spectrum use, PCAST names some of medical applications for monitoring patients as they move or M2M communications which decade ago were thought of as science fiction. To motivate the innovation in new uses, PCAST proposed

[39]*Recommendation 2.1: The Secretary of Commerce, in collaboration with the Federal Communications Commission (FCC), should establish a mechanism to provide the Federal Government with the ability to manage the sharing of Federal spectrum.*

This recommendation is based on the finding that large spectrum blocks should be shared, new effectiveness metrics are needed and coordinated prioritized federal and commercial use by sharing federal spectrum is a new approach to policy, a policy shift.

Recommendation 2.2: The Secretary of Commerce, working through the National Telecommunications and Information Administration (NTIA) and the FCC, should authorize and implement, directly or through commercial providers, a Federal Spectrum Access System (SAS) to serve as an information and control clearinghouse for the band-by-band registrations and conditions of use that will apply to all users with access to each shared Federal band under its jurisdiction.

This recommendation is based on the finding that the way technology has evolved in wireless architectures gives an opportunity to use spectrum more locally through sharing with Federal users, which would not be possible with high power LTE operations.

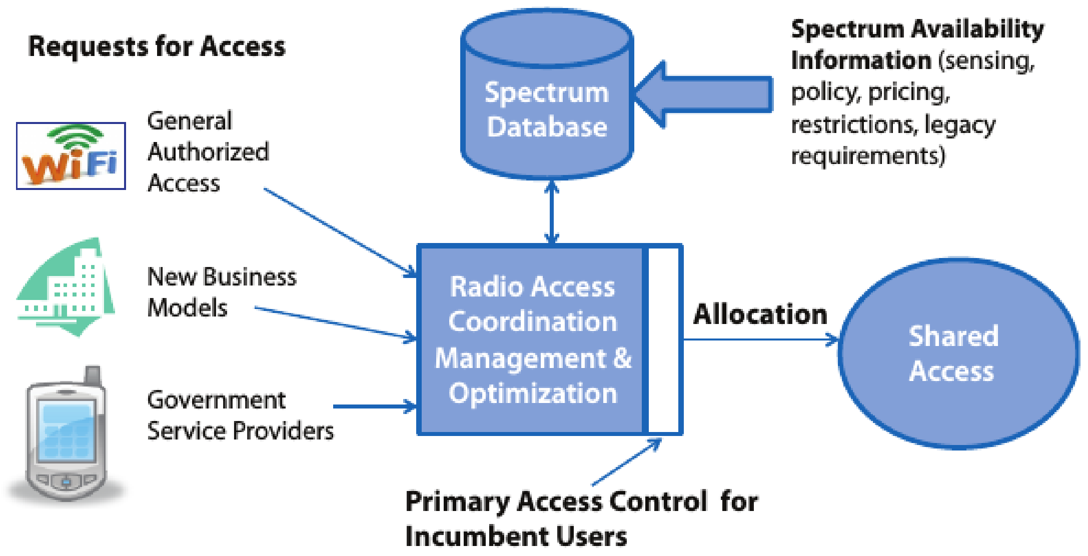

Figure 5.4: Functional architecture: New spectrum management approach, Source: PCAST report

the combination of a long-term licensing for 10-15 years, medium-term licensing for 3 years or less and short-term licensing potentially for few days, hours, minutes. The new short-term licenses were envisioned to be managed solely through protocols and via equipment certification process, without any transaction costs. These market-based assignments were foreseen to generate more revenue in the long term, unlike instantaneous, one time revenues from the auctions in which only few can compete[40].

One of the main goals of the report is contained within its title - to spur the economic growth. They aimed to answer the question in the task given to them: How can new sharing techniques unlock the value of government spectrum for commercial use while keeping missions safe and are current federal efforts in policy optimized to realize this potential?

The economic aspect of spectrum is in the method of assignment, i.e. licensing, where the license describes the right to use the spectrum. It is the ownership model of spectrum, where having the right to access spectrum is like having a property right. Two ownership models exist so far, and they are extreme cases: you can be exclusively licensed to use spectrum over long period of time and also able to renew it, or you

[40] *Recommendation 4.1: PCAST recommends that policies enabling commercial access to Federal spectrum be based primarily on their effects on innovation and growth in wireless devices, services, and associated markets; direct revenue considerations should be treated as secondary.*

This recommendation is based on the following findings: (1) dynamic sharing would unlock economic benefits and open up new use cases and new business models, which cannot be imagined now, (2) revenues will be generated from having a new shorter term licenses model appropriate for new and innovative spectrum-based services and products.

Recommendation 7.1: PCAST recommends that the Federal Communications Commission (FCC), working with the National Telecommunications and Information Administration (NTIA) and the Federal agencies, immediately start the process to modify its rules to allow "general authorized access" devices to operate in two bands in the NTIA Fast track list, specifically the 3550-3650 MHz (radar) band and another to be determined by the NTIA and FCC.

This recommendation is based on the finding that GAA users could immediately be accommodated in the band because of how white space systems evolved (recall the technology section from Chapter 2).

can get instantaneous access to spectrum by being unlicensed, through opportunistic use like in 2.4GHz and 5GHz bands, described in Part 15 rules for WiFi services. The first model is reflected in a wireless market which has few service providers dominating the rest, making infrastructure investments, deploying networks nationwide and collecting revenue from served customers. The second model is a success story[41] that spurred innovation, growth and competition, benefiting from the Internet companies ecosystem, where the US is dominating.

What PCAST proposes is a hybrid model, having both of these models in the band but also adding a middle layer: medium-term licensing model, where licenses are for 3 years or less, non renewable. A user might lease the right to use, at a given power level for 1 year frequencies that Department of Defense is using. Leasing fees could be set by auction. When the lease expires, there would be no automatic renewal according to the proposal, but users could compete for renewal by bidding against other potential users. This would foster experimentation, in a sense that providers could experiment with networks and business models, while they can still extend the lease for longer periods. It was suggested it would encourage market-based competition among commercial users, as these leases would come up for rebidding. These medium term leases would also be incentive for government users: if their mission critical needs change in the future, they can buy some licenses. It was envisaged that these licenses would be cheaper than longer term licenses.

At the same time, the users can migrate from the middle layer to the unlicensed one. As PCAST explains it, this is a form of automatic congestion pricing, where device can choose to pay a fee for higher priority access only when necesary. This principle assumes the same equipment is operable in both modes. The state gets an opportunity to collect a recurring and growing stream of revenues that would grow larger within a few years. Revenues sources are leases and as an alternative one-time equipment certification fee on new mobile devices, small enough to not impact demand. We can compare it to single-layer models. With a licensed model, through an auction one-time payments to FCC would increase value of spectrum resource. With the unlicensed model, we have seen the impact on value of spectrum and the revenue it created for US economic growth through the success of Wi-Fi[42]. For this new model revenue would be created not through one-time large payments but instead of this system that magnifies spectrum scarcity and maximises revenue from that scarcity, this new model would create an abundance of spectrum access opportunities and maximise the overall value associated with that abundance. Shorter licenses are better than longer term licenses because they expire sooner and are back in the market, turned over more quickly, which motivates a cycle of faster overall industry competition and resulting innovation. The effectiveness of these new solutions, the same as with larger scale

[41] Cooper, M., 2005, November. The economics of collaborative production in the spectrum commons. In New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on (pp. 379-400). IEEE.

[42] Lehr, W., 2004, April. Economic case for dedicated unlicensed spectrum below 3GHz. In New America Foundation Conference.

exclusive license spectrum markets, will depend on transaction costs, administrative and regulatory constraints and the limitations of the sharing rules that are involved.

5.3.1.5 *Spectrum Currency and an Incentive System*

Spectrum currency is an innovative idea to incentivise federal users to share their spectrum. It was devised to work as artificial currency based on a credit system, which would reward the early adopters among federal users, those who embrace sharing. Those credits such users would be able to turn in real dollars over time. Currently, federal users get the spectrum assignments which guarantee the access and first level priority to protection for a long time, almost forever. They do not have the incentive to use their spectrum more efficiently because it is always going to be there. They also do not have an incentive to replace the old systems and technologies they use. The spectrum currency fund is a way of accounting for all those factors, allocating spectrum with incentives in mind and potential for these users to collect fees over time[43]. This concept is illustrated in Fig. 5.5.

5.3.1.6 *Regulation of Receivers*

Interference protection has always been regulated through transmitters. Interference is a reciprocal harm, but power level limits have always been put on a transmitter as if the inability of a receiver to pick up the signal does not affect the quality of communication. What is proposed is to also *regulate the receivers* and come up with a modified approach to interference protection and design new receiver management framework, as shown in Fig. 5.6. PCAST argued that having clearly defined "receiver interference limits" would help achieve more efficient trade-offs between the rights

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[43]*Recommendation 5.3: PCAST recommends that the President indicate that all Federal agencies should cooperate with the SMT and NTIA to establish and implement a government-wide process and mechanism to share Federally-held spectrum.*

Recommendation 5.4: PCAST recommends that OMB, working with the SMT and NTIA, take steps to implement a mechanism that will give Federal agencies incentives to share spectrum.

With the *Recommendation 5.4* PCAST recognises that there is an issue of federal agency incentives, lack of them. The current approach is to have agencies estimate their relocation costs in anticipation of the auction and then the FCC sets the reserve price. It has to be at least 110% of the estimated cost and we have a successful auction if that number is hit or exceeded and then the funds can be used to compensate the agencies. For the agencies it's kind of a status quo, as it sets them back where they started, which is not exactly a strong incentive.

Recommendation 5.5: PCAST recommends that OMB should implement a sustainable funding mechanism to foster a Federal spectrum sharing system.

With the *Recommendation 5.5* PCAST came up with a new approach on the funding mechanism to deal with the incentives problem: spectrum currency. The idea is essentially that you create a new kind of currency. As agencies prepare to relinquish spectrum, they get credits for this currency and over time those credits build up and then they can use those collected credits to turn them into real dollars to do real acquisitions. It needs to be separated from the standard budget process otherwise you are running a risk of agencies getting credit only to have it taken away when they go back to the budget cycle. When looking at the ways to provide incentives for agencies, broadcast incentive auction idea could be applied: agencies would be entitled to share percentage of auction revenues, but interestingly money would not necessarily go to relocation cause or spectrum cause at all, money could go to anything subject of a successor cut with much flexibility to the agencies and still being authorised by the Congress. The issue of incentives for federal agencies and their usage of spectrum is hence a subject of the bills that then are passed in Congress. Politics decide basically.

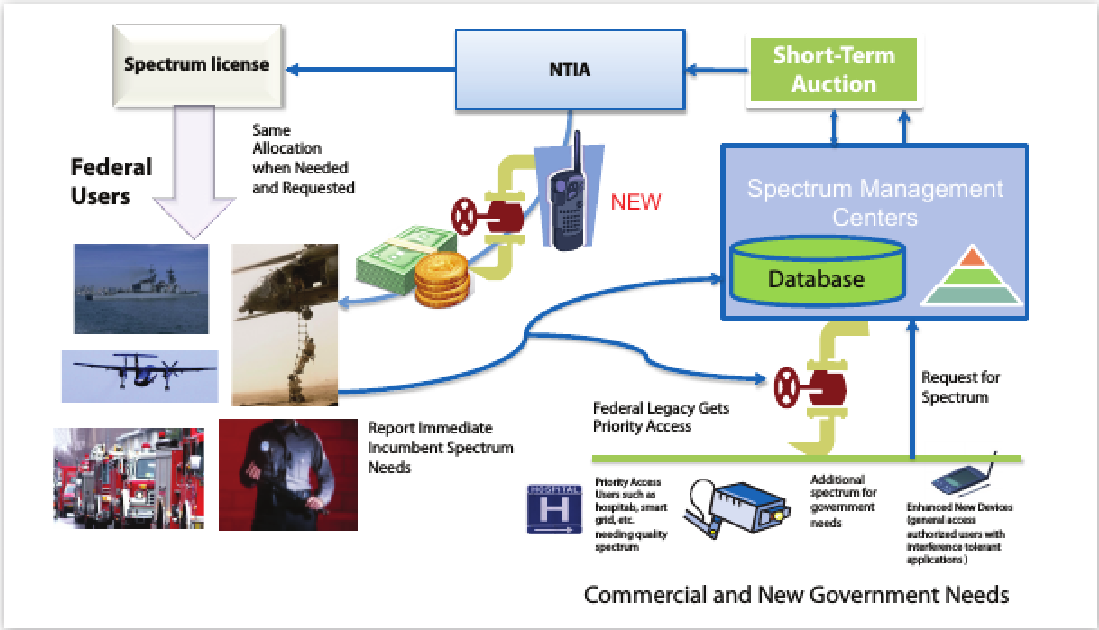

Figure 5.5: Incentive System, Source: PCAST report

of transmitters and receivers, with the goal of maximizing concurrent operations as opposed to minimizing harmful interference[44].

In the early days of radio, allocations were done for one service in one geographic area, as explained in previous section. Those were the days of large tower transmitters and poor receivers picking up their signals. Today's equipment evolved, but the regulation, as we have seen on multiple occasions throughout this thesis, fails to keep up. Picking up and mixing signals from their own and adjacent bands, as well as other consequences of improper receiver design, prevent us from putting spectrum to optimal use and produce its waste rapidly. This corresponds directly to what we have seen in the Aspen report: PCAST made an attempt to convert some of the Aspen ideas into usable concepts and practical solutions.

5.3.1.7 *New Metrics*

There is a need for new *spectrum effectiveness metrics* with the new sharing architectures that enable shared licensed and unlicensed use, because it will change the way the value of spectrum is assessed. Spectrum efficiency metrics account for a data capacity and coverage, but the metric should measure not only capacity and coverage needed for a user in communication, but also should measure an extent to which that user precludes others from using the resource. In other words, metric should measure spectrum effectiveness not only efficiency and should balance between the quality of

[44] *Recommendation 3.1: The Secretary of Commerce working through the National Telecommunications and Information Administration (NTIA), in cooperation with the Federal Communications Commission (FCC), should establish methodologies for spectrum management that consider both transmitter and receiver characteristics to enable flexible sharing of spectrum.*

This recommendation is based on the finding that spectrum management and regulation is always focused on transmitter regulation, and the receiver characteristics are the ones that constrain flexible and effective spectrum usage.

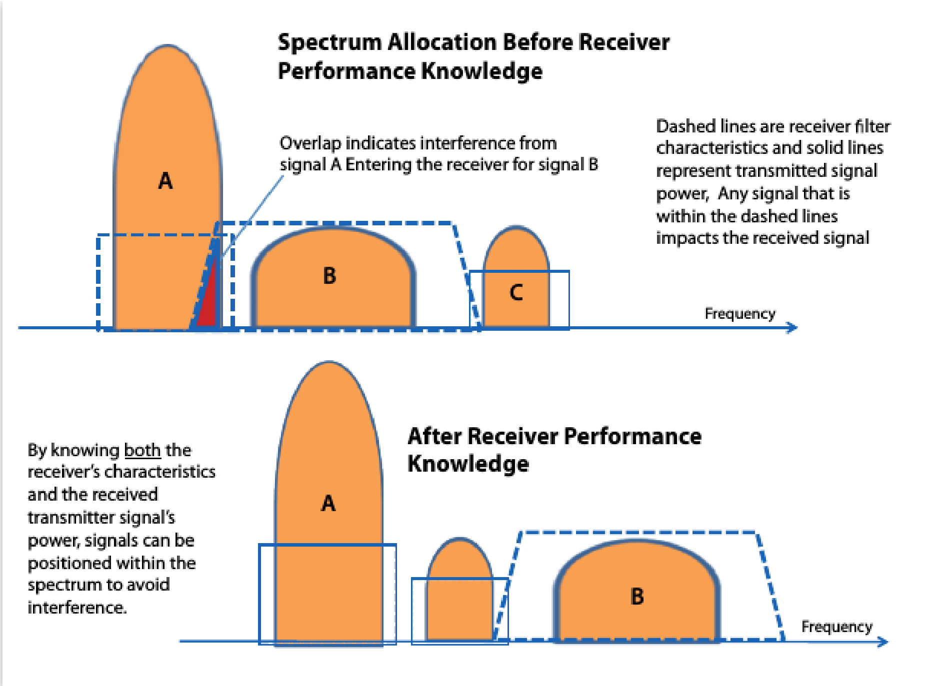

Figure 5.6: Knowing receiver characteristics in spectrum management, Source: PCAST report

a spectrum use and its opportunity cost. That metric can quantitatively compare architectures and protocols used for a given block of spectrum and how that spectrum block is suitable for that architecture. While the metric should be technology-agnostic, it should favour constructive behaviors and efficient modulation schemes[45].

5.3.1.8 *Test Cities and Experimentation*

To try out all of these concepts, PCAST proposed to have a *Test City*. In such urban test sites, Mobile Test Service allows efficient and quick tests, trials and experiments of both components we mentioned earlier: the technology and the regulation and management. PCAST assessed the test city concept to be essential for the Super Highways and for putting public safety spectrum services up for sharing with other users[46].

[45] *Recommendation 2.1: The Secretary of Commerce, in collaboration with the Federal Communications Commission (FCC), should establish a mechanism to provide the Federal Government with the ability to manage the sharing of Federal spectrum.*

This recommendation is based on the finding that large spectrum blocks should be shared, new effectiveness metrics are needed and coordinated prioritized federal and commercial use by sharing federal spectrum is a new approach to policy, a policy shift.

Details are given in the Appendix B of PCAST, with the discussion of potential "effectiveness metrics that take into account capacity, communication range, interference range, time and spectrum precluded to other users" (The metric and discussion presented in this Appendix are adapted from P. F. Marshall, "Scaling, Density, and Decision-Making in Cognitive Wireless Networks." Cambridge University Press (August 2012)).

[46] *Recommendation 6.1: PCAST recommends that the Secretary of Commerce, working through the National Telecommunications and Information Administration (NTIA) and the National Institute of Standards and Technology (NIST), provide test services (a Test City and a related Mobile Test Service) to support the development of the policies, underlying technologies, and system capabilities required to support dynamic spectrum sharing.*

This recommendation is based on the finding that there is no opportunities to test new architectures, policies and new systems proposed in this report.

Formally, PCAST expressed the views on spectrum in the form of recommendations, and we now briefly outline them and interpret in more details.

5.3.2 *Looking at the Recommendations from this thesis perspective*

What is of interest to this research is how the PCAST recommendations were acted on. The 3.5 GHz band was selected as a band in which to implement the PCAST ideas. The specific framework devised is termed CBRS, Citizens Broadband Radio Service. Hence CBRS is a natural case study and a test for PCAST ideas in practice.

In our point of view, the key takeaway from PCAST recommendations is that not every market entrant can compete in costly auctions. What the success of unlicensed use shows is the hunger for free cost entrance in the band with additional possibilities of leasing and renting in the spirit of emerging economies. Having the exclusive property right to a resource is becoming outdated way to generate profit, since sharing economies show that profit can be generated based on having the rights to access to a resource and not necessarily the ownership rights.

The type of questions that are of interest stem from the nature of the rulemaking process. The process of rulemaking, as we will see, is not one of imposing but one of discussion and lobbying. How did it affect CBRS and how close is CBRS to the principles of PCAST it started from? Is the divergence of PCAST and CBRS for the better or the worse? These are the aspects from which we observe PCAST, and in order to do so, we need to delve into the rulemaking process.

5.4 FROM RECOMMENDATIONS TO RULEMAKINGS

In the context of our case study, the PCAST has shown the motivation for the establishment of the new 3.5GHz band, so we can start the story of the CBRS right away from that perspective. However, the CBRS rulemaking story would be extremely hard to follow without understanding the organisational architecture behind rulemaking and management and the procedures that are performed by the units within this organisation.

In this section, we bring the US regulatory establishment to the reader, in order to: (1) understand the structure that governs the spectrum in 3.5GHz band, (2) get an insight in what kind of legal process is behind policy making decisions and (3) trace how we got from PCAST recommendations to the final rules. We introduce stakeholders community for the 3.5GHz sharing, an *epistemic community*[47]of the policy process, whose involvement in the rulemaking is documented through hundreds of comments and replies to comments submitted to the FCC 3.5GHz proceeding database. To track and analyse the evolution of the rules and to document their development through the

[47]`https://en.wikipedia.org/wiki/Epistemic_community` The definitive conceptual framework of an epistemic community is widely accepted as that of Peter M. Haas. He describes them as

"...a network of professionals with recognised expertise and competence in a particular domain and an authoritative claim to policy relevant knowledge within that domain or issue-area."

voices that contributed to the dialogue on sharing in the next chapter, we identify all of these events as milestones and note their importance in terms of regulatory actions they caused in the remainder of this chapter.

5.4.1 *Organizational Structure behind CBRS*

What follows is the description of the organisation governing the spectrum in the United States. Since our focus is on the particular case of the CBRS, this section should be read as the one providing the organisational details for CBRS, and not an attempt to cover all aspects of the national management apparatus.

Recall that the regulation of spectrum in the US is divided between two organizations: (1) the FCC[48], established by the United States Congress through the Communication Act of 1934, and (2) the National Telecommunications and Information Administration (NTIA)[49]. The NTIA governs *federal use* of spectrum (national defense, law enforcement, online security etc.). The FCC governs *non-federal use* (commercial, private, state local governments, public safety and media: TV and radio).

Fig. 5.7 illustrates the interaction between many organizations within the two bodies which are in charge of spectrum. The coordination of spectrum issues between the two and amongst various other agencies happens through a group called Interdependent Radio Advisory Committee (IRAC)[50], chaired by the NTIA. Besides acting as federal spectrum manager, NTIA also reports back to and serves as an advisor to the President. The FCC is an independent agency, something like a branch of Congress but independent. The sources of the regulations are: (1) several volumes of the book called Code of Federal Regulations[51] which contains the rules of the FCC[52] and (2) the Redbook[53] where NTIA publishes its policies. Regulatory actions are also taken based on stipulations of the US Code, i.e. legislation passed by Congress[54].

Spectrum is managed by multiple regulatory agencies within this structure, so regulating the shared spectrum in the U.S. is quite complex [55]. Other areas of government also have impact on spectrum: The State Department, the Congress, the Office of Management Budget (OMB), the Office of Technology, Science and Policy (OTSP) and other agencies that have relationship with the FCC. It is a much bigger regulatory establishment that one would imagine, but these are the main players.

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[48] https://www.fcc.gov/what-we-do

[49] http://www.ntia.doc.gov/book-page/who-regulates-spectrum

[50] Serving on IRAC are 19 federal agencies (three from DoD) and the FCC

[51] https://www.law.cornell.edu/cfr/text

[52] https://www.fcc.gov/general/rules-regulations-title-47

[53] Mannual of Regulations and Procedures for Federal Frequency Management

[54] https://www.law.cornell.edu/uscode/text/47/11

[55] On top of this structure, we can imagine the International Telecommunications union (ITU), a treaty organisation which grew out of the UN. Within ITU, the ITU-R is the radio communication sector that handles spectrum issues.

Other countries also have split responsibility for government and non-government spectrum, and sometimes for different kinds of services e.g. broadcast often has its own ministry. (Cf. Musey, J. Armand, The Spectrum Handbook 2013, https://ssrn.com/abstract=2286901)

The key organization in the NTIA is their Office of Spectrum Management (OSM), which is advised by the Interdepartment Radio Advisory Committee (IRAC). There is another organization, Commerce Spectrum Management Advisory Committee (CS-MAC) which is an outside group of spectrum experts that advise the Assistant Secretary on spectrum management issues. Key bureaus and offices within the FCC which handle spectrum issues are Wireless Telecommunications Bureau (in charge for commercial wireless service), The Office of Strategic Planning and Policy Analysis (OSPA) (involved in policy and economic analysis[56]) and the Office of Engineering and Technology (OET) (spectrum allocations, unlicensed operations and equipment certification issues)[57].

Final decisions are made by the Chairman and the Commissioners[58], appointed by the President and confirmed by Senate, for a five-year term. In US spectrum policy, the most important player is the FCC Chairman. Only she sets and manages FCC policy agenda. Other bureaus and offices technically work for all five of the Commissioners, but in reality they answer to the Chairman. She has very important power of deciding which items will be put for a full FCC vote, i.e. if she is not ready to examine and decide upon an item, it does not come up. Remaining FCC Commissioners are important because the Chairman needs their vote to get anything done on the agenda and also over the years some Commisioners have been more influential in spectrum matters than others. It is a political game of spectrum in which operating bureaus have an important influence on spectrum policy but also the legal advisors [59].

In the past few years, the concept of sharing through static allocations has been challenged - so new regulations are being looked at for federal and non-federal use to utilise more dynamic sharing, improving spectrum efficiency to free spectrum for new applications. The Communications Act of 1934 did not exclusively differentiate allocation for federal or non-federal use, so in practice, all spectrum allocations are an outcome of close FCC and NTIA collaboration and agreement.

[56] with the offices of Chief Economist and Chief Technologist

[57] There are other bureaus in charge for particular licensed services and the technical rules they follow, e.g. International Bureau for commercial satellites, Media Bureau for broadcasting, Public Safety Bureau etc.

[58] Two from President's political party, two from the other party

[59] Commissioners are prohibited by the Sunshine Act from meeting each other in groups of more than two outside an open FCC meeting but legal advisors are not so restricted. This is a common manifestation of the 'lobbying in Washington DC'

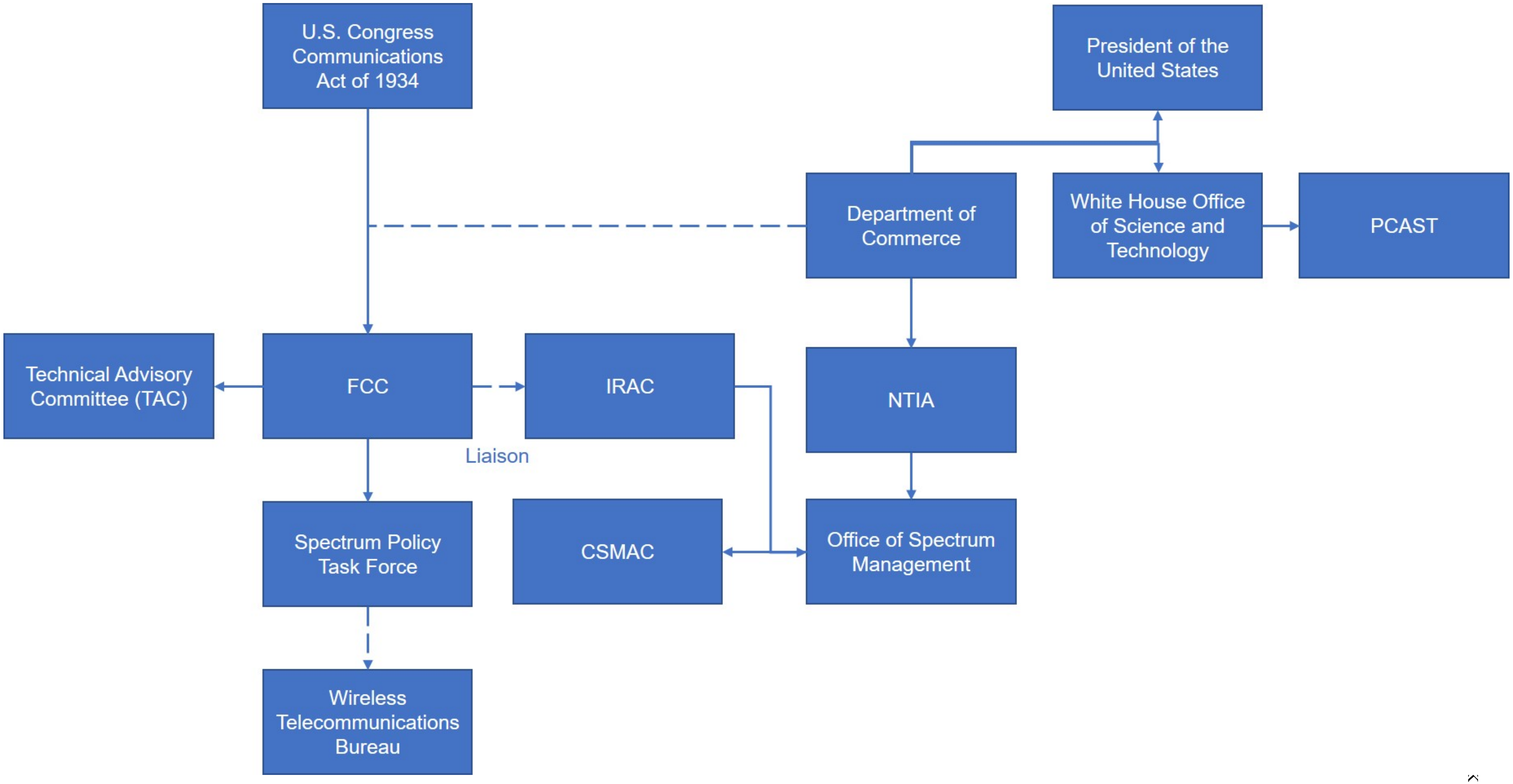

Figure 5.7: Organizational structure that regulates spectrum sharing in the U.S.

So, how does this collaboration actually happen between the FCC and the NTIA and via IRAC? If there is a situation where non-federal use may impact federal use, FCC then has to file the application to get frequencies for non-federal use of a shared band. Then, according to NTIA's Redbook: (1) service needs are evaluated (technical studies, frequency selection and requirements), (2) application submitted to NTIA's OSM for the IRAC (with information on: transmit and receive equipment, geolocation, spectrum usage, permanent, temporal or trial assignment request), (3) policy guidelines consulted to assign frequencies. When a frequency is assigned, it is for a specific geographic location, specific service area with specific performance requirements to not interfere with the stations nearby. In case of multiple assignments in the same area, priority access is given to the assignments made first.

Next, we will discuss legal documents and legislation forms of spectrum policy in this proceeding. There is a whole legal structure backing up the process of rulemaking, which enables interaction between the FCC and the public (stakeholders) resulting in a final decision which sets a particular spectrum rule.

5.4.2 *The FCC Rulemaking Process*

The FCC creates its regulations through a rulemaking process. The legal process that governs the FCC rulemaking ensures that the FCC decisions comply with the Administrative Procedures Act (APA), U.S.C. &706(2)(A)[60]. In addition, the FCC decisions must be consistent with the US Constitution, the Communications Act and other applicable laws.

The ways in which the FCC can make a policy change or introduce new policies on spectrum to the public are[61]: (1) Notice of Inquiry (NOI), (2) Notice on Proposed Rulemaking (NPRM), (3) Report & Order (R&O), (4) forum or en banc hearing or (5) initiate the change through Task Force reports. For the 3.5GHz, the FCC practiced all of these options except en banc hearings, which are usually held in front of the court, in cases when it is convient to avoid preparing a NOI or an NPRM and convey the FCC interest in promoting a particular policy goal to the public in a more digestible way than it is a hundred-page report which only few will read. Task Force Report and Proceeding is a good way to explore the policy issue in depth, gather information and provide policy framework for future FCC decisions. Examples relevant to the 3.5GHz proceeding are National Broadband Plan[62] and Spectrum Task Force Report[63]. This instrument is best used when the FCC seeks input on a wide range of related issues and does not have pressing deadlines, because the staff resources need to be reallocated from doing other activities (rulemaking, allocations, licensing etc.).

[60] `https://epic.org/open_gov/Administrative-Procedure-Act.html` "APA requires that any Federal agency findings must be set aside if they are arbitrary, capricious and abuse of discretion or otherwise not in accordance with law."

[61] `https://www.fcc.gov/general/understanding-fcc-processes`

[62] `https://transition.fcc.gov/national-broadband-plan/national-broadband-plan.pdf`

[63] `https://transition.fcc.gov/sptf/files/SEWGFinalReport_1.pdf`

Two traditional options that FCC uses are NOI and NPRM. A NOI is launched when the FCC has not yet fully developed a proposal in a particular subject area and it is issued to seek comments from the public and collect general information about the issue that can then be used to formulate more concrete proposal, the NPRM. Similarly to the Task Force report, a NOI can serve to support a more substantive NPRM in the future. An NPRM is generally put out when the FCC has decided to move forward in a specific policy direction, which is what PCAST recommendations initiated. Just a few months after the PCAST report was published, in Dec 2012. the FCC issued an NPRM for 3.5GHz with which they proposed to create a *Citizens Broadband Radio Service* (CBRS), new class of service in the 3.5 GHz band and implement the multi-tiered shared access model in the band, along the lines of the PCAST proposals.The NPRM for 3.5GHz was submitted for public comments under an electronic file called docket, specifically docket GN 12-354[64], opened to collect the comments for a review. After the review, FCC can issue Public Notices (PN), a Further Notice on Proposed Rulemaking (FNPRM), or a final Rule and Order (R&O) after which, if certain issues are not resolved or the decisions do not get approval, a Petition for Reconsideration or a court review of the decision can be formally requested. When rules and regulations are finalised they can be found in the Title 47 of CFR. Everything related to the same proceeding is stored in the docket, including filings of the public.

This brings us to the ways in which the general public and the private sector or stakeholders can affect the policy change. They may have the policy goals of speeding up the decision process, framing the issues, building the stakeholders community or developing an extensive public record on a certain policy issue. Four general ways to do that in the US regulatory establishment are: (1) filing comments and proposals (on NOIs, NPRMs, petition on rulemaking etc.), (2) requesting a rule waiver, (3) congressional legislation or (4) through white papers and ex parte filings.

Careful examination of the 3.5GHz proceeding in the FCC database, shows that the stakeholders have extensively submitted comments and proposals, replies to comments, petitions for reconsideration and white papers. These choices of policy action are the best options when the policy goals are to frame the issues for the band in which they have interest in and at the same time build a stakeholder coalition because you can target the groups you think will like your proposal and develop a comprehensive public record. The essence of ex parte filings is that the communication is not made in the presence of all the parties, as is the case for a filing on a docket[65]. When you file an ex parte in an open docket, the FCC primary goal is to resolve the issues pending on that docket. It all happens through the comment cycles, which overall enables a policy issue to be framed and addressed thoroughly, with the outcome of the FCC making informed and thoughtful decisions.

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[64] `https://apps.fcc.gov/edocs_public/Query.do?numberFld=&numberFld2=&docket=12-354&dateFld=&docTitleDesc=`

[65] See e.g. `https://www.fcc.gov/proceedings-actions/ex-parte` “An ex parte presentation is a communication, written or oral, directed to the merits or outcome of a proceeding that, if written, is not served on all the parties to a proceeding, and if oral, is made without giving all the parties to the proceeding advance notice and an opportunity for them to be present.”

5.4.3 *Regulating for CBRS*

Looking from outside the system itself, the regulatory process behind CBRS sharing model can be broken down in steps. To design policies necessary to make sharing of 3.5GHz band a reality, there were several *general steps* that we could identify as FCC actions behind the scenes that resulted in legal framework. These steps also partially reflect how new spectrum regulations work in general. The actions are focused on answering some questions. First, users need to be defined and classes of services. Then the band plan needs to be worked out to accommodate the different classes of services/uses. When fitting a diverse use in on specific band, there needs to be appropriate spectrum allocation put in place to avoid conflicting issues, because spectrum users will use different technologies to provide different services, while coexisting with all other users under some kind of interference protection umbrella. This framework in particular, promoted technology neutrality. Also, as a regulator, you have to make sure that the rules are tailored to ensure there is enough interest in the band because stakeholders' interest is what determines the success of sharing. The underlying assumption behind this policy fact is a pure economic, incentive-oriented one: the markets for equipment and devices will be boosted, ecosystem will be created, innovation and competition will be spurred and the sharing will eventually be a success.

Once the rules are sketched so that there is general satisfaction within stakeholders community, the next steps need to answer questions about implementation of such systems. To have successful real-world implementations of the system, technical rules and specifications need to be defined so that they match with the current state of technology. For example, power levels limitations could be set as interference mitigation techniques to fall within a certain standard which is already defined, adopted and widespread or determine if new standard is needed altogether. Once devices are specified in terms of how they can share the spectrum, engineering design gets put to work to make those devices capable of sharing at these frequencies and to make the database capable of coordinating and managing them. When the technical rules behind spectrum sharing system are defined, standards and the architectures that will enable sharing, then usually prototypes are built to show the feasibility of a system. This is left to the industry, i.e. the stakeholders.

Fig. 5.8 illustrates the involvement in rulemaking process of major mobile carriers, independent wireless providers, database providers, equipment manufacturers, companies based on the Internet, as well as individual spectrum economics experts and consultants. With the comments and replies to comments they provided, they helped to shape the rules of the spectrum access model for 3.5 GHz sharing. The stakeholders' involvement in the CBRS was crucial for the framework development, as we will see in the next chapter. What this shows is the decentralised attempt of governance over spectrum and a real, significant step away from the command and control approach. In this spirit, the CBRS is governed by the SAS, which takes over the regulatory role by performing active, real-time, dynamic spectrum management.

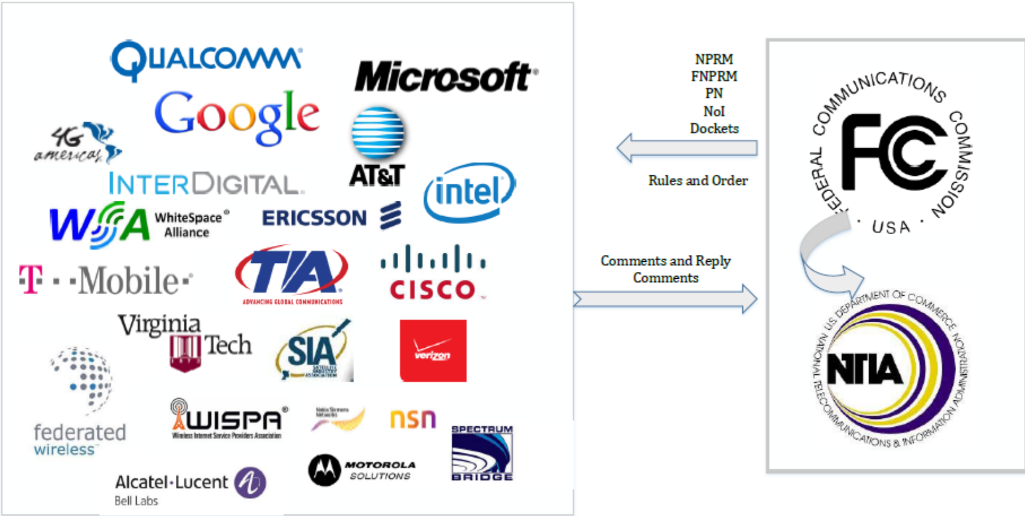

Figure 5.8: Users of the band get involved

The stakeholders' involvement is important from several perspectives: (1) the success of the band and sharing is dependent on their interest, (2) they get the chance to frame the rules so that they are also responsible for the decisions made, (3) economic perspective: they invest in equipment, they spur the ecosystem of the band, they bring competition in the band. Stakeholders form their positions based on what others have proposed. Early identifying with whom you can do business in the band is always an advantage over competition and it means positioning yourself as a leader early on. This is what the US leadership in economy and technology means, and what the competition for spectrum is about: strong crystallisation and filtering within their own boundaries, to excel in the outside world.

5.5 CHAPTER SUMMARY

The historical approach to allocation and assignment of spectrum shows the exhausting, tortoise-hare race of technology and regulation and tells the few incidental stories of success. The way in which we continue to regulate spectrum on service-by-service and band-by-band basis is not a recipe for the future. The PCAST laid out progressive ideas for contemporary policy design and proposed ways to satisfy the future demand for wireless services. There exists a complex organisational structure that needs to unlock the potential of PCAST ideas and implement them. This infrastructure is not only organisation of the regulator, but also stakeholders epistemic community.

The complexity of the policy process is best reflected in the fact that there are multiple technical truths. What each stakeholder advocates for is well elaborated through their proposals and each of those proposals is a technical and economic truth as it is the foundation of their business in the band. The PCAST report did envision this diversity, in services and in users. The stakeholders group in the CBRS is far from a unified group with common interests and it is one of the reasons why coming to the final rules and decisions was a complex task. Excessive complexity leads to uncertainty and perfection can be doomed.

The tasks of our next chapters are to explore if there was a way to reach the balance - the balance between designing the framework and the new CBRS system to be perfectly adaptive and smooth and between building something less complex but that is perfectly understood and manageable. The next chapter is a dive into industry policy propositions to explain how they shaped the rules.

Christmas Banquet for Rich Staff

"Many of them have a collection of rare toys,
and we are going to make sure they expand the collection."

Audio version at: `https://www.youtube.com/watch?v=D2vrvede-ig`

6 THE CBRS DOCKET 12-354: TEXT IN CONTEXT

In this chapter, we perform the content analysis of the CBRS proceeding docket motivated by the pursuit of the defining features of the CBRS band. The culture of sharing is not a generic category, and in order to see it developed in a spectrum sharing ecosystem we need to: (1) understand what is the ecosystem about: what has put it together, what is its framework and the rules, and (2) meet the inhabitants of the ecosystem - the stakeholders that should be the bearers of the culture of sharing. With the content analysis, we are getting to know what is the framework imposed by the regulator within which stakeholders exist, and get to know the commercial stakeholders, the ones who need to adopt the culture of sharing. We are trying to find the symptoms and causes of the non-existence of sustainable spectrum sharing, and we present here one such way.

We start with the research design of content analysis for CBRS spectrum sharing proceeding in Section 6.1. We proceed by performing the analysis in three stages in Sections 6.2, 6.3, and 6.5. We discuss intermediate results in Section 6.4 and final results in Section 6.6. Reliability and validity is discussed in the last section before the chapter summary.

6.1 DESIGN OF THE CBRS CONTENT ANALYSIS IN THREE STAGES

Our design of content analysis fitted to the CBRS spectrum sharing framework is illustrated in Fig. 6.1 and it follows from the general framework of Krippendorff[1] (Fig. 4.3) introduced in methodology chapter.

[1] Krippendorf, K., 1980. Quantitative content analysis: An introduction to its method. Beverly Hill: Sage publications. and the 2003 edition under the title Content analysis: An introduction to its methodology

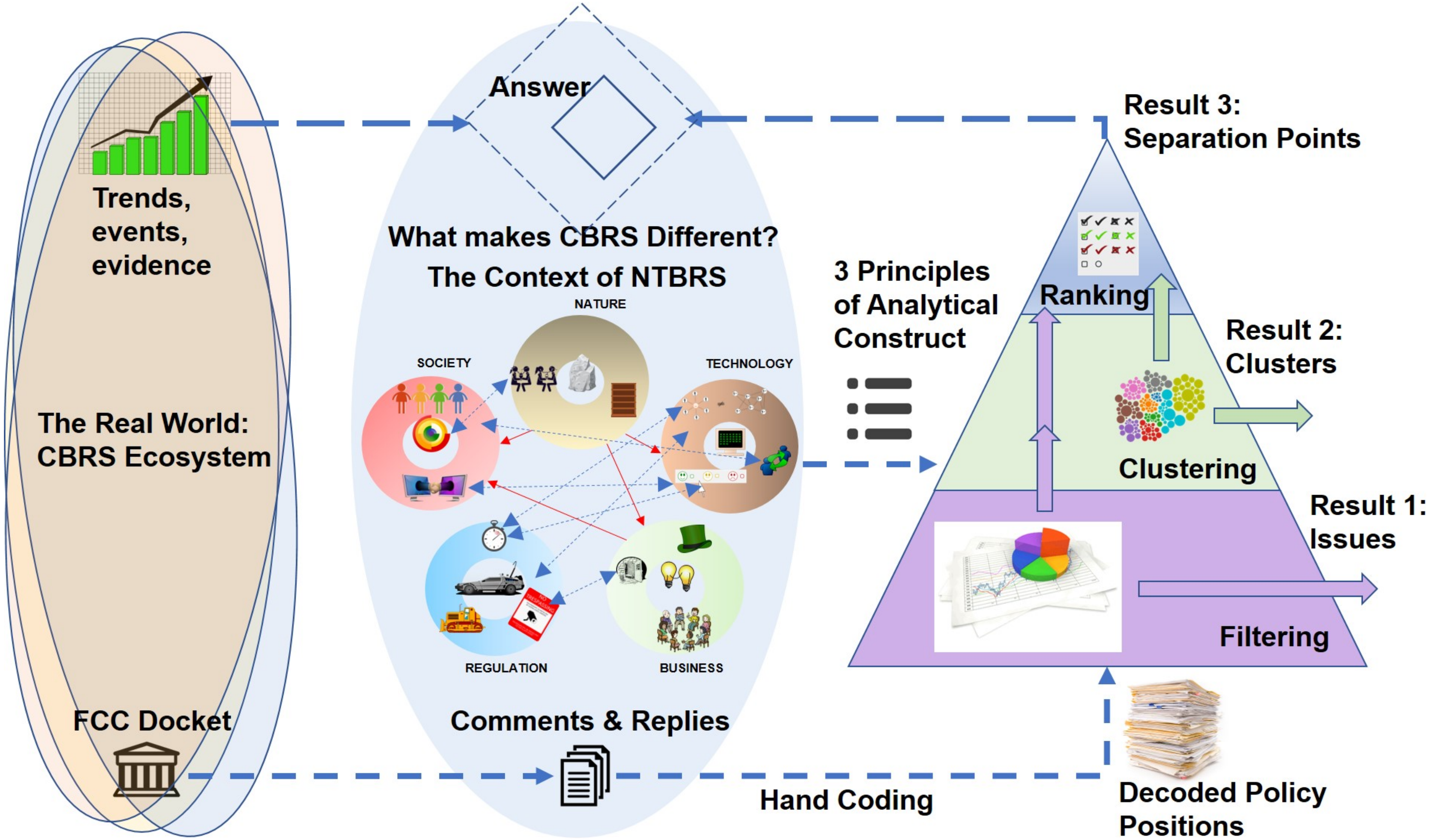

Figure 6.1: Applying Content Analysis on CBRS Rulemaking

This is a problem-driven content analysis. It starts from the *research question*: **How is CBRS band different from exclusive-use bands, those shaped by current commercial norms (traditional bands)?** We want the answer from the stakeholders community, as this thesis is about the culture of sharing and those who should host it. We cannot do a poll of stakeholders[2] but we believe that we can extrapolate the answer from their policy positions, as the initial examination of the documents stored in the CBRS docket shows the structured policy positions, technical and economic proposals and suggestions to the regulator on how to design the rules for CBRS sharing. The question, as posed in all its generality, does not allow the analyst to plug the numbers and results of analysis and get the answer to the question, as it is a question from the real world, the spectrum ecosystem world and not the question from the texts space[3]. This is why we break the question in three sub-questions whose answers gradually make the transition from the texts to the real world. The three sub-questions are answered in three stages on the analysis. Each of the answers is needed in the next stage but also produces an intermediate standalone result.

1. First, we are interested in what the stakeholders were concerned about and how their individual concerns reflect on the interaction within the whole stakeholders' community in the CBRS band. For that, we first need to identify what their policy positions are and then observe around which questions they disagree. The first question is: **What issues emerged in the CBRS proceeding?** We answer this in stage 1.

2. Then we are interested to find out how did the stakeholders group around those issues and how did their policy positions assemble within a collective mind of stakeholders community. The second question is: **Which interest groups emerge in the CBRS band?** We answer this in stage 2.

3. And the third question is: **What the interest groups and their policy issues expressed can tell us about the CBRS band?** We answer this in stage 3, which uses inputs and intermediate results of stage 1 and 2 to answer the main research question asked in the chapter.

The *data* for the analysis are the texts in the FCC CBRS proceeding database[4] under the docket 12-354 and the choice of data (texts to analyse) was a direct one[5]. It consists

[2]We cannot email the CEOs of these companies and ask them why is CBRS band different from other bands.

[3]The research question of content analysis needs to be about the real world and not about the texts to analyse. Krippendorff in his book provides both good and bad examples of research questions.

[4]The stakeholders submit their comments and reply comments through an Electronic Comment Filing System (ECFS) that serves as the repository for official records in the FCC's docketed proceedings. `https://www.fcc.gov/ecfs/`

[5]The choice was between research papers on CBRS model, mass-media coverage of CBRS or the FCC proceeding database for the 3.5GHz CBRS sharing framework which is the official record of CBRS policy design. While the mass-media coverage is of some interest to us and we cite it elsewhere, for this chapter we focused on the FCC proceeding database, as the only relevant source of data to put under the scrutiny of content analysis tools. Unfortunately, there are no research papers on this topic. If there were, however, they would serve as a validity reference point and not a primary source for the analysis.

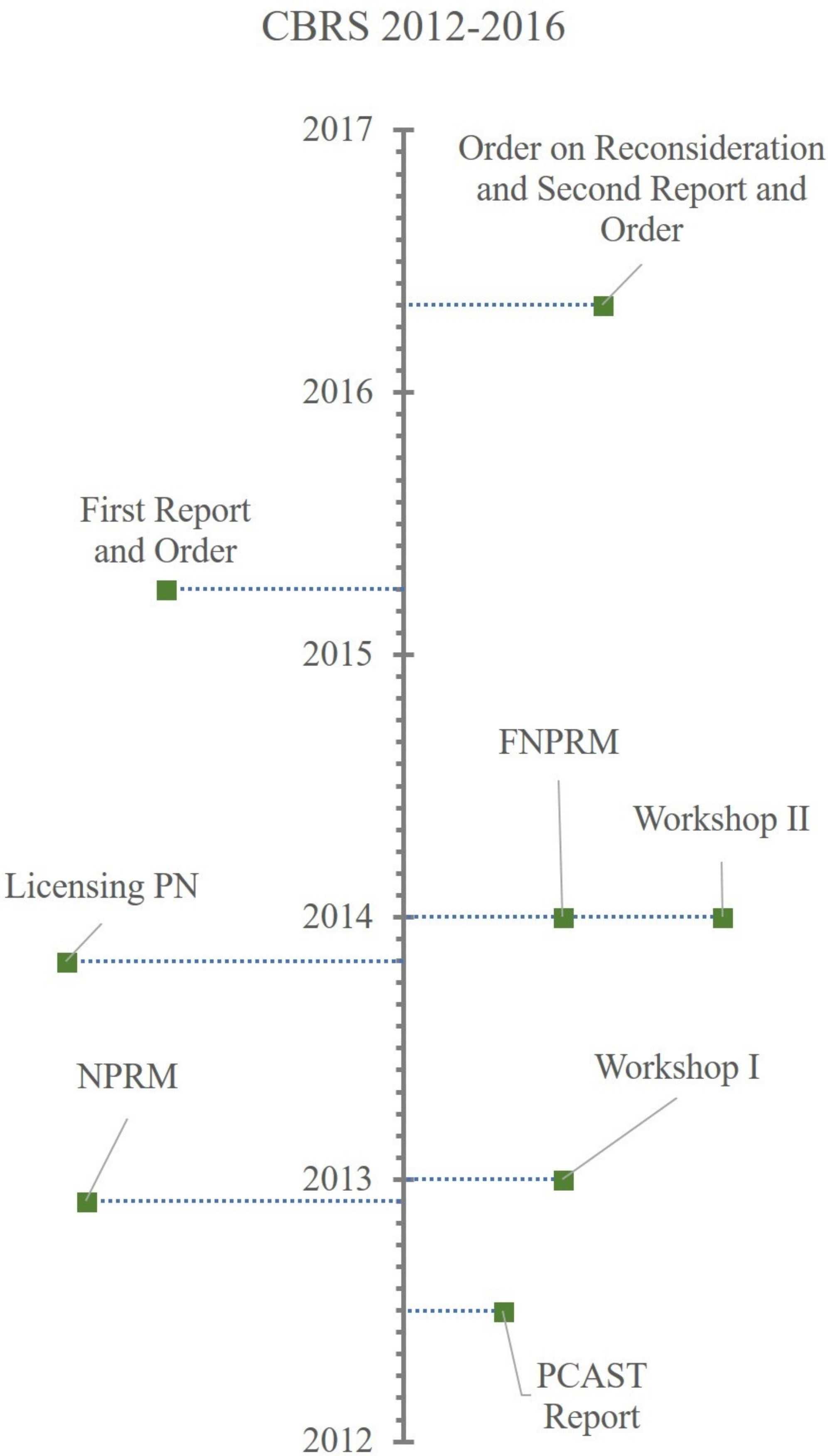

Figure 6.2: The timeline

Table 6.1: Stakeholders Actions subject to Content Analysis

Filings	**NPRM**	**Lic. PN**	**FNPRM**	**Workshops I,II**	**Second FNPRM & R&O**	**Total**
	2012	2013	2014	2014	2015	
Comments	52	40	74		28	194
Reply to Comments	24	15	29		15	93
Petitions					8+1	9
Reply to Petitions					2	2
Oppositions to Petitions					8	8
Reply to Oppositions					7	7
Presentations and white papers				30		30
						343

of: (1) regulatory deliverables and (2) the stakeholders reactions and proposals (comments, reply comments, white papers, presentations at the workshops). We term the regulatory deliverables as *milestones*, as analysis is performed while the CBRS docket was developing and it chronologically follows publication of the FCC documents and the stakeholders' responses to them. The timeline is shown in Fig. 6.2. The milestones[6] are: (1) NPRM and the Workshop I, (2) Licensing PN and the Workshop II, (3) FNPRM, (4) Second FNPRM and R&O, (5) Order on Reconsideration and Second FNPRM. The two workshops are held as part of the corresponding deliverable they aimed to elaborate on and are grouped in such way in the analysis. The documents in the proceeding submitted by the stakeholders are *public filings*, their instruments to state policy positions once when the FCC starts the consultation process, as explained in Chapter 5. The number of documents analysed per each milestone is shown in Table 6.1

We were non-selective in units of analysis since we did not do the sampling, but the full reading of the texts stored in the docket[7]. Full reading of the texts means human expert reading and is an important part to highlight. Software tools are focused on natural language processing. But the regulatory language is not natural at all, it is a language of diplomacy, market maneuvering, legal terms, politics and indirect messages to the competition. At the same time, a comment of a stakeholder is not a

[6]We have introduced the terminology in Chapter 5, so here we list the milestones in acronyms as they are known for.

[7]The only type of documents we disregarded are the *ex parte* letters and notices. Sometimes ex partes contain slide decks and sometimes they are used to file engineering reports, but this was not the case in CBRS docket. Most of the times they report on meeting held within FCC facilities with different stakeholders, and as such they are inherently unstructured.

structured answer to a questionnaire, and the regulatory deliverable is not a structured questionnaire to begin with. This asked for full reading and interpretation of the texts.

The texts are interpreted from the context of spectrum sharing. According to Krippendorff, the context component of the analysis aims to explain what the content analyst does with the text/data and how that particular context embraces the knowledge that the analyst applies to a given text. We need the context for: (1) understanding the origin of texts and the information within, (2) grounding of the inference process and (3) the interpretation of the answers. This means that the context for our analysis is taking into account the entire ecosystem: the stakeholders, their relationships on the market, the regulator, the technology. Therefore, the context of the CBRS content analysis is the NTBRS framework introduced in Chapter 3 as a useful conceptual model of spectrum sharing context and this is why we are interpreting the results through it as well. In one of its corners, the NTBRS framework explains the rulemaking (Regulation). For the analysis, that domain is where the texts are, and the more narrow context of rulemaking. That means that the NTBRS framework as a context in this analysis is wide enough to answer the research question about the real world (CBRS ecosystem) and suitable enough to be narrowed down and extract its parts to form a formal "if-then" structured list of statements to guide the inference and question-answering, the *analytical construct*.

The analytical construct is the analyst's take on the context. We need it to govern the reasoning which will take us from the data to meaningful answers. The data itself is not enough: it is a matrix (policy topics x stakeholders) which has as many columns as there are policy topics raised in the proceeding and as many rows as there are stakeholders who stated their policy positions. It is a sparse matrix, mostly empty, as the stakeholders aimed to answer particular questions in their interest to respond to. That is all of the data we have. Everything else has to come from the context.

Our take on the analytical construct is a list of three rationale statements, each one corresponding to one of the sub-questions, and accordingly, to one of the stages in the *inference process* as represented in Fig. 6.3.

1. The first part of the analytical construct, the **rationale 1** is: *if it is important, then it is expressed in the documents*. While it may sound trivial, this observation stems from the context of text generation (rulemaking) and might not hold for a different class of documents. This is the basis of the *inference stage 1 - filtering* which results in the list of relevant *issues,* the answer to research sub-question 1.

2. The second part of the analytical construct, the **rationale 2** is: *if the stakeholders express similar opinions, then it is meaningful to group them*. Again, this would not be true in a different context where the stakeholders might be highly unique and individual, but here it is justified. It is convenient to group the stakeholders for several reasons. First, it gives us an idea of the common interests and values they share, and second, it allows us to relativise the numbers in the analysis. Relativisation means observing an issue as divisive if two or more interest groups have shown different opinions, no matter what their relative strength in numbers in

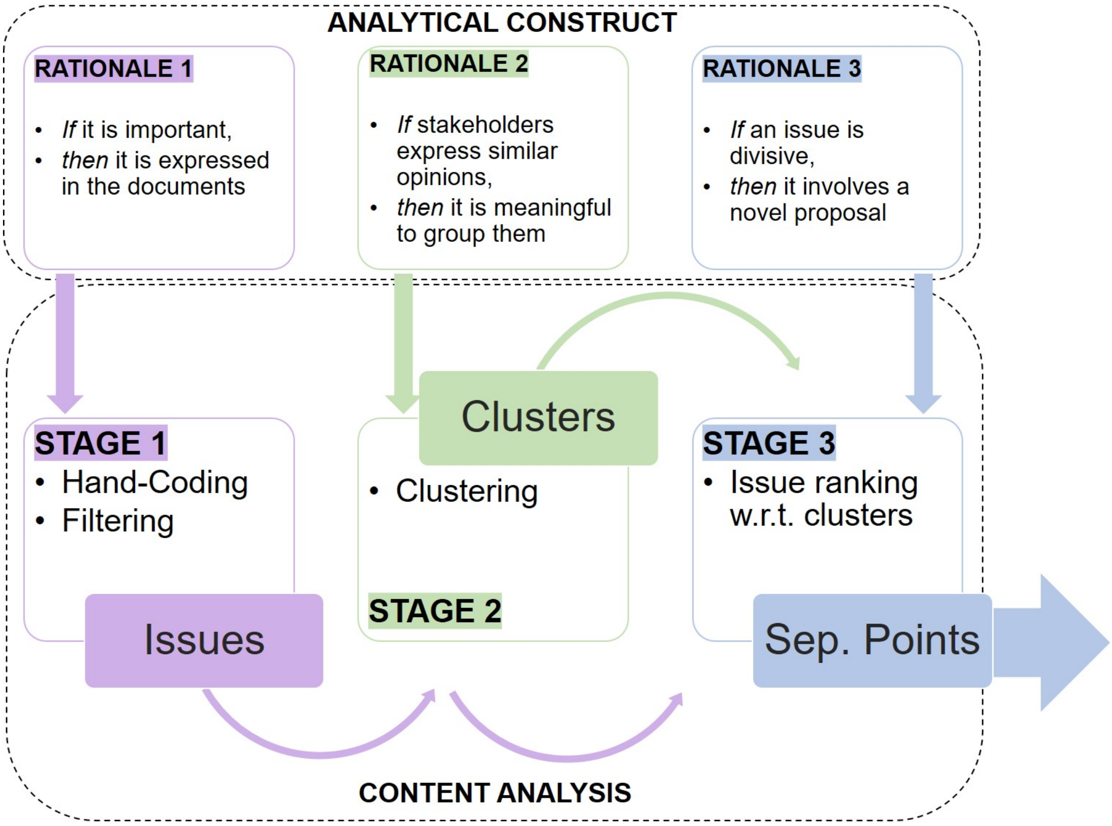

Figure 6.3: Stages of CBRS Content Analysis and the Analytical Construct

the particular issue is. That shifts the emphasis from the distracting numbers which can be a result of stakeholder mobilisation on a topic. Inference based on this rationale is performed in *inference stage 2 - clustering*. The result are *interest groups* of stakeholders in the CBRS band, the answer to research sub-question 2.

3. The previous two parts combine in the **rationale 3** of the analytical construct: *if an issue is divisive, then it involves a novel spectrum sharing rule proposal*[8]. In a relatively unimportant issue, the stakeholders can afford to have an opinion of their own, submit a white paper on a technical solution or result of a research instead of a firm policy position. However, if a novel regulatory rule proposal is brought to the table which changes the way they operate (and make profit) in the band, all the stakeholders act on their survival instincts (and in the light of rationale 2, circle the wagons of their interest group). By extracting the most divisive and the most important issues in *inference stage 3 - ranking*, we arrive at

[8]One might argue that divisive issues are often long-standing differences of interest, and do not necessarily correlate with novel proposals. While that may be true for another case in another band where there is no a novel policy proposal for spectrum sharing, in the case of CBRS the analysis has shown that this rationale holds: if an issue is divisive, it is an attempt for a new approach in band management. It is either newcomers complaining about the licensed carriers attempting to do something classically conservative or the carriers complaining about the newcomers attempting to "destroy the band". And this holds for any band where innovative proposals are on the table, as opposed to "business-as-usual" bands.

the list of separation points between the CBRS and traditional bands[9]. While being an answer to the sub-question 3, the list and its interpretation in the NTBRS context represents the answer to the main question of the chapter.

At the end of the chapter, we will discuss reliability and validity of the research design choices made so far.

6.2 STAGE 1: WHAT ISSUES EMERGED IN THE CBRS BAND?

This section covers the process of hand coding the texts and the process of filtering the encoded data. We analysed 7 regulatory deliverables and the analysis of a regulatory process behind the CBRS framework design is presented historiographically, milestone by milestone. We discover the issues that arose from the stakeholders' reactions to the FCC proposals on rules for sharing as this process is what shaped the rules of CBRS band[10]. We proceed by defining what an issue is, in the light of analytical construct's *rationale 1: if it is important, then it is written about*.

6.2.1 *Filtering: from (unstructured) questions to issues*

The difference of opinions around crucial policy issues that emerged in the dialogue between the regulator and the stakeholders is what dictated the course of regulatory actions for the CBRS band. So, what constitutes an issue? To answer this question in the context of our analysis, we refer to the structure of the regulatory documents. Each of them first gives background and builds the context on what the change is about and then discusses item by item from the policy agenda. Within these framed discussions, lie the questions. Dozens to hundreds of questions are asked per deliverable, but not

[9] Again, one might argue that divisive issues could be ones that are also found in other bands, e.g. license duration arguments, size of license area, which frequencies should be included in an allocation, triggers for auctions, relative importance of licensed vs. unlicensed use, etc. However, the issues might sound similar to other bands, but the options appearing as their solutions are nowhere near other bands. So, it's not just the questions, it's the answers as well, e.g. the way the licenses are discussed in CBRS band is not to be found in any other band, solutions suggested to innovative proposals are also innovative themselves.

[10] As seen from the timeline in Fig. 6.2, first the FCC chose to use the instrument of the NPRM to move quickly towards the actions and build a proceeding which frames the policy issue well with the imperative to respond to the PCAST calls for action. The next instrument used was public forum workshop, which helps both sides of the policy theater, the regulator and the stakeholders: for the regulator it is helpful to clarify and frame the issues better through extensive live discussions and for the stakeholders besides that same goal, it also helps building the epistemic community and evolving their own policy positions based on what the competition thinks. The review of feedback received on NPRM and Workshop I (comments and reply to comments) led the FCC to issue a Revised Framework in the Licensing PN (public notice) and to host another public forum workshop. Then the review of feedback received on Licensing PN and Workshop II led the FCC to issue the FNPRM to further discuss the CBRS policy with the stakeholders. The FNPRM is a preparatory step to the First Report and Order which delivers the final rules of CBRS. If there are still unresolved matters at that stage, the stakeholder may submit petitions for reconsideration of rulemaking, and the FCC can issue another document that further clarifies the rules - and this is what happened.The rules were amended by the next milestone, Order on Reconsideration and Second Report and Order in 2016.

in a structured list of questions - they are dispersed around the document. The issues are not merely verbatim questions from the FCC documents, but the essence of the discussions led around them. As such, they could not be identified by a mechanical search or sampling the texts, but by a human expert interpretation. The hand coding did not mean filling out a predefined matrix whose rows were the stakeholders and the columns were the questions posed by the FCC: the formulation of the columns in such decoded table was a task of its own.

Some of these questions become an *issue* and we identify them using two criteria.

1. The first criterion is the existence of conflict in policy positions.
2. The second criterion is if the question attracted enough attention from the stakeholders.

Not all the questions raised are equally important. Leaving all questions in the pool brings in the problem with the signal to noise ratio, as the steps of the analysis to follow will have to handle irrelevant data together with relevant issues. The question of the threshold, where to put the bar for filtering is important, and the quality of the choice is possible to assess after the filtering is done, to validate the procedure. This is done by observing the number of stakeholders having policy positions on the issues left in the pool: if the vast majority of issues has position counts significantly higher than the threshold, this is the indicator that nothing important has been filtered out[11]. We have set the threshold to 5: *receiving at least 5 comments from 5 different stakeholders to each question*. Then, for each issue identified, we identify exactly which stakeholder had a policy position on that particular issue and what was it.

Now we proceed to listing the issues and the corresponding statistics per milestone. Each milestone will be briefly introduced before listing the issues and commenting on them. Based on the timeline and the stages of policy development, the workshop I and II feedback is integrated with the NPRM and Licensing PN, respectively. For compact presentation, the results of the analysis are summarised for each milestone, their detailed exposition is given in tables and charts in App.A.

6.2.2 *Result 1: The issues*

While the issues are an intermediate result and an answer to a subquestion in this chapter, the only way to present them is through a discussion in the context of the rulemaking process, the administrative frame of their genesis. We present the issues following their evolution and placing them in a wide context, extended to reflect the relevant course of events. This interpretation of all issues is going to be helpful for understanding the final results as well.

[11] This procedure is not equivalent to sampling the material to be used for analysis: all comments and reply comments have been analysed and the policy positions have been hand coded.

6.2.2.1 *The NPRM and the Workshop I*

There are 76 relevant documents (texts) submitted in the record on NPRM (52 comments and 24 reply comments). The comments are strictly addressing the NPRM questions; reply comments are addressing the Workshop I and the NPRM (not all stakeholders submitted comments in the first cycle of consultation, some responded to the second cycle of reply to comments only)[12].This is a joint analysis of those two regulatory milestones. The issues raised in the comments to NPRM became a part of the discussion at the Workshop I where stakeholders elaborted on their proposals and framed them into the structured documents after the workshop and submitted to the proceeding database.

The NPRM is the regulatory milestone which initiated the design process of the CBRS rules and therefore it established its founding elements: (1) created the new class of service called CBRS, (2) proposed the three-tier access model for CBRS users, (3) defined the CBRS users as PA and GAA tier sharing the spectrum of IA tier, primary holders of the 3.5GHz frequencies, (4) determined that the SAS should run the band and manage CBRS users (proposed the inclusion of dynamic database and interference mitigation techniques). These are the structural elements of the CBRS defined at the beginning as starting points of framework creation.

With the NPRM the FCC introduced several key proposals for the CBRS tiers:

1. PA tier is to be consisted of critical users only. The critical users are hospitals, public utilities and other mission critical users that need quality of service assured spectrum from this band.

2. GAA tier are accessing the spectrum opportunistically, whenever it is free from PA use, cannot cause interference to PA tier and have to accept the interference from other users in the band.

3. Both tiers of CBRS are proposed to be licensed by rule. This is a licensing scheme that FCC uses to authorise very localised, specific uses without the burden of exclusive licensing, while devices are complying with the FCC certification and qualification criteria, similarly to unlicensed, WiFi bands (Part 15 of the Commission rules).

There are 5 issues diagnosed as NPRM issues.

ISSUE1 How should the rights be assigned among PA and GAA tier? (Table A.1, Figure A.1)

ISSUE2 Should CBRS (both tiers) be licensed-by-rule? (Table A.2, Figure A.2)

ISSUE3 What is the right methodology for PA tier? (Table A.3, Figure A.3)

[12] The deadline for the comments was in February 2013, while the replies to comments deadline was prolonged from March to April 2013 to allow the commenters to take into account the Workshop I, which was held in mid-March.

Table 6.2: Policy positions of stakeholders per NPRM issue and Workshop I

No.	Policy position 1	Policy position 2
Issue 1	3-tier	2-tier/transitional
Issue 2	Agree to have both tiers licensed-by-rule	Oppose to have both tiers licensed-by-rule
Issue 3	Broader PA tier	Critical users in PA tier
Issue 4	Agree to add adjacent 50MHz to CBRS band	Oppose to add adjacent 50MHz to CBRS band
Issue 5	GAA throughout the band assigned dynamically	Oppose to dynamic assignment, should be static

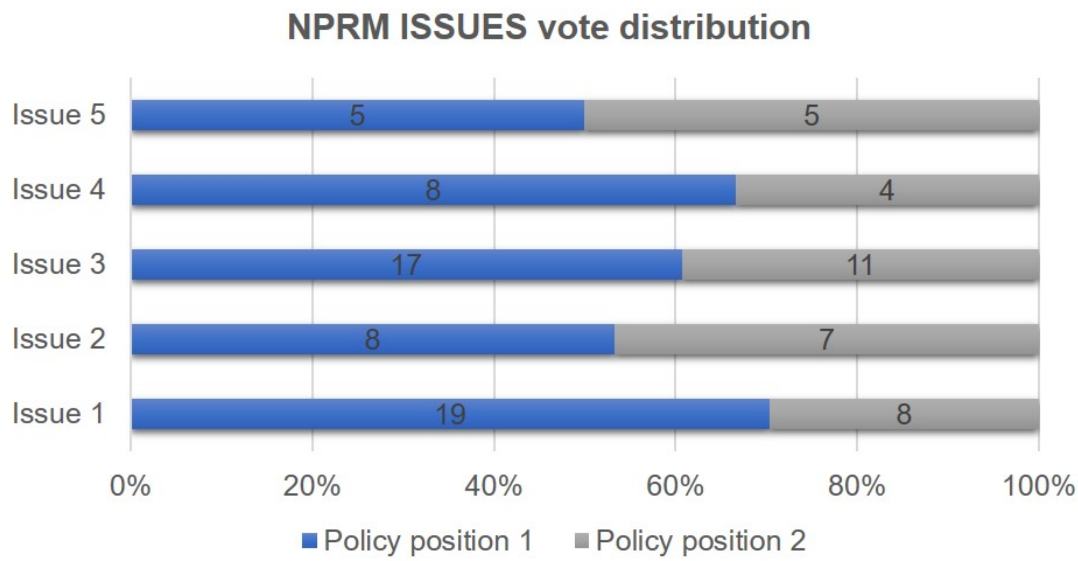

Figure 6.4: NPRM issues votes distribution per each NPRM issue

ISSUE4 Should the adjacent 50MHz be added to the CBRS band? (Table A.4 , Figure A.4)

ISSUE5 GAA throughout the band: dynamic vs. static assignment? (Table A.5, Figure A.5)

Policy positions for each of the issues are summarised in Table 6.2.

Distribution of the votes per issue for each policy position is shown in Fig. 6.4.

6.2.2.2 *The Licensing PN and the Workshop II*

The Licensing PN came as an FCC reaction to the comments generated by the NPRM and the discussions at the Workshop I. The record showed significant resistance to the licensed-by-rule licensing model, so the FCC opened a consultation on other approaches to licensing with this deliverable and called it the Revised Framework. This resistance led the FCC to propose specific solutions for the CBRS tiers authorisation methods, band plan and technical specification of the devices, CBSDs.

Table 6.3: Policy positions of stakeholders per Licensing PN issue and Workshop II

No.	Policy position 1	Policy position 2	Policy position 3	Policy position 4
Issue 1	3-tier	2-tier/transitional		
Issue 2	Agree with census tracts as license areas	Oppose, as census tracts have issues	Census blocks are a better option	Larger licenses area needed: counties, EAs, CMAs
Issue 3	Agree to open eligibility and broader PA tier	Oppose, as critical users should be in PA tier		
Issue 4	Agree to add adjacent 50MHz to CBRS band	Oppose to add adjacent 50MHz to CBRS band		
Issue 5	Agree with license term of 1y + multiple agg. cap	Oppose, license term should be for less than 1y	Oppose, lic. term should be for 1y and no aggregation allowed	Oppose, longer lic. terms are needed, 1-15 years
Issue 6	Agree with non-renewable short term licenses	Oppose, lic. terms should be renewable		
Issue 7	Oppose, GAA should access unassigned PAL channels only	Oppose to GAA access to PAL channels	Agree with GAA access to PAL ch. not in actual use	
Issue 8	Oppose, reject GAA	Oppose, there should be more of fixed PA frequencies	Agree with GAA floor of 50% throughout the band	
Issue 9	Oppose to dynamic SAS, should be static and more restricted	Agree with more dynamic and responsive SAS		
Issue 10	Oppose to dynamic, frequency assignments should be static	Agree with dynamic frequency assignment		

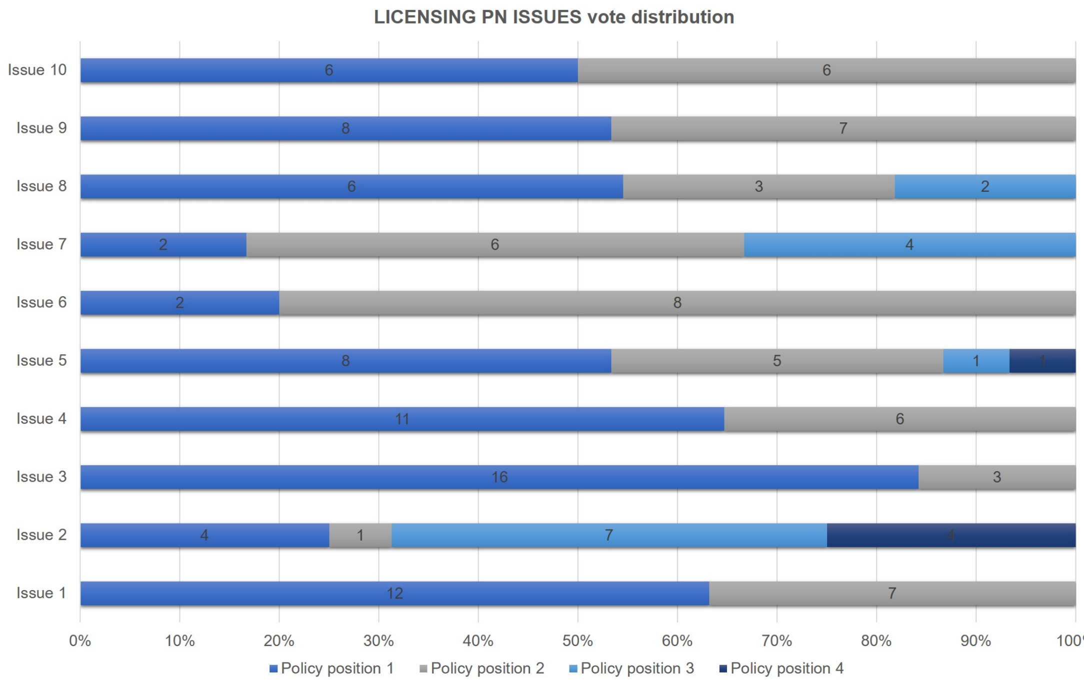

Figure 6.5: Licensing PN issues votes distribution per each issue

There are 10 issue diagnosed as Licensing PN issues.

ISSUE1 3-tier or 2-tier and transitional approach? (Table A.6, Figure A.6)

ISSUE2 Census tracts as license areas? (Table A.7, Figure A.7)

ISSUE3 Open eligibility for PA tier? (Table A.8 , Figure A.8)

ISSUE4 Supplemental proposal: extend Part 96 rules to 3650-3700MHz? (Table A.9, Figure A.9)

ISSUE5 The license term of 1 year with up to 5 years aggregation cap? (Table A.10, Figure A.10)

ISSUE6 Non-renewable licenses? (Table A.11, Figure A.11)

ISSUE7 GAA to access 'unused' PAL channels? (Table A.12, Figure A.12)

ISSUE8 Proportional assignment of GAA and PA frequencies? (Table A.13, Figure A.13)

ISSUE9 The SAS - dynamic or static and more restrictive? (Table A.14, Figure A.14)

ISSUE10 Static vs. dynamic frequency assignment? (Table A.15, Figure A.15)

Policy positions for each of the issues are summarised in Table 6.3. Distribution of the votes per issue for each policy position is shown in Fig. 6.5.

6.2.2.3 *The FNPRM*

With the FNPRM, the FCC proposed specific rules for CBRS in 3.5GHz band that would make sharing regime originally described by PCAST a reality. The rules proposed in this document built upon the record developed in response to a series of prior proposals and workshops over that 16 months. The issues presented below are related to specific proposals that the FCC introduced with the FNPRM, as a step towards First Report and Order.

There are 14 diagnosed FNPRM issues.

ISSUE1 Multi-tiered access model (Table A.16, Figure A.16)

ISSUE2 Census tracts as license areas? (Table A.17, Figure A.17)

ISSUE3 Supplemental proposal: extend Part 96 rules to 3650-3700MHz? (Table A.18, Figure A.18)

ISSUE4 Dynamic frequency assignment by the SAS? (Table A.19, Figure A.19)

ISSUE5 Proposed GAA floor of 50% of frequencies available to GAA always in entire band? (Table A.20, Figure A.20)

ISSUE6 Setting aside frequencies for CAF users? (Table A.21, Figure A.21)

ISSUE7 Mutual exclusivity triggering competitive bidding (Table A.22, Figure A.22)

ISSUE8 What is the appropriate license term and temporal aggregation cap?(Table A.23, Figure A.23)

ISSUE9 Proposed rules for a robust, dynamic and responsive SAS to manage three-tier model? (Table A.24, Figure A.24)

ISSUE10 Proposal of reducing Exclusion Zones? (Table A.25, Figure A.25)

ISSUE11 Proposal to allow GAA access to unused PAL frequencies? (Table A.26, Figure A.26)

ISSUE12 What should be the spectrum aggregation limit for PA spectrum? (Table A.27, Figure A.27)

ISSUE13 Authorising multiple SAS operators nationwide? (Table A.28, Figure A.28)

ISSUE14 The SAS collecting fees from CBRS users? (Table A.29, Figure A.29)

Policy positions for each of the issues are summarised in Table 6.4. Distribution of the votes per issue for each policy position is shown in Fig. 6.6.

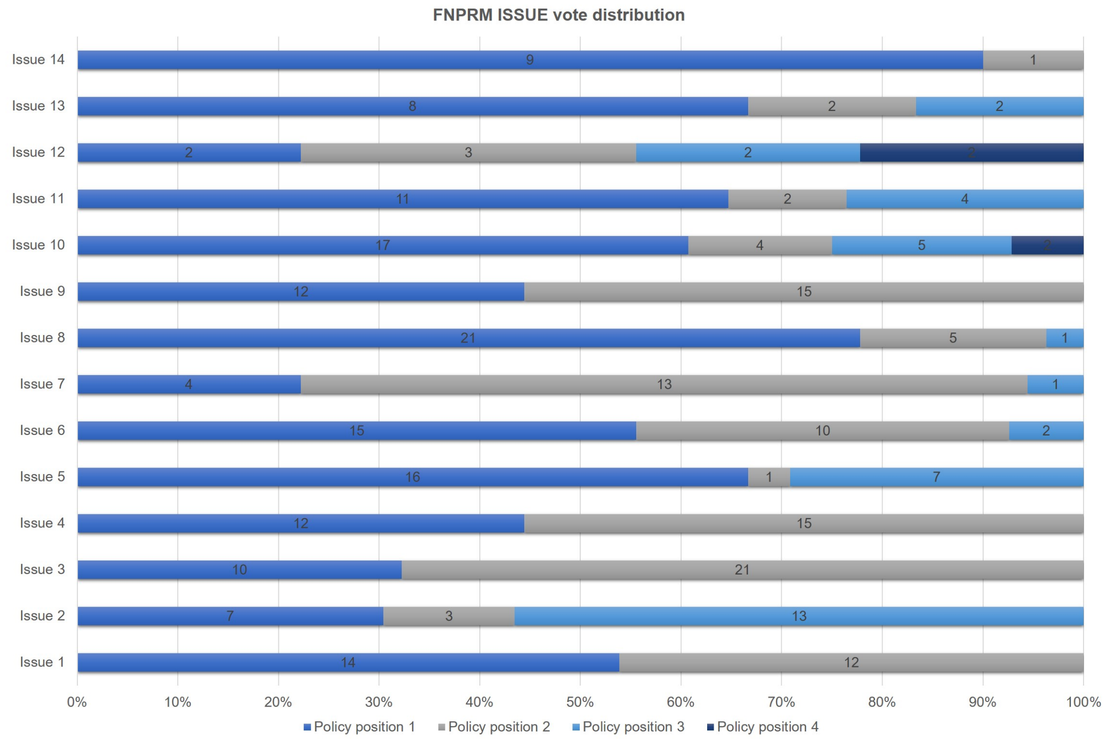

Figure 6.6: FNPRM issues votes distribution per each issue

6.2.2.4 *The Second FNPRM and Report and Order*

This document is also known as *First Report and Order*, as it establishes the CBRS sharing rules. It also contains a Second FNPRM, to open the discussion on the remaining minor issues to be resolved, not expected to significantly affect the essence of the specific rule they relate to. The point of the CBRS framework design process was to consider all of the options based on what stakeholders' policy positions are and the FCC aimed to adopt a middle ground solution for each of the issues in order to come to a balanced regulatory decision about the band. The extent to which this was achieved is a subject of the remainder of this thesis, but here we summarise the rules adopted at this point of the timeline - 2015 publication of final rules in the First Report and Order. Within the pool of diagnosed issues about the nuances of PA and GAA CBRS tiers - this is the list of the issues resolved by the publication of First Report and Order.

Table 6.4: Policy positions of stakeholders per FNPRM issue

No.	Policy position 1	Policy position 2	Policy position 3	Policy position 4
Issue 1	3-tier	2-tier/transitional		
Issue 2	Agree with census tracts as license areas	Oppose, as census tracts have issues	Larger licenses area needed: counties, EAs, CMAs	
Issue 3	Agree to add adjacent 50MHz to CBRS band	Oppose to add adjacent 50MHz to CBRS band		
Issue 4	Agree with dynamic frequency assignment by the SAS	Oppose, frequency assignments should be static		
Issue 5	Agree with GAA floor of 50%	Oppose	There should be more spectrum for PALs	
Issue 6	Agree to set aside CAF spectrum but with changes as the CAF tier should be broader	Oppose	Agree to set aside 20MHz for CAF users from GAA pool	
Issue 7	Agree with auctions as assignment	Oppose to competitive bidding	Avoid mutual exclusivity	
Issue 8	Oppose to short lic. terms, longer lic. terms are needed, 1-15 years	Agree with license term of 1y + multiple agg. cap	Oppose, license term should be for less than 1y	

No.	Policy position 1	Policy position 2	Policy position 3	Policy position 4
Issue 9	Agree with the dynamic band management by the SAS	Oppose, the SAS should be restricted and more controlled, static		
Issue 10	Agree that exclusion zones should be reduced	It is better to use coordination zones	Exclusion zones should be reduced and dynamic with the help of sensing aided SAS	Oppose to reducing exclusion zones
Issue 11	Agree with allowing GAA access to unused PAL spectrum	Oppose	Agree, but with concerns	
Issue 12	Agree with the proposed 30MHz aggregation limit for PAL spectrum	Agree, but the limit should be 20MHz	Oppose, there should be no cap for PAL spectrum	The limit should be more than 40MHz
Issue 13	Agree to allow multiple SAS administrators and nationwide	Oppose, there are challenges.	Agree to allow multiple SAS administrators but regional, not nationwide	
Issue 14	Agree to allow SAS collect fees from both CBRS tiers	Oppose, collect fees from GAA		

1. CBRS is authorised in 3550-3700 MHz band and will be based on a three-tier shared access model. The CBRS tiers are second tier PA users and third tier GAA users, that both need to coexist with the first tier IA users, that are governed and regulated by the NTIA and the FCC (grandfathered Fixed Satellite Services (FSS)). PA tier will operate in 3550-3650 MHz, and GAA in 3550-3700 MHz.

2. PA tier will be licensed within a novel licensing framework, which has similarities with exclusive licensing model. GAA users will be licensed-by-rule.

3. It was decided to adopt open eligibility for PA tier, therefore the initial "only critical users in PA tier" proposal is modified and critical users are excluded.

4. The GAA access to unused PAL channels is adopted as a rule. But the proportional percentage reservation of GAA frequencies throughout the band is rejected: instead, the fixed reservation approach is adopted to have 70MHz of the band for PA and 80MHz for GAA . Also, when spectrum is not used by the PA users that leaves GAA with potential 150 MHz spectrum.

5. The license term is increased to 3 years with the aggregation cap defined as possibility to have the license for 2 consecutive terms, which means temporal aggregation of up to 6 years. The licenses are in essence non-renewable, but the middle ground solution is adopted of allowing 2 consecutive applications for licenses. Moreover, applications for PALs will be accepted every three years.

6. The rules around the SAS define the SAS as a dynamic and responsive multi-database system. Also, there can be multiple SAS administrators, that will operate nationwide. The SAS, as a pillar of CBRS model, is left to the multi-stakeholder group gathered around WinnForum to proceed with the standardization and implementation of the SAS. This is why the FCC held the two workshops in parallel with publishing the regulatory deliverables.

7. The frequency assignment by the SAS is to be dynamic. This means for PA users that the SAS can re-assign them in the band based on radio environment in real time - if they were initially assigned with 10MHz channels in one portion of the band, that does not mean they are guaranteed those same frequencies during the entire license term or at the time of operation. The PALs are authorised for 10MHz channels and no more than 7 PALs can be assigned in census tract.

8. The GAA get assigned dynamically as well, but not for 10MHz channel - for frequencies out of GAA pool that are available at certain time in certain census tract, whenever the spectrum is free from PA use and within the rules described in 4.

9. Licensing scheme is based on census tract area units. Each PAL is an authorisation for single census tract, PAL license area.

10. Each PAL may aggregate up to 4 PAL channels in a census tract, which is a specified spectrum aggregation in frequency dimension of spectrum space.

11. The competitive bidding is adopted for PALs to resolve mutual exclusivity at the auctions.

12. The technical specifications for CBSDs were a subject of discussion as well, but they were not listed here as one of the issues diagnosed, as each stakeholder had a different proposal of what the allowed EIRP and transmit power for both categories of CBSDs should be (Category A indoor, Category B outdoor). The FCC initial proposal was EIRP of 30 dBm and transmit power of 24dBm for both categories, but the stakeholders in majority asked for higher power levels and differentiation between urban, rural, indoor and outdoor deployments, depending on the use case they favor. The final rules adopted are shown in Table 6.6.

13. Supplemental proposal of adding the adjacent band in CBRS was adopted as a rule.

14. Exclusion zones are reduced. And the approach to dynamic exclusion zones is adopted.

15. The SAS will collect fees from both tiers. Also competitive market of SAS is encouraged.

Even though most of the issues got resolved, for some of them, certain points still required clarification. Here we list those points.

1. How to define the USE of PAL frequencies? - This point is a part of the issue of allowing GAA access to unused PAL frequencies. The point that was still ambiguous was the definition of "in use". It was not clear how to define when PAL frequencies are in use, as stakeholders advocated for their policy positions based on the claims of what the "in use" means for their specific use case. The options offered for the definition of "in use" are:
   (1) *engineering definition*[13],
   (2) *economic definition*[14],
   (3) *hybrid definition*[15].

[13]proposed by several commenters (*See* FNPRM Comments of Google, Pierre de Vries, AT&T, WISPA, Federated Wireless, WISPA, InterDigital, Microsoft, PISC, Shared Spectrum) has in essence the SAS enforcing the boundary that will forbid GAA access near PA CBSD, determining protection areas based on information on PA device location and technical characteristics, including the aggregate effect of multiple devices operating in the vicinity as demonstrated by Google SAS prototype, available at: `https://ecfsapi.fcc.gov/file/60001014789.pdf`

[14]proposed by W. Lehr (*See* William Lehr FNPRM Reply Comments), which in essence means that PALs could in economic terms interpret the channels "in use" as an option to exclude GAA from their spectrum - they would buy the licenses as the right to exclude GAA. This would be the right for PALs but not the obligation - to chose the option of excluding the GAAs. The cost of the license would depend on whether the option is used and if GAA is restricted form their channels.

[15]proposed by Federated Wireless (*See* Federated Wireless FNPRM Comments) combines the engineering approach to frequencies in use and the economic one. Federated Wireless proposed that the

Table 6.6: Source: FCC Second Report and Order, CBSD categories and power levels for operation - main technical specifications

CBSD Category	Maximum Conducted Power (dBm/10 MHz)	Maximum EIRP (dBm/10 MHz)	Maximum Conducted PSD (dBm/MHz)	CBSD Installations	Operations in 3550-3650 MHz	Operations in 3650-3700 MHz
Category A	24	30	14	Indoor; outdoor max 6m HAAT	Everywhere outside DoD Protection Zone	Everywhere outside FSS and DoD Protection Zone
Category B (Non-Rural)	24	40	14	Outdoor only, professional installation	Outside DoD Protection Zone & requires ESC approval	Everywhere outside FSS Protection Zone and DoD Protection Zone
Category B (Rural)	30	47	20	Outdoor only, professional installation	Outside DoD Protection Zone & requires ESC approval	Everywhere outside FSS protection zone and DoD Protection Zone

2. Implementing secondary markets in PALs - with the emphasis that auctions would be primary method of assignment, the secondary markets could provide ways of matching supply and demand in units more granular than proposed PAL structure based on census tracts. Developing spectrum exchanges within secondary market rules could facilitate vibrant and deep market for PAL rights. Commenters were generally supportive of the proposal to trade PALs on the secondary market. The FCC initially prohibited the disaggregation and partitioning of the census tract license areas in the FNPRM as they are of small size and short term of 3 years and also the spectrum is significantly available for GAAs in all license areas. They asked further questions on how to implement the approach to partitioning and disaggregation, as many commenters asked for it. This rule relates to the aggregation caps for PALs and how should that combined with the secondary market rule be included in the model design of an auction.

3. Optimising protection for FSS - in band protection of FSS in 3650-3700 MHz and out-of band protection of C-band FSS Earth stations. This remained an open question, regarding the right calculation methodology for coexistence analysis, propagation modelling and interference protection criteria.

At this stage, the regulatory process of defining the rules was still not finalised, as the stakeholders raised the petitions to rulemaking.

6.2.2.5 *The Order on Reconsideration and Second Report and Order*

There were 8 petitions to the rulemaking and they are concerned with:
(1) *the auction rules*[16],
(2) *the license term and renewability*[17],
(3) *the power levels for CBSD categories A and B*[18],
(4) other issues such as *increasing the 60 seconds of SAS response time in coordinating CBSDs* (deactivation of change in frequency) to 600 seconds[19], *protection of C-band operations above the 3700MHz band edge*[20], *geo-location data reporting method* (built in device vs. professional installation)[21], etc.

There were 8 oppositions to petitions for reconsideration[22].

PALs should deploy sensing and then pay a certain fee for usage only for those periods when they need spectrum. They argued that this fee is an incentive for PALs to reserve spectrum only when they actually plan to use it. This proposal raised the questions by the FCC on how to set the price for such a fee and the quantity of use which it corresponds to. How could that be applied for auction model and should the unit perhaps be on census block level, as subdivisions of license area.

[16] *See* Jon Peha Petition, opposing the FCC rule to now issue a license in a census tract when there is only one applicant for one or more PALs in a given census tract, and proposing that "PALs should be granted in every market where there is demand, even if there is only one bidder". This petition is also supported by Motorola Solutions, *See* Motorola Solutions Petition

[17] *See* CTIA Petition, asking for a 5-year license term with renewal

[18] *See* Nokia Solutions Petition, CTIA Petition, Verizon Petition, WinnForum Petition, SIA Petition

[19] *See* Nokia Solutions Petition, WinnForum Petition, SIA Petition

[20] *See* SIA Petition

[21] *See* NAB Petition

[22] CTIA opposed the petition of SIA and supports the petitions of Jon Peha and Motorola Solutions. Federated Wireless opposed the petition of NAB and supports petitions asking for higher power levels

The Commission modified the following rules:

1. The auction rule is modified to allow PALs to be issued in rural census tracts when there are no mutually exclusive applications (there is only one applicant for a license);

2. The SAS reconfiguration time is increased to 300 seconds.

3. Power levels (CBSD categories A and B are differentiated by the max allowed power: Category A CBSDs are limited to maximum conducted transmit power of 24 dBm and a maximum EIRP of 30 dBm in 10MHz and may be deployed indoors or outdoors. Category B CBSDs can only be used outdoors and the condcted power limit in non-rural areas is the same as for Category A (24dBm/10MHz) but the EIRP limit is increased to 47 dBm/10MHz (was 40 dBm/10MHz). In rural areas the conducted power limit is increased to 30dBm/10MHz and EIRP to 47 dBm/10MHz).

The *Second Report and Order* therefore adopts the following changes:

1. Regarding the issue of the definition of "in use": two-step approach to the definition of "in use" is adopted (PA self-report their protection contour based on their actual network deployment and the SAS enforces the default protection contour around CBSDs within -96dBm/10MHz maximum power limits) and the CBSDs must inform the SAS of the change in status if they do not operate for 7 days as additional measure of actual transmissions is adopted.

2. Light-touch leasing regime is adopted for secondary markets and the lessees cannot sublease, or partition or disaggregate their licenses in the band.

3. Protection to FSS stations in the band is defined so that it does not mandate methodology for establishing protection areas, but gives guidelines. Proposal to adopt static default protection zones based on worst case assumptions is rejected. The areas are defined to be 40 km distance for adjacent emissions within which SASs must account for aggregate interference from CBSDs when calculating protections for individual FSS earth stations.

6.3 STAGE 2: WHICH INTEREST GROUPS EMERGED IN THE CBRS BAND?

This section presents the clustering of stakeholders performed using the information on their policy positions. We pursue it in order to detect the interest groups formed in the CBRS band rulemaking. A success in group discovery both verifies the information quality of the result 1 and paints a picture of the CBRS landsape with its inhabitants.

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and change in the auction rules. Google opposes SIA and NAB petitions and supports the petitions advocating for change in technical rules for CBSDs. SIA supports the petition of NAB and proposes other options for category B. Qualcomm supports CTIA petition. T-Mobile supports CTIA petition and rejects NAB petition. Verizon opposes SIA petition and supports higher power advocates. WISPA opposes most of the petitions and argues the FCC should retain majority of its rules.

No.	FCC proposal
A1	Innovative 3-tier access model?
A2	License-by-rule for both CBRS tiers?
A3	Limit PA tier to CAF users?
A4	Supplemental proposal to add 3650-3700 MHz band?
A5	Dynamic frequency assignment and GAA throughout the band?

Table 6.7: Diagnosed issues from the NPRM

No.	FCC proposal
B1	Innovative 3-tier access model?
B2	Smaller license areas, census tract as the license area units?
B3	Open eligibility for PA tier?
B4	Supplemental proposal to add 3650-3700 MHz band?
B5	Dynamic frequency assignment and GAA throughout the band?
B6	The license term of 1y + 5y aggregation cap?
B7	Non-renewable (and short term) licenses?
B8	GAA to access to "unused" PAL channels?
B9	Proportional assignment of GAA and PA: GAA 'floor' of 50% in entire band?
B10	Dynamic and responsive SAS?

Table 6.8: Diagnosed issues from the Licensing PN

The data is a set of matrices representing policy positions of the stakeholders in 29 issues we found in Stage 1. Stakeholders usually do not state their policy positions on every issue (the only stakeholder to do it was WISPA), which means that the full matrix of stakeholders and issues is sparse, dominantly filled with unknown values. This is a challenge for the clustering, as the method we choose has to meaningfully extrapolate the unknown positions with the help of known ones.

A meaningful extrapolation will enable us to detect stakeholders with similar policy positions throughout the proceeding. These naturally fall in common interest groups, as their positions in the important questions (i.e. issues) represent the attitude of the group. Hence, we act according to rationale 2: if the stakeholders opinions align on multiple issues, then they belong to the same interest group.

The summary of stage 1 results, previously shown in figures and charts per milestone is presented in tables 6.7, 6.8 and 6.9. The tables show the 29 issues diagnosed for each regulatory deliverable before the final rules were put in place.

The relationship between the issues and the interest group clusters is reciprocal: we will use the issues and the attached policy positions to determine the groups, and then observe the issues through the lens of stakeholders groups instead of individual stakeholders. In that sense we revisit the evolution of issues (intermediate result 1) and do a joint analysis of the results of two stages.

No.	FCC proposal
C1	Innovative 3-tier access model?
C2	Smaller license areas, census tract as the license area units?
C3	Multiple SAS administrators nationwide?
C4	Supplemental proposal to add 3650-3700 MHz band?
C5	Dynamic frequency assignment and GAA throughout the band?
C6	Short license term and non-renewable
C7	GAA to access to "unused" PAL channels?
C8	Proportional assignment of GAA and PA: GAA 'floor' of 50% in entire band?
C9	Dynamic and responsive SAS?
C10	Limit PAL spectrum aggregation?
C11	Set aside 20 MHz for CAF users from the GAA pool?
C12	Competitive bidding via auctions for PALs?
C13	Exclusion zones, initial estimation by the NTIA: reduce or not?
C14	SAS to collect fees from PA and GAA users?

Table 6.9: Diagnosed issues from the FNPRM

6.3.1 *Clustering: from policy positions to interests groups*

Clustering of stakeholders could in principle be performed without content analysis: it is known what group of businesses does each stakeholder belong to, and that is the interest group they represent in the proceeding. However, we argue that this information is already encoded in the data, so there is no need to add it from the context. The contextual knowledge of business nature will be used to verify the clustering after it is performed. This verification serves not only to confirm the applicability of the selected clustering algorithm, but also the relevance of data. If the data is rich enough to allow us to profile the stakeholders without additional help from the context, it is rich enough for the other conclusions we make in this content analysis.

On the technical side, clusterisation is a problem of pattern recognition. In the most general form of the problem, we do not know how many clusters can be distinguished, and the data is not readily separable in one or two dimensions. When we use computer support for clustering, it is not because we cannot perform it ourselves (pattern recognition predates its computer-supported variants of machine learning), but because the computer is performing it faster on a large set of data. Since not all stakeholders are replying to all issues, the datasets from the analysis need to go to an algorithm that is based on probabilistic approaches to "filling the blanks", as opposed to deterministic "fill by the mean" approach of algorithms such as K-means clustering. Furthermore, we do not wish to impose the number of clusters on the clustering algorithm. An algorithm which can deal with blanks is the expectation-maximisation algorithm (EM)[23],

[23]Dempster, A.P., Laird, N.M. and Rubin, D.B., 1977. Maximum likelihood from incomplete data via the EM algorithm. Journal of the royal statistical society. Series B (methodological), pp.1-38.

and its Weka implementation[24] can determine the optimal number of clusters based on cross validation. These are the motives for our use of this particular algorithm, which is a popular example of maximum likelihood based methods, and it aims for simplification of data representation by assuming missing values and/or non-observed instances.

6.3.2 *Result 2: The Interest Groups*

Based on the tables and pie charts presented, we performed clustering over the 74 instances (stakeholders)[25] for all 29 diagnosed issues in NPRM (A1-A5), Licensing PN (B1-B9) and FNPRM (C1-C14). The clustering gave us 3 clusters of stakeholders based on mapping the answers on a numeric 1-10 rating scale[26]. The "answers" are the stakeholders' policy positions described in the comments and reply comments documents, therefore they cannot be mapped as "yes or no" answers. The mapping of the elaborative answers is done for each of the vote in each of the milestones for each of the issues. The clusters and the 29 issues diagnosed are shown in Table 6.10 and tables (we summarise the issues here for the reader, previously shown in figures and charts per milestones).

What is their group identity? Let us interpret the Table 6.10 from the market perspective.

Cluster 1 contains licensed carriers and equipment vendors. They are grouped together in the algorithm because they share the same interests in the CBRS band. The interests that the big mobile carriers have in the CBRS band is first, the straightforward one - the need for more spectrum. But the way they will access the CBRS spectrum is what will fully unlock the potential of gaining revenue from spectrum. In this sense, they are interested in two-tier model, ASA/LSA which as already noted is a form of spectrum leasing - it is based on exclusivity and full protection, essentially it is not different from traditional exclusive licensing model where sharing is not involved. As with ASA/LSA model, carriers get spectrum when incumbent is not using it, they are willing to put up with certain degree of unavailability of that spectrum, because when they get it, it will be nationwide license, for large area and for a very long term, also renewable and this satisfies their level of QoS guarantee needs. The Qualcomm, chip equipment provider for mobile carriers, together with the NSN, equipment manufacturer introduced the ASA model to the EU regulation, back in 2012. The LSA model then developed out of this model within EU regulation, but it is in essence the same two-tier model that the Qualcomm and NSN proposed. Within CBRS proceeding, from

[24]Hall, M., Frank, E., Holmes, G., Pfahringer, B., Reutemann, P. and Witten, I.H., 2009. The WEKA data mining software: an update. ACM SIGKDD explorations newsletter, 11(1), pp.10-18.

[25]For accuracy, we removed the stakeholders who had only 1 vote in the entire record, i.e. clustering was performed on 58 instances.

[26]For example, in an issue with four different policy positions, two strictly opposite ones would be coded with 1 and 10, and the other two would take intermediate values depending on how close to the conflicting positions they are, e.g. 3 and 7.

Table 6.10: Stakeholders clusters (* probability of belonging to a different cluster non-negligible)

No.	Cluster 1	Cluster 2	Cluster 3
1	AT&T	WISPA	UTC
2	T-Mobile	Google	API
3	Ericsson	Microsoft	SIA
4	Verizon	PISC	BliNQ
5	Qualcomm	Federated Wireless	Exelon
6	CTIA	Motorola Solutions	Neptuno Networks
7	Alcatel-Lucent	Spectrum Bridge	WiMAX Forum
8	NSN	InterDigital	SIEMENS Industry
9	PCIA	OTI/PK	XCEL Energy Services
10	4G Americas	Motorola Mobility	Cantor Telecom*
11	Mobile Future	WiFi Alliance	CEA
12	TIA*		TIA*
13		Shared Spectrum	HKT Limited
14		WinnForum	ITI Council
15		Sony Electronics	Cambium Networks
16		DSA*	DSA*
17			Cloud Alliance
18			FWCC
19			Great River Energy
20			KanOkla
21			NCTA
22			Oncor
23			Sacred WindComm.
24			Shure Inc.
25			Southern Company
26			EDISON
27			Ameren Services
28			BLOOSTON 3.5GHz Coalition
29			Iberdola
30			Keep Enterprise
31			NRECA

the very beginning they have been advocating for a two-tier model, not changing their positions even when the First R&O was about to be published.

Cluster 2 contains GAA prospectives, database providers and advocates of dynamic spectrum sharing to be managed by the sophisticated, dynamic and responsive SAS database(s). They can also be perceived as newcomers in the market.. For database providers, the CBRS band is an opportunity to showcase their solutions and advocate for their own solution for a SAS implementation. The rules about the SAS describe the SAS administrator eligibility criteria, multi-SAS environment is encouraged for the band and the very important decision of the FCC to let the SAS standardization and implementation process to the multi-stakeholder group, gathered around WinnForum - is an important point towards realisation of fully dynamic spectrum sharing. The GAA prospectives are the newcomers in the band, in the sense that the market is opening for new types of services providers, which did not have their market share so far.

Cluster 3 contains everybody else, namely the CAF (critical access facilities) prospectives, incumbents in 3650-3700 MHz band, the utility companies, CII (critical infrastructure industry) users etc. These stakeholders have a different vision for the band, not as another cellular band but as band for emergency services, industrial IoT, smart grid networks etc.

6.4 DISCUSSION (STAGE 1 AND STAGE 2): EVOLUTION OF THE ISSUES

This section combines the results of stage 1 and stage 2 to discuss the evolution of opinions, which provides a way to describe the issues previously summarised in stage 1 and build the context for what the rules mean for stakeholder's interest groups of stage 2. We do this by grouping the issues into five distinct topics that represent the components of a sharing framework.

6.4.1 *Access Model*

6.4.1.1 *Three tier or two-tier / transitional approach?*

The very essence of PCAST recommendations is the three-tier shared access model. With an NPRM, the FCC initiated the regulatory actions towards realizing PCAST vision and implementing the recommendations. Therefore, the three-tier model was proposed for the NPRM-established new class of service CBRS in 3.5GHz band. The stakeholders responses to the NPRM showed the first sharp division in CBRS policy around this very essential enabler of CBRS sharing.

Figures Fig. 6.4(1), 6.5(1), 6.6(1) show the evolution of opinions on this issue, throughout the milestones NPRM, Licensing PN and FNPRM and the corresponding tables and charts in the Appendix A(Table A.1, Figure A.1, Table A.6, Figure A.6, Table A.16, Figure A.16). Even though the numbers show a substantial support for the three-tier model (70%), several influential stakeholders expressed their support but only if their modifications are taken into account (e.g. See NPRM Reply Comments of AT&T and Ericsson).

These modifications revolve around the concept of separation (as in the deeply coded language) between users in the band, leaning more towards two-tier approach as more feasible for immediate release of the band under the reasons of complexity of the framework. The other stakeholders supporting the three-tier are mostly future GAA users, dynamic spectrum sharing database advocates and the utility companies. The opposite camp strongly advocates for implementing two-tier model, cellular carriers and the equipment vendors supplying them. Among them the proposal of Verizon is an interesting one (it will showcase in the story): start with the adoption of a "transitional model", first implement the two-tier model while experimenting in the portion of the band with the three-tier. This is an impactful policy position, as it implies pushing for two-tier and the uncertain future of three-tier model considering that the ecosystem for two-tier access to the band will already be established by then.

The Licensing PN record shows exactly how impactful it was: number of three-tier supporters reducing, but number of transitional model supporters increasing (e.g. Ericsson shifts the initial position). This is due to the context in which Licensing PN was published as it is a result of diverse opinions on the record and loud voices proposing the two-tier model. The support for three-tier is still substantial, but slowly diverging from the FCC initial idea driven by the PCAST report.

The FNPRM deliverable that followed is an important one as it assumes resolution of most issues and preparing the final rules of the band, prior to issuing the First Report and Order. But the division on the premise defining the CBRS, multi-tiered access model, was sharp. The support for the two-tier increased, with the issue resulting in a tie. This result of the evolution marks the first separation point in the CBRS landscape and contributes to a series of other issues.

6.4.1.2 *The issue of PA and CAF users?*

Figures Fig. 6.4(3), 6.5(3), 6.6(6) and the corresponding tables and charts in the Appendix A(Table A.3, Figure A.3, Table A.8 , Figure A.8, Table A.21, Figure A.21) show how the commercial users took over the PA tier. This was one of the few issues where mobile carriers and prospective GAAs sided together. This is also a building block in the CBRS context that led to Licensing PN, as it showed the record opposing to critical users in the PA tier and instead having PA tier for those users who prefer the option of exclusive licensing model. In the FNPRM record, the CII users (critical infrastructure industry) who asked to be included in the definition of "critical users" by the FCC and the incumbents in the band (50MHz in 3650-3700 that is about to be added to the CBRS) proposed modifications and changes under which they would accept the rule. The FNPRM is the point on timeline when they started submitting comments more actively advocating for their positions, forming coalitions and submitting letters to defend their place in the band. In the NPRM, the proposal was for PA tier to consist out of critical use facilities (CAFs) only and the licensed carriers were not supposed in there at all. The question asked in NPRM was what is the right methodology for PA tier, though. That resulted in majority of votes advocating for broader PA tier, which was framed as adopting the open eligibility rule for PA tier - so that it consists out of diverse types of users. Some of the prospective CAFs accepted this proposal, as it meant spectrum was for them too. The developments in the Licensing PN record, had the stakeholders now commenting on the open eligibility proposal for PA tier, with which majority agreed as it still didn't mean complete exclusion from the band for the CAF users. But the comments also are influenced with the policy context in which this is happening: the proposals about spectrum proportion for PA tier and the GAA floor proposal. This is why this question ended up being framed in the FNPRM as proposal to set aside some frequencies for CAFs from the GAA pool of spectrum, namely 20 MHz which they can get through exclusive licensing model (same as the PAL). And here the stakeholders claimed that this proposal would lead to creation of a fourth tier, which would over-complicate already complex CBRS rules. At this point, the CAFs lost the battle. The major shift in positions happened, 63% expressed the support for assigning 20MHz from GAA pool for the CAFs, but the FCC declined to adopt this rule which left the CAF without their place in the band.

6.4.2 *Band Plan*

6.4.2.1 *Supplemental proposal add band?*

The PCAST report called for a creation of a multi-band framework establishing the rules of multi-tiered access model, but not being tied to one band. The FCC supplemental proposal of adding the adjacent 3650-3700 MHz under the CBRS umbrella was a first step towards making larger swaths of spectrum available under sharing models (the PCAST goal was 1000GHz superhighway).

Figures Fig. 6.4(4), 6.5(4), 6.6(3) and the corresponding tables and charts in the Appendix A(Table A.4 , Figure A.4, Table A.9, Figure A.9, Table A.18, Figure A.18) show how commercial users united again, as it would mean a 150 MHz of spectrum highway instead of initial 100 MHz. The current licensees in the 3650-3700 MHz opposed the addition, as it opens the issues of their protection under new CBRS rules. Their strong position is best reflected in the FNPRM rounds of comments and reply comments, as that is the time for advocating before the rules become final. The last voting on this issue show 70% of stakeholders against this rule proposal (21 oppose, 9 agree), but this rule is adopted.

6.4.2.2 *Proposed GAA floor of 50% in the entire band?*

Allowing the GAA use in the band was a conflicting policy issue throughout the entire process, but reserving 50% of frequencies in the band always for GAAs caused an even bigger clash. The licensed carriers expressed how uncomfortable they are with mixing something like the unlicensed use in the band where they will be operating.The FCC wanted to spur competition and innovation with this rule and properly open the door for new players in the band. Once licensed carriers saw that the framework will not exist without the GAA and they have to find ways to co-inhabit, they started arguing that the FCC should at least make sure that this percentage is not fixed and that it would have to adjust in dependence with the PA use of spectrum, basically asking to make the PA use superior over GAA.

Figures Fig. 6.4(5), 6.5(8), 6.6(5) and the corresponding tables and charts in the Appendix A(Table A.5, Figure A.5, Table A.13, Figure A.13, Table Fig.) show the evolution of opinions on this issue. In the NPRM, the FCC proposed to allow GAA use on opportunistic basis throughout the entire band (and licensed by rule, without protection guarantee) whenever the the IA and PA spectrum was free. In the Licensing PN, proposal was to reserve GAA frequencies, which is the GAA floor of 50% in the entire band. The NPRM saw the utility groups and some of the mobile carriers opposing to the presence of GAAs in the entire band who would be dynamically assigned to free frequencies by the SAS. The divide on the votes was 50-50, as the proponents of dynamic solutions in the band agreed with the proposal. The same group agreed with it in the Licensing PN as well, but this time against the louder voices of licensed carriers and their equipment vendors advocating for more of the PA fixed frequencies instead and proposing even to reject the GAA usage in the band completely. The division was still 55% vs. 45% (55% in favor of GAA reserved frequencies). The licensed carriers and the like-minded continued to advocate that the proposed floor for GAAs is too high, but this time the camp supporting the proposal got bigger. To the dynamic solutions advocates a large group of CAF-prospectives joined, and the vote was 67% this time for the proposal.

6.4.3 *Licensing Model*

6.4.3.1 *Licensing by rule?*

In the NPRM, the FCC proposed both CBRS tiers, PA and GAA, to be licensed by rule in the framework. This is the authorisation based on use, that does not include licenses like in exclusive licensing model. The NPRM record showed that the half of the stakeholders taking a policy position on this issue asked for more traditional licensed model, as seen in corresponding tables and charts in Appendix A, Table A.2, Figure A.2. These are mainly the big carriers and equipment vendors, but also some of the prospective GAA users, and their advocacy led to dropping this issue in the consecutive milestones. In our evolutionary tree, this makes it an extinct species. It partially disappeared as a consequence of the broadening PA tier changing the landscape and the prospective use of the CBRS, but also because of the strong lure of traditional licensing. Licensing by rule is the default way of licensing for citizens band radio service, but the commercial newcomers to the band were not in favour of keeping it.

6.4.3.2 *Census tracts as license areas?*

Ships are a good example of licensed by rule radio users: they do not need a license area in their operation definition. The critical users in the PA tier of CBRS did not need one either, but once the Licensing PN changed the relationships in the band by expanding the PA tier, the question of license area size became a crucial issue. In the Licensing PN, the FCC proposed the license area of census tracts. This proposal was strongly opposed throughout the framework creation, but the opposition was not unanimous on the reasons and the possible solutions. When census tracts were first presented as small, statistically well-surveyed areas, a quarter of the stakeholders expressing their policy positions were in favour of them, and a quarter (mostly the Cluster 2 newcomers) asked for even smaller ones, census blocks. The other half reported border issues and/or asked for significantly larger license areas, EAs and CMAs. In the next iteration, the support from smaller areas shifted back to census tracts, while more than a half of the stakeholders expressed border issues and/or motioned for large license areas. However, the rule on using census tracts is adopted in the FCC First report and order.

Figures Fig. 6.5(2), 6.6(2) and the corresponding tables and charts in the Appendix A(Table A.7, Figure A.7, Table A.17, Figure A.17) show the evolution of opinions on this issue. In the Licensing PN, the FCC proposed the license area of census tracts. This proposal was strongly opposed throughout the framework creation. However the rule is adopted in the FCC First report and order.

6.4.3.3 *License terms and renewability?*

Similarly to the question of census tracts, the one about license terms came into play with Licensing PN's expansion of the PA tier. The reaction of the big carriers and the equipment vendors was to ask for licenses as similar as possible to the traditional ones (up to 15 years), justifying it by the return on investment and the character of investments they would be making. This is shown in Figures Fig. 6.5(5), 6.6(8) and the corresponding tables and charts in the Appendix A (Table A.10, Figure A.10, Table A.23 , Figure A.23). Investments were an argument for large license areas as well: the argument from this cluster always comes in terms of profitability emanating from licenses large in time, space and frequency. In the Licensing PN discussion, these accounted for a half of the stakeholders issuing policy positions. The other half, mostly consisting of Cluster 2 stakeholders, was holding onto FCC's 1 year proposal (+5 consecutive year cap), with a few stakeholders proposing changes and variations: to make it less than one year, or to remove the possibility of consecutive years overall. In the sequel discussion following the FNPRM the supporters of 1 year (+multiple year cap) option remained the same in absolute numbers, but now they were just one fifth of the whole lot discussing the issue. The rest, asking for long term, traditional-like licenses were the members of Cluster 1, but now supported by the critical users from Cluster 3, hoping to retain their PA status and to keep it for a long time without the need to compete.

6.4.3.4 *Frequency assignment?*

Dynamic frequency assignment policy positions is a good way to distinguish between Clusters 1 and 2. As shown Figures Fig. 6.5(10), 6.6(4) and the corresponding tables and charts in the Appendix A(Table A.15, Figure A.15, Table A.19, Figure A.19) this question constantly kept a fifty-fifty ratio in votes and it was always the big carriers of Cluster 1 advocating for static assignment and the new players from Cluster 2 asking for a dynamic one. The constant fifty-fifty ratio throughout the proceedings, from NPRM over Licensing PN to FNPRM indicated the binary nature of the question and the irreconcilable positions of the stakeholders.

6.4.3.5 *Spectrum aggregation limit for PAL spectrum?*

In the NPRM, the critical users supposed to use PA had no need for spectrum aggregation. With the changes in the Licensing PN and preparing for the final rules, the question of just how much spectrum should a PA user be able to take under their license became an issue in the FNPRM. While the issue itself simply emerged at the very end, it had its own evolution through the evolution of the whole band, similar to other issues in this section: as the band changed from critical users in the priority access, over coexistence to the overall domination of commercial users, the issue of spectrum aggregation became a real one. As seen from corresponding tables and charts in Appendix A (Table A.27, Figure A.27)The division of opinions was obvious, as the members of Cluster 2 opted for the FCC's proposal of 30 MHz or less (20 MHz) cap, while the Cluster 1 demanded more than 40 MHz, ideally no cap at all. More spectrum for one PA user is less potential spectrum for another in terms of competition, so it both increases the maneuver space for a big carrier and reduces competition for it in an area. The initial positions of PCAST and CBRS were significantly different.

6.4.3.6 *Competitive bidding (if mutual exclusivity) and auctions as method of assignment?*

The twist in the rules of allowing broader PA tier with the open eligibility, opened the road for assigning exclusive property rights to the PAs. As a consequence, this proposal of competitive bidding to resolve mutually exclusive applications for PALs was introduced in the FNPRM. The proposal caused a major divide as critical users in particular were against competitive bidding, as they operate as utility companies or critical infrastructure industries (CII), with smart grid networks or deployments within one building. Their spectrum usage is of critical nature, but they cannot compete with the licensed carriers at the auctions. The distribution of the vote in corresponding tables and charts in Appendix A (Table A.22, Figure A.22) shows 78% stakeholders opposing this rule and they are mainly the damaged CAF tier users, but the rule is adopted.

6.4.4 *The SAS*

6.4.4.1 *Allowing GAA access to unused PAL channels?*

The FCC proposal to allow GAA users to access unused PAL channels raised the question of how should PA CBSDs be determined by the SAS that they are "in use". Figures Fig. 6.5(7), 6.6(11) and the corresponding tables and charts in Appendix A (Table A.12, Figure A.12, Table A.26, Figure A.26) show the evolution of opinions on this issue. What made the licensed carriers uncomfortable is the fact that the SAS should have the control over determining their use and assigning the GAAs even if their stations are only idling or if they are using spectrum for guard bands. Verizon argued that the guard bands are needed to protect from the interference appropriately and it is a guarantee that their operations are not endangered. Like minded stakeholders also agreed with the proposal but with the similar concerns expressed. The proponents of dynamic solutions advocated for the SAS to assign these channels to GAAs whenever it establishes that the PA CBSDs are not in actual use. In essence, the proposal in the Licensing PN record got the 67% of support, with high concerns expressed but with the licensed carriers camp strongly opposing to GAA access to their channels. In the FNPRM it the percentage of support grew to 88% with the strong concerns still being expressed, which at the end made the FCC to adopt the final rule as is, but asks for more comments on how to define the channels "in use", acknowledging that majority of stakeholders should be happy with the rules.

6.4.4.2 *SAS dynamic and responsive or more static and restrictive?*

The FCC proposal for a SAS to incorporate a dynamic spectrum database and interference mitigation techniques was met with a lot of resistance as well. Majority of opinions are expressed at the SAS-dedicated workshops that the FCC organised, where stakeholders presented their different views on SAS functionality and implementation. Figures Fig. 6.5(9), 6.6(9) and the corresponding tables and charts in Appendix A (Table A.14, Figure A.14, Table A.24, Figure A.24) show the evolution of opinions on this issue. In the Licensing PN, 53% majority was supporting the dynamic and robust SAS solution, capable of managing all three tiers and performing dynamic ad adaptive to radio environment interference protection. The comments to this issue from those opposing it range from literally "SAS envisioned like this is too novel" to questioning the complexities of its implementation. These commenters advocated for a transitional plan, in essence claiming that the FCC should implement the PA tier rapidly without the fully functional SAS as envisioned and at the same time experiment more with the three-approach and such a dynamic set of databases. Most of the concerns are about the security protocols, interference coordinations and protection from the GAAs. These concerns are reflected in the vote on the issue in FNPRM, with larger percentage of 56% opposing to FCC SAS proposal and advocating for a more restrictive and controlled, static SAS. The dynamic solution supporters even demonstrated that the SAS prototype can be built to realise the dynamics envisioned. Some of the stakeholders from both camps were cautious about the misinterpreted proposal to allow SAS to control and manage the networks directly (changing the EIRP and power levels of CBSDs), but the licensed carriers did not have anything against the SAS managing in that manner only GAA users. The SAS micro-managing the real-time operations of CBSDs in the band was never a level of control given to SAS by the FCC and was not proposed as such. The SAS will be responsible to set the maximum allowed power levels for CBSDs which will not affect operator's capability to manage its own network.The issue of a dynamic SAS caused a major clash and division, but this rule is adopted by the FCC as one of the pillars of the CBRS framework.

6.4.4.3 *Multiple SAS adiminstrators nationwide?*

This is an issue which did not see the evolution moments throughout all of the milestones, as it only became a proposal for the FNPR and an FNPRM issue. The FCC proposed to authorise multiple SAS administrators that satisfy the qualification criteria prescribed. This rule proposal aims to foster competition on the SAS market, among many CBRS markets. There was a general support of the commenters to the proposal, but division on the issue on allowing the SAS administrators to also act as PAs in the band. Some of the dynamic solution proponents thought this should not be forbidden (Google), but others claim it would cause a conflict of interest (Microsoft). Allowing multiple SAS administrators in the band from the other perspective, opens an issue of their synchronisation and coordination as they all need to have consistent and accurate information about the spectrum. In this sense FCC called for SAS administrators cooperation. Also, the FCC allowed SAS administrators to hold a PAL and be PA user and also to be a GAA user. Majority of stakeholders accepted this rule, except for one commenter who argued that the fees should be collected from GAA users, but not PAs, as shown in corresponding tables and charts in Appendix A (Table A.29, Figure A.29) This rule is consistent with the general policy of having interchangeability of the users in the band - meaning, that the PA and GAA can become either of the tiers if they chose to do so, as their devices are all the same specifications CBSDs. Concrete issue however, had stakeholders mostly agreeing (67%) with allowing multiple administrators in the band as shown in corresponding tables and charts in Appendix A (Table A.28, Figure A.28), but dynamic solutions proponents asked for this authorisation to be regional and allow more competition in that way, instead of nationwide as proposed and adopted by the FCC.

6.4.5 *Technical Specifications*

There were some topics in the milestones that have attracted attention and responses, but with all of the opinions pointing in the same direction. This is the case of technical questions, and that aligns with our proposition that filtering out the NTBRS components of issue reporting would leave us only with technical questions and dilemmas. One such topic is the question of power regulation, where all replies spoke in favour of the power level increase, with opinions differing only in the quantity and principle of the increase. Hence, it was not an issue in the way we defined it in this analysis (as it lacks conflict), and instead represent a point of convergence for the stakeholders.

Another such topic is the proposal related to reducing exclusion zones initially proposed by the NTIA[27]. The exclusion zone is an area within which CBSDs cannot operate. They are there to protect the incumbent operations in the band. Initially, the exclusion zones as proposed by the NTIA would preclude 60% of US population from the band (60km around the ground-based radar incumbents with large frequency offsets of 40-50MHz). As the band is one of a limited propagation, and therefore not suited for macro-cell deployments, NTIA argued that this can be turned into an advantage if the FCC enables the 3.5GHz band for small cell use[28]. As the FCC proposed the entity Environmental Sensing Capability (ESC) to operate in CBRS band as well, to collect the sensing data on incumbent's presence, the status of exclusion zones proposed by the NTIA was put on comments, proposing to reduce them. Some of the commenters agreed with it stating that the exclusion zones with small cell use cases in band can be reduced to less than 10km along the coastline (incumbents are mainly radars on ships), and some of them proposed that the exclusion zones need to be dynamic as it is possible through SAS and ESC interaction for the SAS to enforce exclusion zones based on the real-time radio conditions. This analysis on this issue is shown in corresponding tables and charts in Appendix A (Table A.25, Figure A.25).The licensed carriers advocated for the concept of coordination zones, which means that this would allow the incumbents and the prospective PAs to coordinate mutual agreements on operation. The way that the concept of dynamic exclusion zones works is through converting the exclusion zones into protection zones, once the ESC and the SAS entities get the approval for operation and are deployed in the band. The ESC equipment will be deployed in proximity of the exclusion zones and protection zones to detect incumbent's presence more accurately. The SAS will enforce exclusion zones dynamically, based on the conditions in the band.

6.5 stage 3: what do we now know about the cbrs band?

This section presents the ranking process in which we look for the most important separation points between the CBRS band and the traditional band. The CBRS docket is different from any other docket in US spectrum policy, as its development was a response to the calls for paradigm shift in US spectrum policy, laid out in PCAST report in 2012. A paradigm shift in spectrum policy means a separation from traditional spectrum management in both sharing and non-sharing bands. There are no clear border lines between spectrum management approaches to a sharing or a non-sharing band,

[27] 2010, US Department of Commerce, An Assessment of the Near - Term Viability of Accommodating Wireless Broadband Systems in the 1675 - 1710 MHz, 1755 - 1780 MHz, 3500 - 3650 MHz, and 4200 - 4220 MHz, 4380 - 4400 MHz Bands
`https://www.ntia.doc.gov/files/ntia/publications/fasttrackevaluation_11152010.pdf`

[28] `https://www.ntia.doc.gov/category/3550-3650-mhz`

as the same elements for building a spectrum framework are applied. The paradigm shift however, places the CBRS band in contrast to all other traditional bands and we aim to identify those separation points at this stage.

The data for this part of the analysis is consisted of both the record of issues (result 1) and the clusters of interests groups (result 2). To get to the result 3, we look at the issues which define the stakeholders' alignment with the other members of the interest group. This task is performed using attribute selection.

The third rationale gives the needed bridge from the matrix of stakeholders and issues to the general notion of the CBRS band. The results from the previous stages are still closely tied to the texts, and speak mostly about the stakeholders. However, the stakeholders actions and policy positions are triggered by the nature of the band and FCC's proposals: hence, we should be able to infer what are the most novel and revolutionary aspects of CBRS by observing the stakeholders reaction. The sharp differences between the CBRS and other bands are bound to generate sharp differences within the interests groups according to our *rationale 3*: *if an issue is divisive, it is about a novel regulatory rule proposal.*

The results of ranking will be the answer to the main research question as well. The validation of this answer will follow from the interpretation within the (NTBRS) context, the events happening at the time of writing this thesis and the nature of stakeholder philosophies, which will be visible from the representation of results. At this stage, we are moving from the domain of texts into the domain of the real CBRS world, the band itself and its nature.

6.5.1 *Ranking: from grouping to separation points*

Since we have the list of issues with policy positions and a set of stakeholders clusters, we can go back to the second rationale from the analytical construct and recall that crucial issues (according to third rationale, novel issues) polarise the debate and homogenise the clusters, reducing the chances for outlier opinions. Hence, if we rank the issues in the order they define the clusters of stakeholders, the resulting list (terminated once no novel information for clustering can be inferred from lower-information-content issues) will be the list of the crucial points of division between the stakeholders. According to the third rationale, these will also be *points of separation* between CBRS and traditional bands. This is a typical instance of attribute selection, the broad problem of pattern recognition we are using to answer our question about key issues: what issues among those which we filter out based on answer frequency are the fundamental ones, generating all others? One of algorithms devised to extract the essential features subset from a large set is the correlation-based feature subset selection (CFS), proposed and implemented in Weka[29]. This algorithm balances the

[29]Hall, M.A., 1998. Correlation-based feature subset selection for machine learning. Thesis submitted in partial fulfillment of the requirements of the degree of Doctor of Philosophy at the University of Waikato.

novelty of information contributed by a feature added to the chosen subset and its correlation with already selected features.

6.5.2 *Result 3: The Separation Points*

Here we draw a map with all the fault-lines of the proposed framework and its rule-making process to answer the main research question of the chapter. We get to see how the inhabitants behave in such a world and how stereotypical they are. The CBRS landscape where the three clusters of stakeholders live is illustrated in the spider chart in Fig. 6.7. This is the result of attribute selection we performed on the three clusters obtained in previous step and the 29 issues they were defined by.

6.6 DISCUSSION (STAGE 3): TEN SEPARATION POINTS

Before getting into the details of the ten fault lines illustrated, we note the obvious. Further you go from the center of the spider web, further you reach out of the traditional licensing comfort zone into the innovation space. The group we identified as Cluster 1 stays in the comfort zone reaching out only when they see a chance to get more spectrum. This is the umbrella incentive for their existence in the band in the first place. The other end of the spectrum is the Cluster 2, made of those who support innovation alas for their own interest. The cohort of newcomers sees innovative potential of CBRS as a playground where mammoth carriers lose their advantage and have to share the playground with them. The Cluster 3 in the middle shapes the middleground but was not initially envisioned as such. In the original idea of CBRS, they would be the most conservative users, critical users (the original PA), adjacent incumbents and the industrial players. But the inclusion of the big carriers made them look even liberal. The appearance of this spider chart validates the result on its own: it shows consistency of the interest groups in their policy positions with respect to novel ideas. The attribute selection removed highly correlated issues: the repeated issues through the milestones and the issues that are closely tied with others. It also removed issues that were not the cause of "circling the wagons", i.e. the ones that did not change the CBRS landscape. Now we proceed with the interpretation of the result, the points of separation in our context of choice, the NTBRS framework.

C1 - Innovative 3-tier access model?

As noted multiple times so far, the question of the underlying access model for CBRS was kept open by the stakeholders and the regulator from the beginning to the alleged end. It does not surprise, as the 3-tier model was sufficiently different from the existing solutions in traditional bands to encourage those with new and flexible business models while alarming those with business models relying heavily on the status quo. The original proposal of CBRS is the one representing a search for middle ground of the spectrum debates, but the evolution of it seemed to bias it towards the traditional property rights model. The mere existence of the GAA still keeps it from being "just another band" and guarantees the tension on this issue.

This and every other point of separation can be examined from the NTBRS perspective as well: now we do not ask what makes it different from the existing models, but what prevents it from fitting as a puzzle piece in a sustainable spectrum sharing model. Could a revolutionary change in technology, business, regulation or society make it slide between other pieces and click? In case of the adoption of the 3-tier model, a societal change would do the trick, coupled with the business model change. In our opinion, if the radio was a new discovery and if no economy existed around it and if this model was the first proposal of a systemic solution, it would be accepted and praised. The lack of acceptance comes from the established culture of spectrum ownership and business built on it. Technology has done its part, and the regulation, after dropping the authoritarian approach of command and control will have to wait for the stakeholder society to act.

C4 - Supplemental proposal to add 3650-3700 MHz band?

Another step away from the tradition, made in the spirit of PCAST is the proposed merger of bands at 3.5-3.7 GHz, contrary to the traditional balkanisation of spectrum. Here the resistance came from the "Cluster 3", incumbents of the adjacent band planned to be assimilated into the new model of CBRS, while the future users of CBRS spectrum were eager to have an extended playground. In the NTBRS space, in our opinion, the resistance of incumbents towards a model in which they would share their spectrum with the third tier of CBRS is a societal and regulatory problem. The regulatory issue is the one of legacy it made in dissection and *security* for the incumbents in *their* bands, while the societal failure is in contempt of sharing as a bad solution, one of loss.

C5 - Dynamic frequency assignment and GAAs throughout the band?

Dynamic frequency assignment is a step forward from both traditional non-sharing models and static sharing models. It puts the available technology to use in order to pack tightly spectrum users and leave enough space for additional users. This, of course is a disruptive move for more static-oriented users and it causes their resistance. As such, this is a societal problem of NTBRS: in our opinion, if sharing was a widely accepted norm, there would be no reason to deny the need for dynamic assignment. As it is not, and since spectrum scarcity is cited by the opposing stakeholders only when discussing the need for getting more exclusive spectrum, dynamic assignment is a nuisance for them.

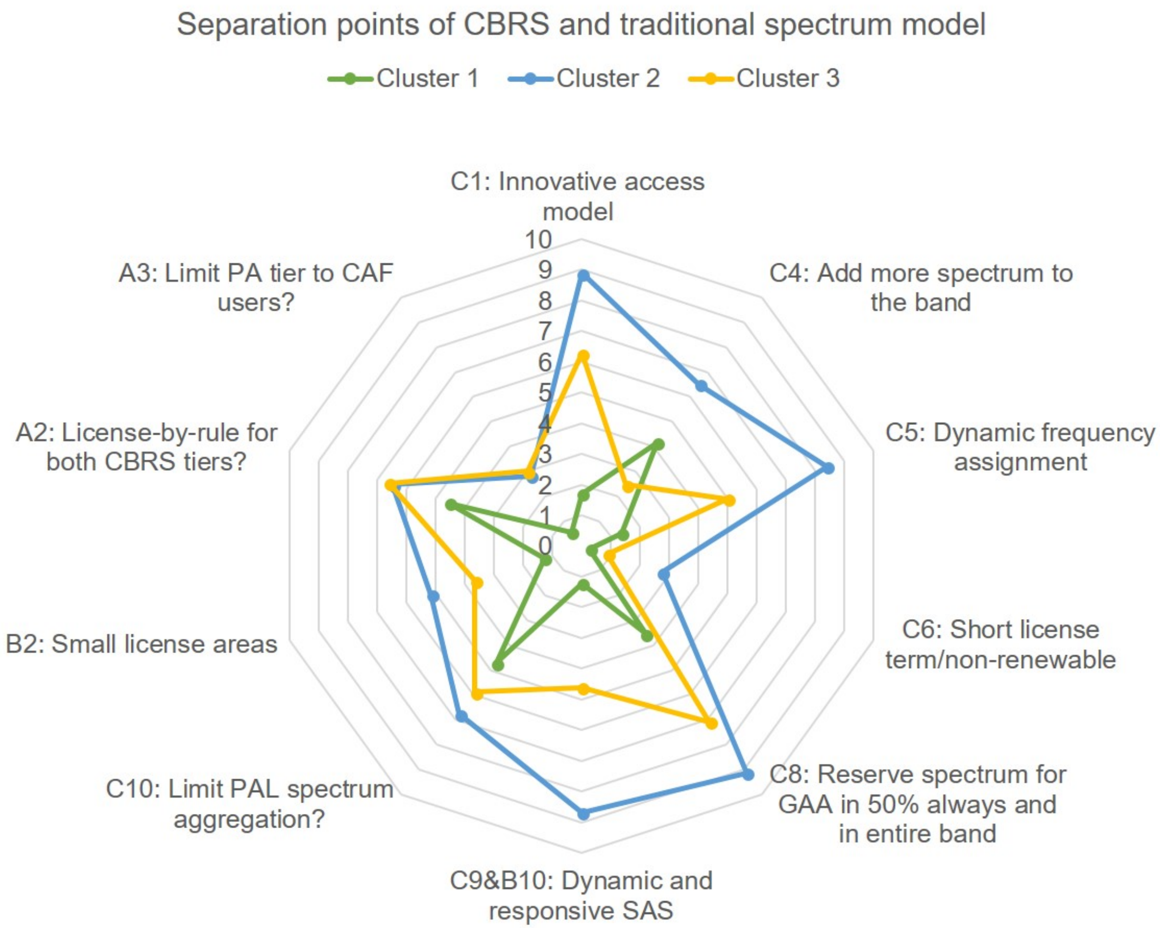

Figure 6.7: Separation points

C6 - Short license term and a non-renewable license?

Short term licenses and small licensing areas were deemed crucial for innovation: however, the inclusion of mobile operators in the PA tier shifted the attention from the innovativeness of the CBRS band to the question of revenues and profit. The deviation from traditional long-term, renewable licenses was not seen as a profitable option.

The approach in which the new band is extra food for old, traditional consumers is not a fertile ground for sharing. In the view of NTBRS, this is a failure of regulation, as it leaves the door open for reversion to old models that have proven to work for the old conditions of non-sharing. For the big carriers, there will always be a reason why to give up sharing, if that option is on the table. This again necessarily corresponds to the necessity of societal, cultural change.

C8 - Proportional assignment of GAA and PA: GAA 'floor' of 50% in entire band?

The existence of GAA users and spectrum dedicated to their use was an effort to move from tradition and incorporate multitude of users halfway between unlicensed and traditionally licensed use. In the originally planned PA tier the resistance towards guaranteed GAA spectrum share would be expressed differently from what we have seen in the proceeding once PA tier was expanded. The traditional-like users of CBRS aiming for the PA tier see an opportunity for widening their own operating spectrum at the expense of the GAA.

In the NTBRS sense, this is, as many other fault-lines here, a matter of societal perception of sharing and regulatory wisdom. A non-issue in the original idea of CBRS, the portion of GAA spectrum is an important definitional aspect of the "new" CBRS with commercial PA tier, and the regulator's responsibility in order to stay faithful to the PCAST report. On the other hand, the favouring of the PA tier by the aspiring PA users indicates lack of interest for incorporating novel GAA option in their business plans.

C9 & B10 - Dynamic and responsive SAS?

Even though the title of this section speaks of ten separation points and the spider web features ten axes, the attribute selection algorithm picked eleven issues from the CBRS proceeding. Issues B10 and C9 are the same issue, discussed in Licensing PN and then in FNPRM and as such would not provide new information if the same stakeholders delivered the same answers. However, the difference in the composition of stakeholders stating their policy positions in the two deliverables and change of opinion with some (e.g. Ericsson) made this an important attribute. On average however, little has changed: in both cases, the innovation champions advocated for a more dynamic SAS, big carriers stuck to their visions of a static database, and the third group was divided in opinions. As SAS brings the regulation down to the field and detaches it from a centralised, distant and slow decision-making mechanisms it is a firm step away from the tradition. The technological prospects of SAS allow unprecedented level of granularity and dynamic sharing; this sentence causes both delight and dread among the stakeholders community. Dynamical businesses ask for dynamical management solutions, static ones abhor it.

That is where the NTBRS space obstacle lies as well, in the business models. While the technology is there, the idea of rapid changes and adaptation is a hard limit for large systems relying on long times, large spaces and large quantities.

C10 - Limit PAL spectrum aggregation?

Large-scale aggregation reduces competition and enables monopolies for PA users, allowing them to behave in CBRS license areas the same way they would behave in traditional bands. The effort was made to make CBRS different and allow a diverse set of users. It was an attempt to keep the band open for innovation in both technical and economical sense, with new radio solutions and new business plans for shared access. The hunt for more spectrum and the ability to take the majority (if not all) of the PA spectrum in a license area is a natural one for the large carriers, one that stems from their practice elsewhere. The point in order to establish a working sharing model was originally not to have them in a position of the PA at all, and once they managed to get a place in the tier, restrict their spectrum aggregation.

In the NTBRS sense, this is a missed chance by the regulator to make a different band, but also a failure of the society to recognise the need for a playground of this sort: turning a playground into a parking lot is an effort for the present, not for the future. And of course, the inability to sustain a single experimental band is not promising much for the PCAST's plans of test cities.

B2 - Smaller license areas, census tract as the license area unit?

Never before CBRS were census tracts proposed as licensing areas. Small areas with known demographic structure, they were a significant change compared to nationwide licenses and a signal what CBRS ecosystem should be built on. When opposing census tracts, every stakeholder goes from the position of a potential PA user, the option they originally would not have at all. The debate over census tracts hence shows another important point, together with all other PA-related issues: the lack of intent to act as a GAA user.

While the question of license areas is again one of business models, where larger areas suit the large operators, we can note that in the NTBRS framework this is a question of technology as well: as we have seen (and as we will see in more detail in the next chapter), urban census tracts are deemed often too small to be both properly covered with signal and isolated from making significant interference with adjacent tracts. If we imagine a hypothetical super-directive technological solution keeping all of the radio waves emitted in one census tract within it, the opposition against the tracts loses an important argument and they become much more acceptable.

A2 - License-by-rule for both CBRS tiers?

In the move to bring together the best of both worlds, the original CBRS proposal had licensing by rule as an option to replace unlicensed and traditionally licensed users. While still being a license, the form of license by rule would be significantly less property-driven than the traditional licenses. The separation from tradition is clear, and the reaction of the stakeholders does not surprise. The bias towards more traditional licensing is one towards the sense of security.

This is where the barrier in NTBRS lies as well, the societal perception of security in spectrum use, reinforced by the regulator's traditional licensing values.

A 3 - Limit PA tier to CAF users?

We recall that CBRS started off with the PA tier reserved for critical use, which would leave most of the spectrum, most of the time, available to the GAA users. With the intervention of big carriers, they first got the chance to enter the PA tier and get the protection guarantees they are accustomed to, and in the next step they got a chance to remove the original inhabitants completely. Similarly to the effects of the supplementary spectrum in the adjacent band, this is a pragmatic question and the strategic position of future users of the band, both PA and GAAs is to remove the critical users.

In the NTBRS worldview, the whole issue is one of society and regulation, where the regulator fails to protect the idea the model was originally built on. Once the structure of PA tier was changed, the role of critical users in the band was lost as their ways of spectrum use were the reason why they made a good choice for PA in the first place. In a (stakeholder) society which could accept this model without trying to broaden the PA tier, sharing would be a norm.

6.7 RELIABILITY AND VALIDITY

Reliability in this context corresponds to the reproducibility of the study results when performed by other knowledgeable analysts using the same data and methods. Validity is the measure of truthfulness and the fit of the results in the body of knowledge and society.

Even though the extraction of stakeholders' opinions asks for the human insight on decoding of the political and strategic statements, another analyst with expertise in spectrum policy would fit the statements in the same answer boxes as we did, as they are disjunctive and crisp (not fuzzy). This makes our analysis reliable, but does not say much about validity.

Validity, according to Krippendorff may stem from its *face value* (do the results match the common sense?), *social value* (do the results contribute to a social issue discussion?) and *empirical value* (where do the results fit in the body of knowledge, existing evidence and is the structure of the analysis valid on its own?) In our case, the analysis fits the bill in all three sections. On the face value, the results are hardly surprising and from the big capitalist perspective they match reality, expectations and economic theories. The social issue of communications, connectivity and the lack of spectrum resource to enable it may be just emerging in the public discourse, but it exists for a while now, and this analysis contributes with its results. The empirical value stems from the sound analysis structure and the non-contradictory results.

In terms of the content, not omitting any of it and having a human, informed read of the documents goes in support of both sampling and semantic validity of the analysis. The validity of the internal structure of our analysis follows from the elaborations on the analytical construct.

The reality is in the end the judge of the results: if the factual evidence contradicts results, the analysis is based on a wrong interpretation of context or there could have been some errors in conducting it. The link between the texts and the real world may have been misunderstood in that case. In our case, the results of the analysis in fact predict the current state of the CBRS rulemaking process (Chapter 7, Section 7.3).

The intermediate results were subject to validation as well: the separation of issues from non-issues is a matter of statistics, and the clustering was compared against the known nature of the stakeholders. This internal validation ensured meaningful transition towards the final results and validated the original proceeding data and intermediate results for re-use in new potential content analyses for other researchers.

6.8 chapter summary

By identifying separation points between the CBRS and traditional bands and between the stakeholders, we drew a map of the CBRS landscape showing where the problems are, what is causing them and what might solve them. Contribution to the body of knowledge lies within the analysis results: issues, interests groups and the separation points.

In terms of methodology, contribution is made with introducing the content analysis to spectrum sharing policy, a successful application of our NTBRS conceptual framework as the context for content analysis, and in order to obtain meaningful results, we limited the use of AI, performed no document sampling and used innovative ways of validating the analysis.

Through the process we observe both, the interaction of stakeholders amongst themselves and the role of the regulator. The regulator is not a mere narrator in the drama, but takes the role of the balance maker, the judge who seeks middle ground. We have seen the middle ground being sought (and found) in most of the cases, but not on the ground itself. The license areas stood the test of the clashes and that is why we put more attention to it in the next chapter.

Citizens Will Pay for the Walls

"A flat is a place where people live, not a building block of a place where people live."

Audio version at: `https://www.youtube.com/watch?v=lF8-kXJKokI`

7 THE CBRS GEOGRAPHIC LICENSING: AN INCENTIVE TOOL

The research process at this stage gave us an insight into a particular licensing issue in the CBRS model. The regulators have an incentive tool in their hands when designing a spectrum licensing scheme of a sharing model. An effective licensing framework is a defining factor of a sustainable spectrum sharing framework: it shapes the incentives for future spectrum users and their motivations to share. That in turn makes sharing framework successful and feasible in practice. This chapter deals with the question of licensing areas in the CBRS band in which census tracts are the spatial units of allocation. This is the only issue, as per analysis in Chapter 6, for which the regulator did not reach the middle-ground solution and balance in a policy design.

We investigate the issues with the licensing framework configured on census tracts licensing units in Sections 7.1 and 7.2 and the ways to bring balance into it in Section 7.4, by aggregating census tracts to increase their usability while retaining small licensing areas available to all market players. In parallel, in Section 7.3, we tell the story of the regulatory developments and the U-turn the regulator made with the change of the political climate and the effect of petitions for reconsideration coming from cellular carriers.

7.1 PROLOGUE

Despite being the basic unit on which the licensing framework for 3.5 GHz band is based, the impact of census tracts on the effectiveness of the framework has not been analysed in detail. A *license* to use spectrum is granted with the purpose of avoiding harmful interference that the licensee may experience from the neighboring spectrum users. Therefore to efficiently manage the spectrum use, spectral and geographical neighbors have to be issued with compatible licenses. For the 3.5 GHz band, the spectrum users belong to a new class of services called Citizens Broadband Radio Service (CBRS), established by the FCC in order to promote innovative sharing for 3.5 GHz band. The *rights to transmit* for CBRS users will define the area of operation, the frequencies, and the power levels of operation. One license for CBRS users will be issued per census tract. Therefore to limit the risk of interference to neighbouring census tracts, CBRS nodes cannot be deployed too close to the boundary of the census tracts. More specifically, if two different CBRS networks are operating in two adjacent census tracts, the nodes of these networks can only be deployed within the *set-back distance* from the border of the census tract when both operators are assigned the same channel by the SAS. The distance is determined by the propagation characteristics of the band and FCC technical rules on CBRS operation[1]. As illustrated in Fig.7.1, under these conditions, the existence of a grey space area where CBRS networks cannot be deployed points to the problem of *spectrum waste over the area*, which we address in this chapter.

The content analysis of the CBRS proceeding (previous chapter) gave us the insight into the issues that the stakeholders had with the framework rules. Recall that the FCC's initial proposal in the NPRM to base the licensing scheme on census tracts was challenged by different suggestions to replace census tracts and in general oppositions to this rule. Every milestone reached represented a new regulatory deliverable and with each deliverable the FCC aimed to adopt middle ground solution, consider different options so that the majority of the stakeholders is pleased with the rules. With the census tracts rule however it was different. It was the only rule that was not changed from its initial proposal through the extensive discussions and to the final rules documents.

For some of the stakeholders, once they understood how small census tracts are, border issues were the default concern expressed. For others, different kinds of areas were more appropriate to propose as licensing units (EAs, CMAs, census blocks). Google Inc. has raised the problem of census tracts[2] and carried out a fairly simplified geometry analysis of the census tract area boundaries in which they are represented as equivalent circular areas. Within these circles, the set-back area in which no CBRS devices can be deployed was shown to be substantial. In the same filing, other stakeholders expressed their support for the Commission's proposal on census tracts. The arguments in favour included: (1) population characteristics of census tracts will give operators an option to plan their network deployments to target certain groups of customers for the service they aim to provide in that area and (2) the official census database could be incorporated into SAS to more effectively support the accuracy of spectrum usage information, i.e. geographic data about spectrum users.

The analysis that follows is done for the First Report and Order which defined the final rules for CBRS. As we are analysing the PAL framework, description of the relevant rules is as they were defined at the time.

[1] In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz, GN Docket No. 12-354, *Further Notice of Proposed Rulemaking*, April 2014.

[2] Stakeholders filings to the Commission are available at ECFS home page: `http://apps.fcc.gov/ecfs/`

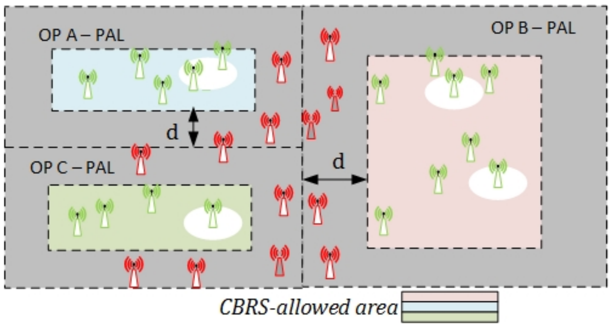

Figure 7.1: Adjacent census tracts allocated to different operators: the set-back distance and the sterile, grey space area in which the red nodes cannot be used.

7.1.1 *The Rules of the Licensing Model*

PA users need to be issued with a license to access spectrum through a geographic licensing scheme - to operate within the boundaries of one census tract area. The U.S. is divided into 74,000 census tracts, whose boundaries follow political (e.g., subdivision of counties) or geographic boundaries like rivers and roads. They are constructed to encompass a population of 2,000-4,000 on average.

A PA network operator will get the license to operate within one census tract in one 10 MHz channel. The license duration is 3 years and is non-renewable. However, aggregation of spectrum is allowed in all three dimensions (space, frequency and time). Spatially, one PA user is allowed to aggregate an unlimited number of census tract areas in order to serve more users. In frequency, a maximum of four 10 MHz channels within one census tract area can be aggregated. In time, PA license (PAL) applicants can apply for 2 consecutive license terms within the first applicant window, gaining in such way the license for 6 years. With respect to the band plan for 3.5GHz and portioning of frequencies between PA and GAA users, the relevant rule for the PAL frequencies says that PA users are to be accommodate in 70MHz of the band. This rule means that up to 7 PALs can be issued per census tract.

The size of the census tracts varies, from areas less than a square mile in highly dense urban regions, to 85,000 square miles in less inhabited rural regions (Alaska). They often intersect roads, strategic touristic attractions or institutions of high commercial interest. Their intersection combined with the technical rules for a licensed operation means that an operator may have to acquire several adjacent census tracts licenses to deploy a small cell network and serve one particular building. On the other hand, when census tracts are too large, spectrum is wasted per area because of exclusivity of only one PAL operating in that tract per one 10MHz chunk. Imagine one large census tract in a rural area through which the oil pipeline infrastructure is laid out. An industrial IoT operator (IIoT) acquires one PAL for that census tract and uses the allotted 10MHz for sensor networks highly localised on the pipeline. That leaves the rest of the area of that census tract permanently locked out of that 10MHz chunk.

GAA users do not need to get a license as they access spectrum opportunistically, similarly to an unlicensed mode of operation but in the CBRS framework they are *licensed-by-rule*. This means that the SAS assigns GAA users dynamically based on the demand, whenever and wherever spectrum is free from PA use. It also means that GAA devices have to be FCC technically certified (ability to tune to given frequencies or having embedded sensing capabilities in the device).

Despite the fixed bandwidth that the SAS will assign to PA users (multiple of 10MHz), according to the demand and interference conditions SAS may move them to other 10 MHz spectrum chunks, if needed. The GAA users SAS will allocate from the pool of frequencies instead of fixed channel chunks, i.e. any frequency free from PA use in the portion of 150 MHz, where interference constraints are satisfied. The dynamic assignments of 10MHz chunks to PAs and free frequencies from GAA pool of 150MHz, performed by a SAS system will follow *the demand and supply* principle whilst providing assurance that some level of assignment convention is met. The directive on more efficient spectrum use also means that spectrum is assigned contiguously and continuously[3]. For this reason, to assure fairness among users in the framework - GAA users are allowed in the entire band of 150 MHz as long as incumbent and PA users tiers are not utilising the specific channels.

While the GAA users do not need licenses, since they get authorized and allocated by the SAS once they register, the adoption of census tracts as the basis of the CBRS licensing scheme has implications on them. This is because the rules of operation adopt the same boundary limits for all CBSDs in the band, which means that neither PA nor GAA users can deploy a CBSD in the the grey space strip area as shown in Fig.7.1, in order to reduce the effect of interference leakage into adjacent census tracts.

Recall from the Chapter 2 the SAS is in charge of PA and GAA assignments and authorization, coordination and management of interference due to tier-interactions. The types of interference that may occur in tier interactions are: (1) *co-channel interference* (from PA and GAA to IA, between two adjacent PA users, between nearby GAAs, between PA and GAA users) and (2) *adjacent channel interference* (from PA and GAA to IA, between PA users within a license area, between PA and GAA users and between nearby GAAs).

Finally, CBRS devices (CBSDs) are divided into two groups, group A is small cell indoor/outdoor low power use and group B is point-to-point use (higher power devices)[4] Technical parameters around CBSD specifications can be found in R&O and 2nd FNPRM and we later summarise the specific parameters used in our study in Table 7.1.

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[3] Initially, FCC proposed frequency assignment for GAA users of minimum 50 percent of the 150 MHz to be reserved for them in any census tract. After commenters questioned the proportional approach as a potential cause of uncertainty in the marketplace, FCC revised the proposal and concluded that a maximum of 70 MHz can be reserved for PALs in any given license area. This means that GAA users may access all of 150 MHz in areas where spectrum is free (no PALs issued or in use) or up to 80 MHz where all PALs are in use.

[4] All CBSDs are required to register with a SAS and provide their location, antenna height above the ground, authorization status they request for (PA or GAA), FCC ID number, serial number of the device. Optionally, CBSDs should report on their sensing capabilities.

7.2 THE LICENSE FLATLAND: CENSUS TRACTS STUDY

In this section, we describe the study conducted and the approach to the problem. First, we introduce the selection criteria for the census tract areas. Methods of collecting and analysing data for the study are described in brief, followed by the propagation analysis and the method for computing the *CBRS-allowed area*, i.e. the portion of the area of a census tract in which CBSD deployment is allowed. To evaluate census tracts-based licensing scheme, we introduce two efficiency metrics, which take into account two main census tracts characteristics: area and their population.

7.2.1 *Census tracts datasets*

The traffic profile of metropolitan areas (particularly highly dense, urban areas) consists mostly of indoor residential and commercial traffic, but also outdoor WiFi traffic. The rules on technical operations in 3.5GHz band describe the PA and GAA spectrum usage corresponding to such traffic profiles, with the small cell deployments for indoor and outdoor categories of CBSDs. Based on their strategic importance and census statistics data, we selected 3 sample cities. The subjects of our study are: (1) New York City (Manhattan Borough), NY, (2) Washington, DC and (3) San Francisco, CA.

The area of Manhattan, as an example of highly dense and urban area, is divided into 288 very small census tracts, with an extremely high population density of 69,467 people per square mile. The population density in urban area profiles of San Francisco and Washington DC is much lower (17,179 and 9,856 population per square mile, respectively), but census tracts areas are still small.

The data for this study comes from the official U.S. census databases[5]. Census tracts are presented in the form of cartographic boundary files, given in .kml and .shp format[6]. To apply Cartesian geometry which is required by our study, we used the UTM (Universal Transverse Mercator) projection maps to convert geodetic coordinates of census tracts to Cartesian friendly, UTM coordinates (WGS84).

7.2.2 *Propagation Analysis*

Although cellular companies keep moving the goalposts (nowadays arguing that even mmWave is good for exclusive, licensed and commercial mobile broadband), being above the 3 GHz threshold up to which mobile cellular spectrum usage is ideal, the 3.5 GHz[7] band is *not ideal* for exclusive, licensed and commercial mobile broadband usage. The core advantage of the band is a huge potential for geographic sharing.

[5] `http://www.census.gov/geo/maps-data/index.html`

[6] We used .kml files, which are based on WGS84 geodetic system. World Geodetic system 1984 is the current geodetic system being used by GPS and U.S. DoD to satisfy mapping, charting and geodetic requirements. It is geocentric and globally consistent within 1m.

[7] Refering to the 3.5GHz band means the 150 MHz of spectrum between 3550-3700 MHz.

Table 7.1: Propagation Analysis - parameters

Deployment	Building Loss	Path Loss	Set-back
Outdoor	-	110 dB	2.1 km
Indoor residential	10 dB (wood)	100 dB	663 m
Indoor commercial	20 dB (metal)	90 dB	210 m

Having low powered deployments with the limited propagation range of the band will allow more users to operate in closer proximity[8].

Geographic-based licensing in this band is on the level of a census tract. Therefore, the power limits on a license boundary are proposed by the FCC in the rules for technical operation in 3.5GHz[9]. The rules specify the conditions in which neighboring CBRS deployments should operate to reduce the risk of interference due to tier-interactions.

Anywhere along PA service area boundaries between different CBRS users, a signal strength level limit of -80 dBm, measured by a 0 dBi isotropic antenna in a 10 MHz bandwidth is proposed. The path loss amount required to meet the boundary limit is the difference of: allowed EIRP (30 dBm/10MHz), the boundary limit and building loss where existing, depending on the type of deployments. The distance, calculated from path loss free space model formula which is also conservative, for frequency of 3.6GHz (the frequency range is 3550-3700 MHz) and antenna gains of 0 dBi is the required set-back distance under different building losses. We summarise in Table 7.1 the path loss for different cases and the corresponding set-back distances.

In the following section, we use this distance to set the constraint on a boundary of the license area in order to compute the portion of the area that would be off-limits to CBSDs deployments, i.e. area in which CBSDs cannot meet the adopted boundary signal strength limit. As per Table 7.1, CBSD deployments considered are indoor residential and indoor commercial and we used full-power CBSDs, Category A.

7.2.3 *Computing the CBRS-allowed area*

Census tracts polygons are not necessarily *convex*, as they are irregular in shape and in size. In general, they are laid out as sets of multiple polygons, each of them given as a set of points in the geodetic coordinate system[10].

[8]The limited propagation of 3.5 GHz needs a technology that requires less range than macrocell networks to meet users demand. Propagation characteristics of 3.5 GHz make the signal decay faster, which is why low-powered and dense small cell deployments empower this band. Small cells bring higher spatial and spectral reuse with its applications, as their low-power operation reduces the risk of interference in geography and spectrally which results in increased frequency reuse and network capacity. In addition, signal propagation of the band still allows flexible topologies, appropriate for non-line-of-site use.

[9]In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz, GN Docket No. 12-354, *Report and Order and Second Notice of Proposed Rulemaking*, April 2015.

[10]To obtain the list of points, coordinates conversion is applied so that the boundary constraint in optimisation model could be set for Euclidan distance (distance between geodetic coordinates is Haversine distance).

The problem of computing the *CBRS-allowed area* is formulated as a collection of quadratic programming problems with quadratic constraints. The assumption underlying the model is that the adjacent census tracts are allocated to different operators. This case can be interpreted as a worst case scenario, but extremely important one to look at since one of the core ideas of 3.5GHz framework is to allow operators to operate locally. For each of the original polygons we compute the largest polygon (if it exists) whose distance from the boundary of the original one is at least the set-back distance determined by propagation analysis, based on FCC technical requirements for CBRS devices.

Let us denote by $\{P_1, ..., P_N\}$ the set of points in UTM that describe a polygon. For each point P_i, we determine a point P_i^* such that the distance between P_i and P_i^* is minimized, whilst a minimum distance d (which is the set-back distance) between P_i^* and every $P_j \in \{P_1, P_2 ..., P_N\}$ is guaranteed, as formulated in (7.1). The set of points $\{P_1^*, P_2^*, ..., P_N^*\}$ defines the new polygon.

$$\begin{aligned} \min_{P_i^*} \quad & (P_i^* - P_i)^2 \\ \text{s.t.} \quad & (P_i^* - P_j)^2 \geq d^2, \forall j \in \{1, ..., N\}. \end{aligned} \tag{7.1}$$

It is important to note that in case the length of the segments that define the original polygon is greater than $2 \times d$, the solution to (7.1) could include points in boundary of the original polygon. To avoid this problem, we 'densify' the original polygon by adding additional points any time the length of a segment is larger than d. This also improves accuracy in the proximity of corners.

7.2.4 *Metrics*

Here, we introduce two efficiency metrics to evaluate the census tract-based licensing. They are selected so that they encompass the main characteristics of census tracts: their boundary and their population. The area of each census tract polygon and the CBRS-allowed area[11] are computed in order to evaluate the licensing scheme through the efficiency metrics of *Area Loss Percentage* and *Population of Census Tract with Access to Spectrum*. The area of each polygon is computed as the area of an irregular polygon with known coordinates, based on Green's theorem.

The ALP metric, as defined in (7.2) takes into account the ratio between the CBRS-allowed area, denoted as A_{CBRS}, and the area of the original census tract polygon, denoted as A_{CT}. Under the propagation analysis applied, ALP gives the percentage of the area which cannot be used under technical rules for sharing in 3.5 GHz band.

$$\text{ALP} = 1 - \frac{A_{CBRS}}{A_{CT}}, 0 < \text{ALP} \leqslant 1. \tag{7.2}$$

[11] As noted in 7.2.3, CBRS-allowed area defines the region where CBRS nodes can be deployed, under the rules on boundary signal strength limits adopted by FCC for CBRS operations.

To account for the basic characteristic of census tracts, i.e. their population - we introduce the metric PCTAS, defined in (7.3) as the percentage of the area of a census tract in which spectrum is not wasted, weighted by the population count P of the census tract.

$$\text{PCTAS} = (1 - \text{ALP}) \times P. \tag{7.3}$$

Under the propagation analysis applied and under the assumption of uniformly distributed population, PCTAS gives the population in census tract that can consume network capacity under the 3.5GHz spectrum sharing rules in the cities selected for the study.

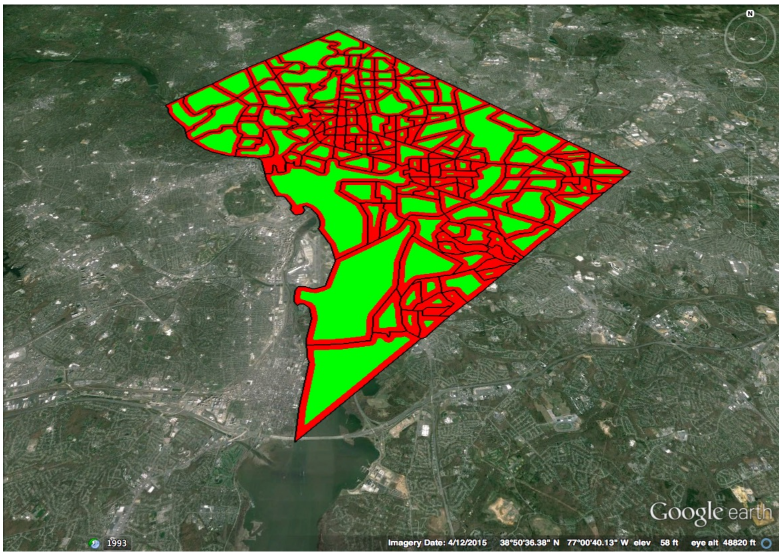
7.2.5 *Results and Discussion*

The results of our analysis are presented in Fig. 7.2, Fig. 7.3 and Fig. 7.4. To give a visual insight into the problem, Fig.7.2a (210m set-back distance) and Fig.7.2b (663m set-back distance) show the results of the area study for Washington DC. Green areas correspond to the portion of census tracts where CBRS deployment is allowed. Red areas correspond to areas off-limits to CBRS deployment. Compared to Manhattan and San Francisco, Washington DC results show a good outcome in terms of spectrum waste over the area for Washington. In fact, in Case I, the red areas cover almost entirely Manhattan and 35% of San Francisco. Only 18% of census tracts in Manhattan could accommodate CBRS deployments to satisfy the boundary constraint on a minimum distance dictated by propagation analysis (i.e., the best propagation conditions case). The impact of 663m set-back distance is severe in all three cities. As seen on Fig.7.2b, only 9 tracts, out of 179 tracts of the District of Columbia - will be available to accommodate CBRS deployments under these conditions. For 2.1km set-back distance, no census tract will be available for use in all the considered cities.

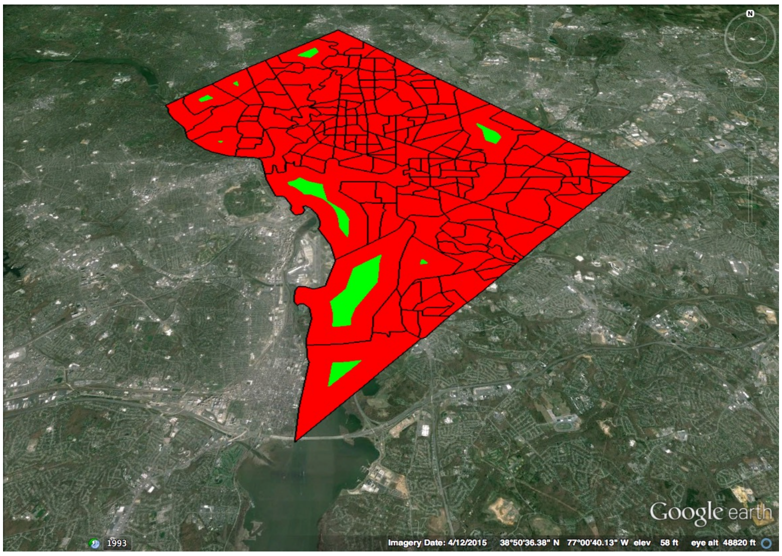
If we look at the cumulative distribution function (CDF) for the two efficiency metrics described in Section 7.2.4, we can get an insight into spectrum utilisation for the cities analyzed[12]. In the Case I, as shown in Fig.7.3a, 82% of Manhattan census tracts will not be available for CBRS deployment. For the rest of the Manhattan areas, where deployment is possible, the area that is available for deployment is limited. For example, the probability that ALP is less than 50% is 0.0035. It means that even in the case the boundary limit can be satisfied, the potential for spectrum sharing could hardly be unlocked. In Case I, San Francisco area will be unavailable for deployments in about 35% of census tracts, but the probability that ALP is less than 50% is still very small, namely 0.025. In the second case of a larger set-back distance, the Fig.7.3b shows that Manhattan area will not be available for deployments at all, and only 3-4% of Washington DC and San Francisco census tracts could be used as license areas.

We now look at the unavailability of spectrum for network capacity consumers within census tract boundaries. Fig.7.4 shows the CDF of PCTAS for 210m and 663m

[12] CDF is chosen for illustration purposes, not to make statistical conclusions.

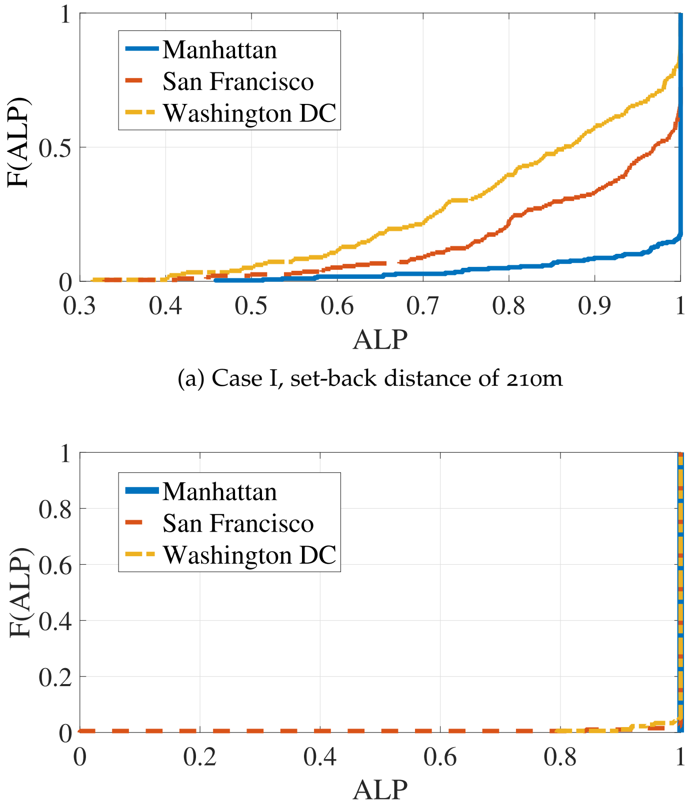


(a) Case I, set-back distance of 210m



(b) Case II, set-back distance of 663m

Figure 7.2: Washington DC area



(a) Case I, set-back distance of 210m

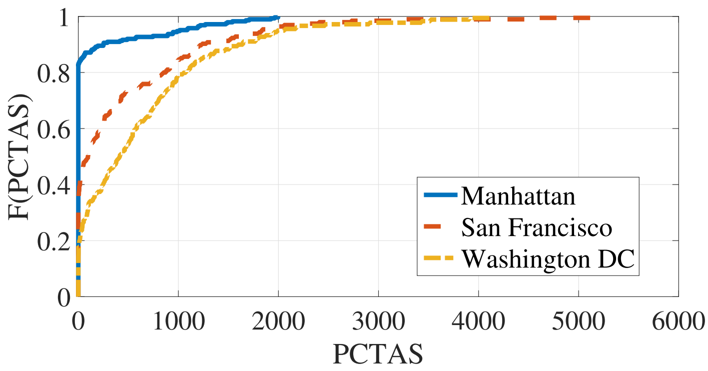
(b) Case II, set-back distance of 663m

Figure 7.3: CDF of ALP - Area Loss Percentage

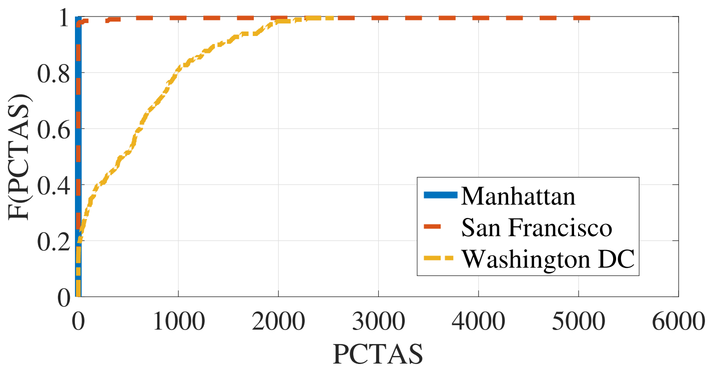
cases of propagation conditions. In the Case I, Fig.7.4a, we can see that the probability that no one in Manhattan can consume the network service is 82%. Further, it is certain that less than half of the average number of people per census tract in Manhattan (5500) can be served. Also, with probability 1, less than three quarters of the average number of people per census tract (4087) in San Francisco will be served. Finally, in Washington DC the probability that less than average number of people per census tract (3360) will have a network service is 0.977. In Washington tracts with size of the population larger than 4000 people per tract, no one will take advantage of spectrum use. In the Case II, Fig.7.4b, no one in Manhattan can be served, almost no one in San Francisco and only less than 2000 people per census tract in Washington DC can consume network capacity.

The main conclusion from the detailed analysis of census tracts is that they cannot serve as the foundation of a licensing framework on their own (without an aggregation mechanism). The FCC rightly recognizes that smaller license areas provide the potential for unlocking efficient sharing of spectrum in 3.5GHz band using small cell deployments. But as our results have shown, even under propagation conditions that are favorable, many unit license areas are hardly usable in localised service scenario described and that potential is not unlocked.

One of the reasons why the *size and the shape of the license area seriously affect the spectrum utilisation* in a geographic based licensing scheme is the following: if the



(a) Case I, set-back distance of 210m



(b) Case II, set-back distance of 663m

Figure 7.4: CDF of PCTAS - Population of Census Tract with Access to Spectrum

license boundary is varied linearly, then the size of the area within the boundary is changing faster. This leads to conclusion that with the larger census tracts, the set-back distance would not cause such a high waste of spectrum over the area and the ratio between the license boundary and the area would have less of an impact. The other reason is a conflicting one. The licensing rules for 3.5GHz impose one census tract license per one operator in one 10MHz channel, regardless if the operator wants to serve a single building or an entire area which leaves large census tracts inefficiently used. For example, the New York Public Library is located on the corner of West 42nd St. and 5th Avenue in the census tract 84, at the intersection point of 84, 82, 94, 96. It is not a tall building Fig.7.5(a)[13] and is neighboring a park on its western side. Fig.7.5(b) shows the minimal aggregation needed to serve the 130x80 meters building in the case of most favorable propagation conditions and the set-back distance of 210m (689ft). The necessity for the aggregation of 82, 84, 94, 96 was obvious but the 210m circle around the northwest corner of the library building shows that if census tracts 113 and 119 are not included in the aggregation, the grey space area of the aggregation adjacent to these two tracts would partially cover the library and preclude parts of the building from spectrum. Situation is potentially even worse as Bryant Park is an outdoor radio environment and may ask for larger set back distances on the western side of the library (possibly even including census tract 109). A hypothetical company

[13] Image credit: `https://www.technobuffalo.com/2013/07/16/nyc-wifi-hotspots-parks/`

(a) (b)

Figure 7.5: (a) NY Public Library, 5th Avenue and (b) CTs needed to serve the library

specialising in library Internet services would hence have to acquire 6 PALs in 6 license areas (census tracts) to serve a single building which is not even that big.

7.3 THE EPILOGUE WE GOT: "LEGACY WINS"

Getting the licensing framework right is essential. The landscape in spectrum management has changed, in that it is accepted that some form of spectrum sharing will be part of the future. However it is still an open question as to which approaches will succeed. The First Report and Order which framed the final rules of CBRS was published in April 2015, but this did not conclude CBRS framework development. The Epilogue of the story is presented here and follows the timeline in Fig. 7.6.

7.3.1 *Protection Contours*

The FCC issued an update in May 2016 Order on Reconsideration and Second Report and Order, a revision of the framework[14] which confirmed our opinion that census tracts would not deliver on exactly what is needed. We discuss here the changes proposed as part of the new rules for 3.5GHz, the changes related to the geographic licensing scheme of the PAL framework. In this deliverable, the FCC discusses the problem of determining when are the PAL frequencies in actual use, taking on board the comments of stakeholders regarding their issues with the PAL framework[15]. As many commentators proposed the engineering-based methodology for determining the PAL frequencies "in use", the FCC agreed with that and consequently adopted to allow PAL operators to report their protection contours to the SAS (truthfully) and

[14] In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz, GN Docket No. 12-354, *Order on Reconsideration and Second Further Notice of Proposed Rulemaking*, May 2016.
Available at: http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0502/FCC-16-55A1.pdf

[15] Order on Reconsideration and Second Report and Order, pp.46-50, available at:
http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0502/FCC-16-55A1.pdf

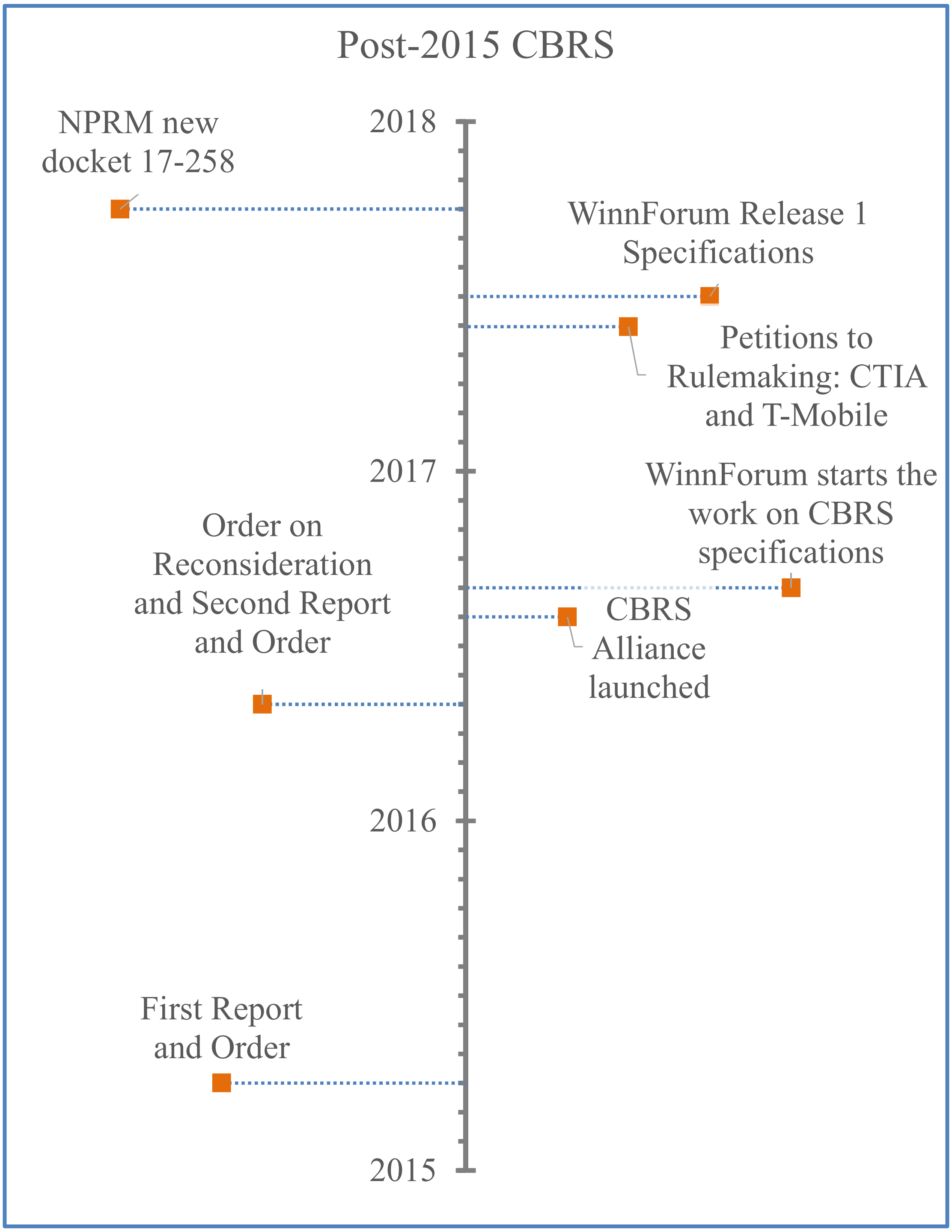


Figure 7.6: Timeline of post-2015 CBRS development

also allowed the SAS to enforce the default protection contour[16] around each CBSD as mechanisms of interference protection. This two-step mechanism is to be enforced by the SAS according to technical assumptions defined throughout the rules of the framework. The main new decisions regarding the PAL framework are:

1. The census tracts remain at the core of the licensing framework - licenses will be assigned for the census tract area which is now called a PAL *License Area*.

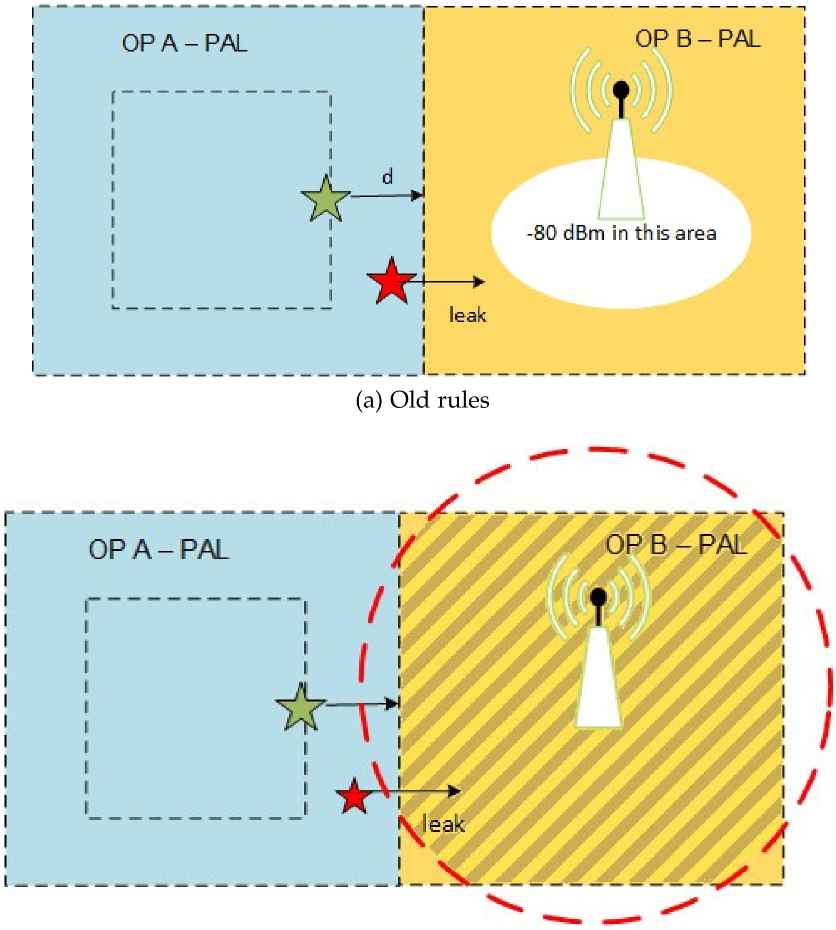
2. However, the -80 dBm signal level limit will no longer be enforced along the boundaries between the service areas of different CBRS users as seen in Fig.7.7(a), but along the contour of the PAL *Protection Area*, which will be determined by either: (1) the default protection contour (enforced by the SAS) around each deployed CBSD, based on a signal strength of -96 dBm in 10 MHz (LTE reference sensitivity); or (2) a self-reported protection contour smaller than the default protection contour. The PAL Protection Area must be within the PAL's service area.

3. A new rule adopts the light-touch leasing framework for the PAL's secondary market. The goal here was to avoid prolonging the leasing process and use the momentum of CBRS stakeholders interests to design the streamlined framework for leasing. Due to the fact that the licensing areas are very small and that there are so many of them, and the fact that the CBRS ecosystem is supposed to be filled with many diverse services and applications - the FCC expects to see a very vibrant secondary market with many thousands of leases[17].

The introduction of a PAL Protection Area based on network deployment addresses some of the limitations of the original rules, but does not impact the analysis presented in the chapter, which relates to spectrum utilization in highly dense urban areas. In fact, even assuming a single CBSD device deployed at the centroid of each census tract and maximum building loss (simplest possible network deployment with favorable propagation), the adoption of the default Protection Area does not significantly change the boundaries between adjacent PALs, as seen in Fig.7.7(b). Under the previous rules, the CBSD deployed in the centroid of a census tract OP B-PAL would not be impacted by the neighboring use outside of -80dBm strip around the base station (dictated by the path loss). Under the new rules, the protection area around the CBSD is so large that it leaks into adjacent tract. This means that if you intersect the previous service area (i.e. census tract) and the circle around the CBSD (default protection contour), what is left for deployment is the strip pattern area, which is essentially the initial census tract minus the corners. In particular, under these conditions, the percentage

[16]The default protection contour will be defined and modeled by the SAS as a -96 dBm/10 MHz cont our around each CBSD operating on a Priority Access basis . If the contours modeled around each individual CBSD overlap, the SAS will combine them into a single contour boundary. 421 The precise shape of the contour will be modeled by the SAS using the characteristics of CBSDs provide d pursuant to sections 96.41, 96.43, and 96.45 of the Commission's rules and commonly applied technical assumptions as determined during the SAS Approval Process. 422

[17]`http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0502/FCC-16-55A1.pdfpp. 58-62`



(a) Old rules

(b) Temporary change of the rules

Figure 7.7: The effect of temporary rule change in 2016

of census tracts for which the default Protection Area covers entirely the census tract is 99%, 97% and 92% for Manhattan, San Francisco and DC respectively.

The PAL operators are expected to submit their network deployment information to the SAS and report what they estimate as their protection contour, driven by the level of QoS guarantee they require as PAL holders. For such an approach to interference mitigation across census tracts to be feasible, the obstacles to sharing (stakeholders sensitivity to revealing information about network deployment and reporting protection contour truthfully) are a big issue and a challenge. That is a question of incentivisation. For the important case of two different operators assigned two adjacent census tracts as their service areas and the problem of interference leakage, the adoption of approach brings at least two different types of *uncertainties*:
(1) The only incentive mechanism in the framework for the PAL operator to report its actual protection contour is the option of subleasing outside the protection area but within the service area - the case which is unlikely in urban areas.
(2) There is no guarantee that the SAS will not deny the authorisation to a PAL, if PAL decides to switch on a new base station in the census tract assigned. Whether or not a PAL can deploy a CBSD is depends on the deployment in adjacent census tracts.
This means that the way you will deploy the network and what type of protection you will get is a function of the other network deployed in adjacent census tract. Therefore, as a PAL - you are increasing uncertainty of your investment. And uncertain investments do not admit strategic bidding.

It is also worth highlighting that the only incentive for a PAL licensee to claim a smaller protection contour is the possibility to lease spectrum on the secondary market, in that FCC rules do not permit a PAL licensee to lease spectrum within the PAL Protection Area. However, since the lessee is entitled to the same protection as the PAL, this would not result in a reduction of the protected area in the census tract.

If thinking in traditional way, aiming for more flexible and effective licensing framework would mean to issue the license for a larger area. However, that does not foster the competition in this band, which is one of the main goals of the proposal on sharing the 3.5GHz in a more innovative, flexible and dynamic way. If the areas are smaller, we have shown that the smaller the census tract areas are, the more spectrum is wasted over the area. We further note that even if the boundary limit is reduced, there is still a problem of 'resizing' the census tracts to fit the diverse spectrum usage so the interference between adjacent tracts is reduced. In highly dense urban areas, census tracts are so small that they cannot be 'resized' at all to form the CBRS-allowed area of deployment.

As we have discussed in the previous section, the balance is crucial: not too small, not too big. Not too many, not too few.

7.3.2 *CBRS Stakeholders Get Ready for the Future*

Right after the final rules were announced, the enthusiastic market players announced their intentions as well: to become SAS operators[18] and to compete for the licenses. Founded in August 2016, CBRS Alliance[19] received a major boost with AT&T, Ericsson and ten other companies joining it two months later. Fall of 2016 also saw equipment testing at a big scale, from SAS[20,21,22] to CBSDs by both the traditional carriers[23,24,25], the newcomers[26,27] and equipment vendors[28]. The final rules opened the space for activities and investments[29],[30].

Significant amount of work was done within WinnForum working groups. Once the FCC adopted the final rules for CBRS in 2016, the WinnForum went on with the realisation of the SAS approval process. This process is about prototyping the SAS, discussing architectural solutions and the SAS functionalities and other activities relevant to getting the SAS architecture design right and ready for deployments in 3.5GHz band. The WinnForum groups worked to align with the FCC rules on SAS administators (eligibility criteria and duties and responsibilities of the SAS administrator and SAS provider) as well. The other important work is around the integration of the CBSD specifications of the FCC to the SAS architecture and in this sense, two deliverables were published: protocols design on the SAS-CBSD interface[31], SAS-SAS interface [32,33]. Major achievement was the finalisation of the CBRS standards[34], Release 1 Specifications published in July 2017.

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[18] https://www.fiercewireless.com/tech/google-federated-wireless-others-apply-to-fill-role-sas-esc-for-3-5-ghz

[19] https://www.cbrsalliance.org/

[20] https://www.fiercewireless.com/tech/google-touts-spectrum-access-system-for-3-5-ghz-spectrum-management

[21] https://www.sdxcentral.com/articles/news/federateds-sas-tech-makes-5g-possible-in-the-3-5-ghz-spectrum/2016/10/

[22] https://www.fiercewireless.com/tech/federated-wireless-alphabet-s-access-hit-milestone-ahead-3-5-ghz-sharing

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[25] https://www.fiercewireless.com/tech/at-t-continues-quest-to-test-at-3-5-ghz

[26] https://www.computerworld.com/article/3055998/networking/google-to-test-innovative-3-5ghz-wireless-in-kansas-city.html

[27] https://www.fiercewireless.com/wireless/federated-wireless-racks-up-40-trials-for-3-5-ghz-cbrs-spectrum-sharing-system

[28] https://www.fiercewireless.com/tech/nokia-ericsson-validate-3-5-ghz-cbrs-gear-federated-wireless-sas

[29] https://www.businesswire.com/news/home/20161214006343/en/Federated-Wireless-Alphabet%E2%80%99s-Access-Team-Demonstrated-Operational

[30] https://www.businesswire.com/news/home/20180426006870/en/Project-Exploring-Application-SAS-Technology-CBRS-Underway

[31] https://workspace.winnforum.org/higherlogic/ws/public/download/3402/WINNF-16-S-0016-V1.0.0%20SAS%20to%20CBSD%20Technical%20Specification.pdf

[32] http://www.wirelessinnovation.org/assets/work_products/Specifications/winnf-16-s-0096-v1.0.0%20sas-sas%20protocol%20technical%20specification.pdf

[33] http://www.wirelessinnovation.org/assets/work_products/Reports/winnf-16-p-0003-v1.0.0%20sas%20to%20sas%20interface%20tr-b.pdf

[34] https://www.cbrs.wirelessinnovation.org/standards

7.3.3 *The Future is Cancelled*

The summer of 2017 was the time of petitions and answers[35,36],[37], as the big carriers made an initiative for the rule change. While Google, Microsoft and others called for the FCC to follow the final rules set in 2015/2016[38], WISPA opposed the motions for change brought by CTIA and T-Mobile[39]. Comissioner O'Rielly, who has been skeptical about the PAL structure from the beginning, insisted on CBRS rule changes[40].

The CBRS band is now in status quo[41]. The petitions submitted by the CTIA and T-Mobile demanded severe changes to the PAL framework, basically asking the FCC to effectively reduce the promising three-tier model to a two-tier model, favoured by the big carriers and traditional licensees alike and by the equipment vendors who depend on them. The CBRS docket 12-354 is not an active docket anymore. Instead the discussion was moved to the docket 17-258[42], once the FCC published the new NPRM[43] re-examining the rules of the CBRS established two years before. With the new NPRM, the FCC proposes the significant changes to the PAL framework, including "longer license terms, renewability, larger geographic license areas, and auction methodology"[44]. These changes mean:

1. Increasing the PAL license term from 3 years to 10 years and making them renewable.
2. Increasing the PAL license areas from census tracts to PEA (partial economic areas).
3. Allowing partitioning and disaggregation of PALs on the secondary market.

We compiled the comments to the FCC regarding these changes and present the one relevant for this chapter in the next section.

[35] https://ecfsapi.fcc.gov/file/10616144416997/170616%20-%20FILED%20CTIA%203.5%20GHz%20Petition%20for%20Rulemaking.pdf

[36] https://ecfsapi.fcc.gov/file/106191696422731/T-Mobile%203.5%20GHz%20Petition%20for%20Rulemaking%20--%2012-354%20--%206.17.2017.pdf

[37] https://ecfsapi.fcc.gov/file/108082560529892/170808%20FILED%20CTIA%20Reply%20Comments%20on%203.5%20GHz%20Petitions.pdf

[38] https://www.fiercewireless.com/wireless/google-boingo-microsoft-and-more-urge-quick-fcc-action-3-5-ghz-cbrs-band

[39] http://www.wispa.org/Wispa-News/ArtMID/13028/ArticleID/146/WISPA-filed-comments-with-the-FCC-PETITION-BY-MOBILE-INDUSTRY-GIANTS-WOULD-STIFLE-INNOVATION-AND-DELAY-ACCESS-TO-BROADBAND

[40] https://www.fcc.gov/document/commissioner-orielly-remarks-cbrs-alliance

[41] https://www.fiercewireless.com/wireless/2018-preview-cbrs-gets-a-makeover-ctia-and-t-mobile-driving-for-change

[42] https://ecfsapi.fcc.gov/file/1003784017554/DA-17-965A1_Rcd.pdf

[43] https://ecfsapi.fcc.gov/file/1024196454861/FCC-17-134A1_Rcd.pdf

[44] In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3700 MHz, GN Docket No. 17 -258, *Notice of Proposed Rulemaking and Order terminating Petitions*, October 2017.

7.3.4 *Recommendations to the FCC*

The FCC decided to re-open the CBRS framework in the phase in which stakeholders were ready to roll out the networks and enter the sharing in the 3.5GHz band. This move was triggered by the petitions by CTIA and T-Mobile in which they asked the FCC for significant changes in the framework which translate to scaling the three-tier model down to two-tier. The regulatory developments in CBRS took a sharp turn, coming after four years long discussions and a lot of effort invested. The rules for the CBRS model had initially originated (PCAST report and the first FCC deliverable, NPRM) to represent a dynamic and innovative sharing model that can adequately respond to the demand pressure. The course of developments that followed, however showed the significant tension on the stakeholders side, pushing the CBRS to a more traditional licensing model. As we have shown, there was a lot of room for improvement in the rules. But, instead of going down that path, the new docket for CBRS is now opened and it seems that the CBRS model is much further from the vision it originated from.

In the comments submitted to the FCC[45], we addressed several points raised by the petitions and the FCC, with a specific focus on a license term and license areas, as defining attributes of the CBRS licensing model. Here, we briefly present the recommendations regarding the geographic licensing model for CBRS spectrum sharing.

7.3.4.1 *Geographic License Area*

The petitions re-opened the discussion about the size of license area. This discussion ended up being framed in three options: 1) leave the Census Tract (CT) area unit, 2) adopt Partial Economic Areas (PEA) as a basic licensing unit, or 3) adopt hybrid approach (CTs in rural and PEAs in urban areas).

The ideal of license area design should be an area of minimal size which is at the same time usable by an operator acquiring a single location for the focused localised service they aim to provide and by a bigger carrier aggregating several of these licenses. While some census tracts do not fulfill the usability criterion, PEAs do not fulfill the minimality criterion which is another founding principle of this framework.

Among the options considered, we believe that the census tracts are still the best option for localised, granular sharing envisioned for CBRS. The combined increase of the license area and term would inevitably result in a higher cost of the license, effectively excluding new players from the market. Under the current rules, with a properly designed auction mechanism and given the possibility of aggregating multiple census tracts, each player will be able to bid for the license area they require to provide a service to their users. This means that the improvement of the licensing scheme based on census tract license area units would need to rely on more realistic models of demand, based on the field data. Some of the possible players have access

[45] *See* Comments of Elma Avdic, Irene Macaluso and Linda Doyle, available at: `https://ecfsapi.fcc.gov/file/1124135896869/Comments_CBRS_EA_IM_LD.pdf`

to real traffic data[46] that will facilitate them in selecting the census tracts they require. If PEAs are the optimal license areas, it will emerge from a market-based mechanism. Adopting the CTs as a license area does not imply that big carriers will not be able to get a license that covers a PEA[47]. Vice-versa, adopting the PEAs as a license area does imply that it will not be possible for smaller players to obtain a license in the PAL market. There is no guarantee that PA licenses will implement disaggregation and partitioning of the license area on the secondary markets and therefore it is uncertain whether small players would be able to obtain protected access in targeted areas.

Amongst the other arguments of the 'petitioners' on rulemaking, we give a brief note regarding the claims that the SAS would not be able to manage and coordinate 74,000 potential census tract licenses. First, according to the authority on auctions, Paul Milgrom [48] the complexity of auctions in CBRS is not an issue. Second, according to the conditionally certified SAS providers, Google and Sony, management of that number of licenses by the SAS is also not an issue. Enforcement and cybersecurity protections, in particular, have been considered from the start for the SAS database systems based on cloud-computing principles, along with the dynamic reassignments, ways of authorisation, interference management and coordination. The FCC decided to leave these concerns to be addressed by the stakeholders, particularly those interested to act as the SAS providers, under the rules obliging them to act in discretion with respect to revealing CBSD deployment data. This way, the FCC opened an opportunity for the SAS providers to compete on the SAS market as well, one of the many markets of the CBRS ecosystem.

7.4 THE LICENSE SPACELAND: BEYOND CENSUS TRACTS

Taking the role of the regulator ourselves, in aiming for a middle ground solution and finding a balance in a policy decision about census tracts as licensing area units, we applied a geometry approach to the problem of CBRS geographic licensing. To achieve the balance we apply the social welfare approach as well, aiming to minimise the waste of spectrum over the area and maximise the number of people with access to 3.5GHz spectrum.

So, what happens if we aggregate census tracts? To aggregate them, we need to devise consistent criteria to determine along which of the polygon edges should the census tract be merged with a neighboring tract. Considering the results of the previous analysis, the goal is to reduce spectrum waste over the area significantly but also to free more population from the grey space, so that they can have access to spectrum in 3.5GHz (recall the problem illustration in Fig. 7.1). If we continue to observe the grey spaces from the edge of census tracts we note that every merger of two tracts

[46]See Google collects Android users' locations even when location services are disabled (Keith Collins, Nov 21, 2017), available at https://qz.com/1131515/google-collects-android-users-locations-even-when-location-services-are-disabled/ (last accessed on Nov 23, 2017)

[47]It means the transaction costs will probably be high, but that is the price to pay with large are licenses

[48]`https://ecfsapi.fcc.gov/file/108082392228281/CBRS%20Auction%20Filing_Milgrom_FINAL.pdf`

deletes a border and eliminates the grey space area surrounding this border. In this section, we will call this process *liberation* and the area that used to be grey space between the two tracts will be called *liberated area*. Correspondingly, the population in that area will be called *liberated population*, while the areas and the population left in grey spaces will be called *precluded areas* and *precluded population* respectively.

The process of merging census tracts in order to minimise precluded area and population resembles the process of merging bubbles: they assume spherical shapes to maximise the volume while minimising the boundary area. Here we have the two-dimensional case and minimise the length of the boundary while maximising the area encompassed.[49] We can devise this procedure as a greedy algorithm:

1. Make a list of borders between all pairs of census tracts
2. Sort the list of borders according to the precluded area or the population at the border
3. Merge along the border on the top of the sorted list and absorb the smaller CT into the larger one
4. Go back to step 1

In other words, in each iteration of the algorithm, one census tract disappears (because it is merged with the neighbour). The new pairs of aggregated census tract (ACT) areas are ordered in the list by the gain which would be accomplished with merging. The results would not be balanced if continued like that, because of the positive feedback loop: as soon as you couple, say 5 census tracts, they become a gang and they will become larger and larger unless there is condition that says "do not merge anymore as you are too big, let the others merge". This would lead to one giant census tracts, where the little ones are waiting to be swallowed. But if we set the condition to penalise big areas in step 2 and sort by the length of borders scaled by the number of census tracts they are composed of - then we get a different metric. Then we get a metric which will attempt to keep the balance in the number of merged tracts all over the map as long as it can. So, we sort the list of borders according to the precluded area or the population **divided** by the number of original census tracts contained in the two (new) census tracts whose border we observe raised to a power. The choice of the power here is a controllable parameter determining how granular we wish our division to be. In this consideration, we go with the second power, i.e. divide the area/population with the square of the number of census tracts aggregated in ACTs.

We need to get out of the algorithm before its end, which results in one big ACT containing all the census tracts, which is the trivial solution of aggregation. We hence put a stopping condition, which can be a certain percentage of overall area loss or population precluded.

[49]We observe this in the previous analysis as well: the increase in the perimeter results in a more significant increase in the area (a linear scaling of the perimeter results in a quadratic scaling of the area).

7.4.1 *First We Take Manhattan*

As seen already, the greatest problem with census tracts is in densely populated city centres, Manhattan being an extreme example. This is why we pick Manhattan for the aggregation experiment using the modified greedy algorithm. Some assumptions were made before the algorithm execution.

1. **The sorting and stopping criteria.** In the previous section, we suggested the use of either the precluded population or area as the metric. The choice of population triggers the issue of the unknown population density distribution over a census tract (we know just the average density, based on the census tract total population). In the previous considerations we have simplified this analysis by assuming uniform distribution. The alternative would be either an attempted approximation or a non-uniform random distribution to vary the density over the area. Neither of the two make much effect in the dense, small-area census tracts of Manhattan. As it turns out, while sorting according to liberated area and population delivers different lists, the end result is similar (~5% of precluded area is ~5% of precluded population as well).

2. **Precluded area calculation along a border.** The calculation of exact precluded areas along a given border for two given neighbouring census tracts is computationally demanding, as seen in the previous presentation. This is why we have taken a path of approximation here, calculating the precluded area as the area of two rectangles constructed at every line segment of the border (on both sides, i.e. into both census tracts) with the height of d, where d is the protection area depth calculated in the previous analysis. Such approach is imprecise in case of very narrow (usually rectangular) census tracts, as liberating one long edge of these tracts will not liberate the whole area d metres deep into the tract (as it overlaps with the protection area of the opposite side). But this, however, influences only the first steps of the algorithm: later on, the census tracts formed by aggregation are big enough for this error to diminish. In this analysis, we used $d = 210$ m. This approximation also means that the algorithm would be reduced to "merge census tracts along the longest border existing in the map right now, as long as the tracts on both sides are not too big already".

Figure 7.8 presents a part of the results of running the algorithm on the Manhattan census tracts (287 of them, CT 1 excluded because it does not neighbour any of the other Manhattan census tracts). ACT area is a *unit* in the algorithm. Precluded population monotonically drops as the algorithm progresses (in each step of the algorithm, a border is deleted and hence a part of population is liberated)[50]. Mean size of the ACTs

[50] The abscissa in Fig.7.8 shows the number of iterations. While the reader might find an abscissa denoting number of ACTs (going from 1 to 287) more logical, we note that such ordering would go against the error of time and the nature of our task. Since we are aggregating small units into larger ones, the left-to-right visualisation had to go from the state of more ACTs to the state of less. The abscissa should be interpreted as inverted ACT count (number of original census tracts minus the number of ACTs).

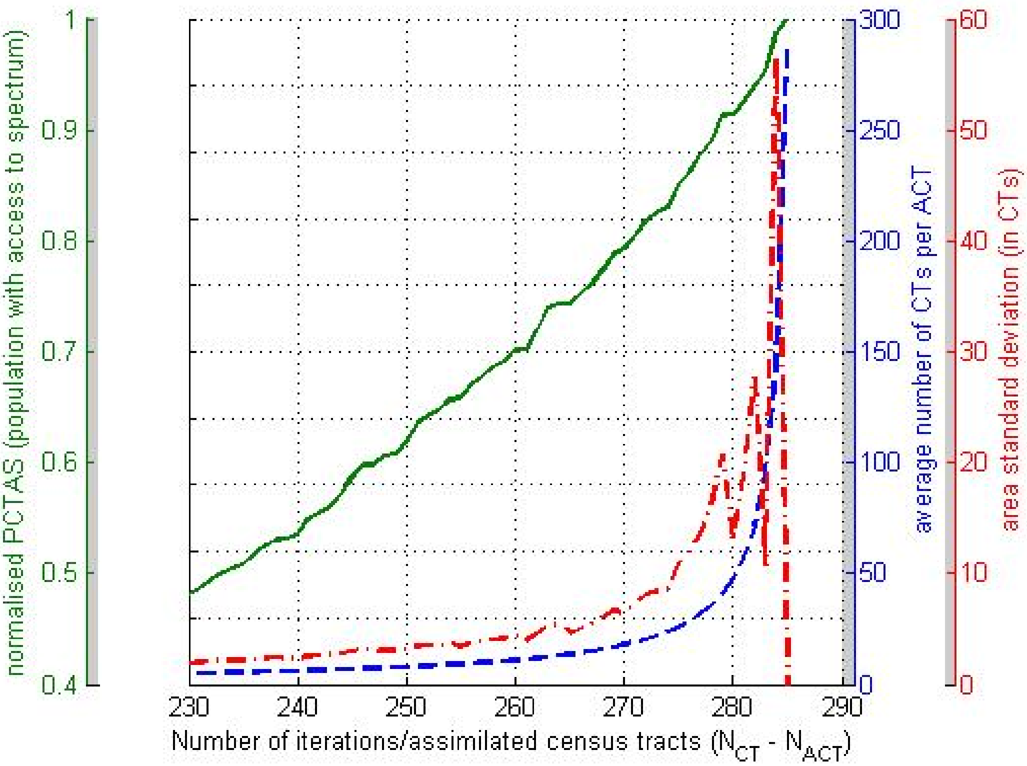
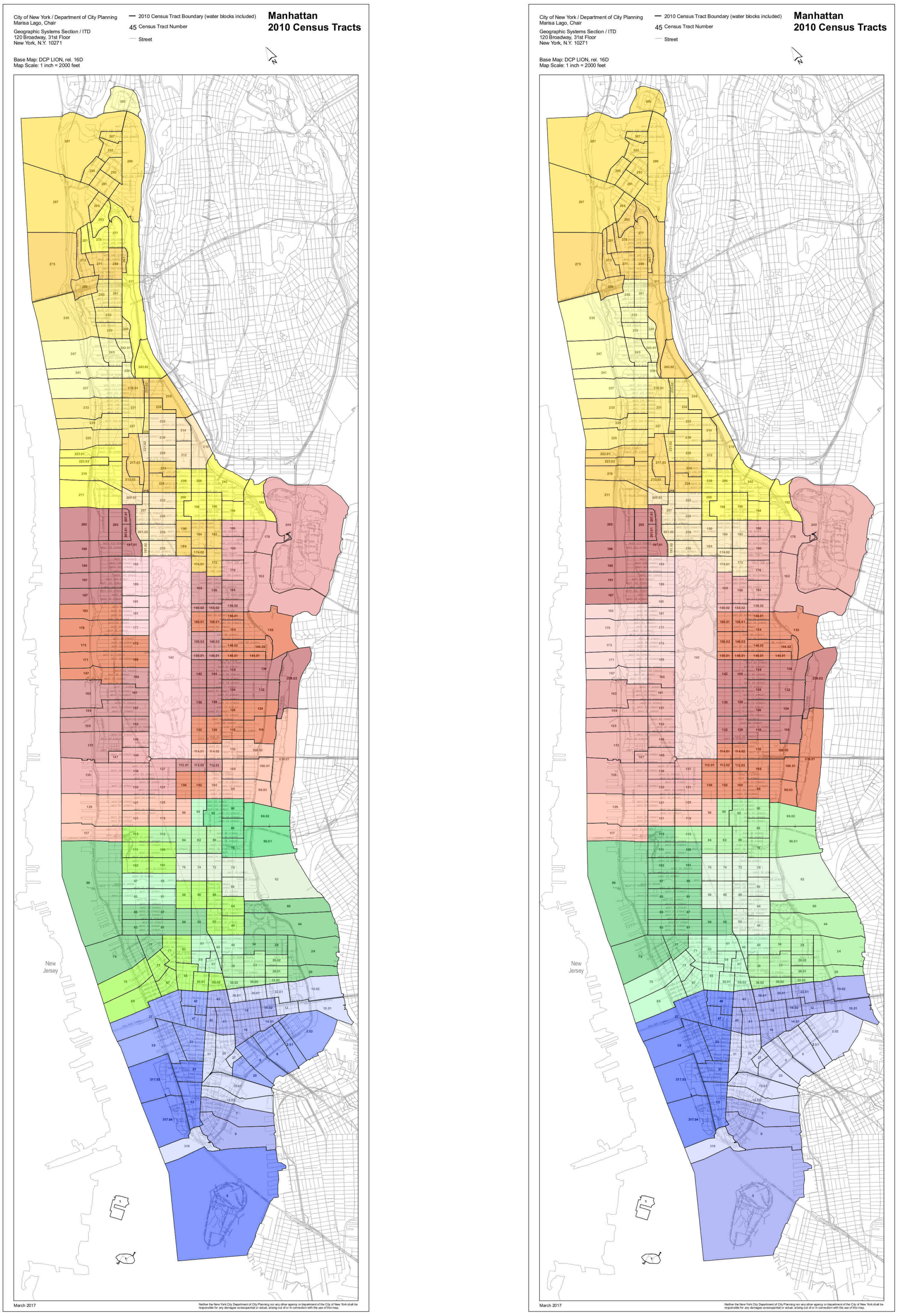


Figure 7.8: Algorithm execution statistics

(number of census tracts within an ACT area) grows monotonically as well, while the standard deviation as the measure of imbalance in area sizes grows, but somewhat oscillates in the process. This shows how the increase in ACT area sizes in our algorithm does not imply the increase in the size difference between them: we can have large ACT areas with approximately same size as a result of our algorithm. Since that is our goal - to have a balanced progression resulting in balanced ACT areas, it verifies the applicability of the algorithm for a showcase like this one.

The process of aggregation is represented through several stages in Figures 7.9 and 7.10.

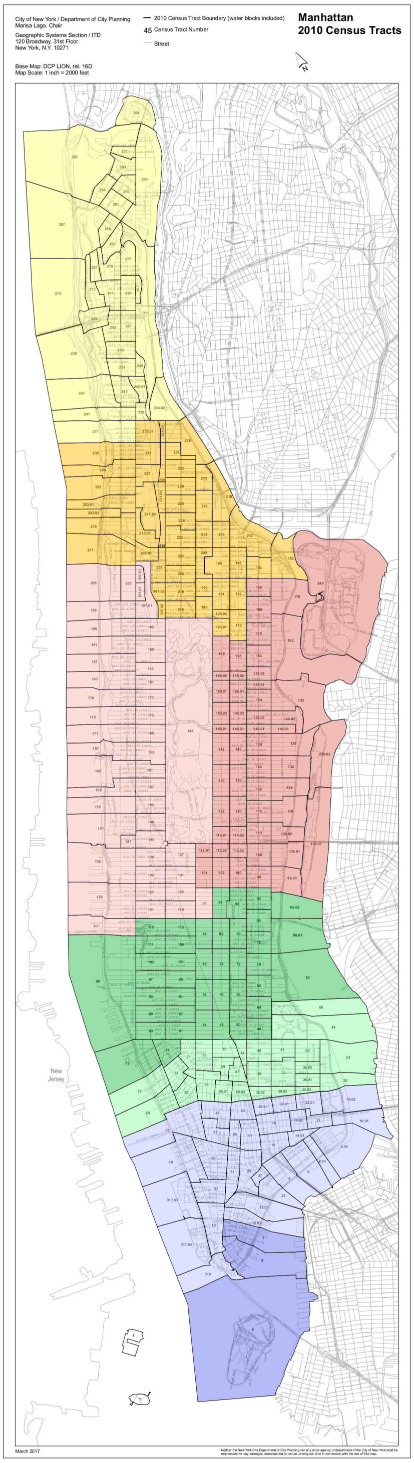
The maps show the effects of aggregation, and two aspects are of importance to us. First is the size, as the census tracts merge into ACT areas of comparable size both in terms of the area (and population) and the number of census tracts included. Aggregation of 11-12 census tracts per ACT leaves us with 25 ACT areas with the decrease of the ~100% precluded area and population figures to <30%. Further increases in area size, while they decrease the precluded area and population significantly (see Fig. 7.8) also decrease the potential of small players to compete. An argument against aggregating too few census tracts on other hand is the fact that a significant number of algorithm iterations (i.e. census tract aggregations) is required to get the precluded area and population out of ~100% saturated area due to high density in the downtown Manhattan.



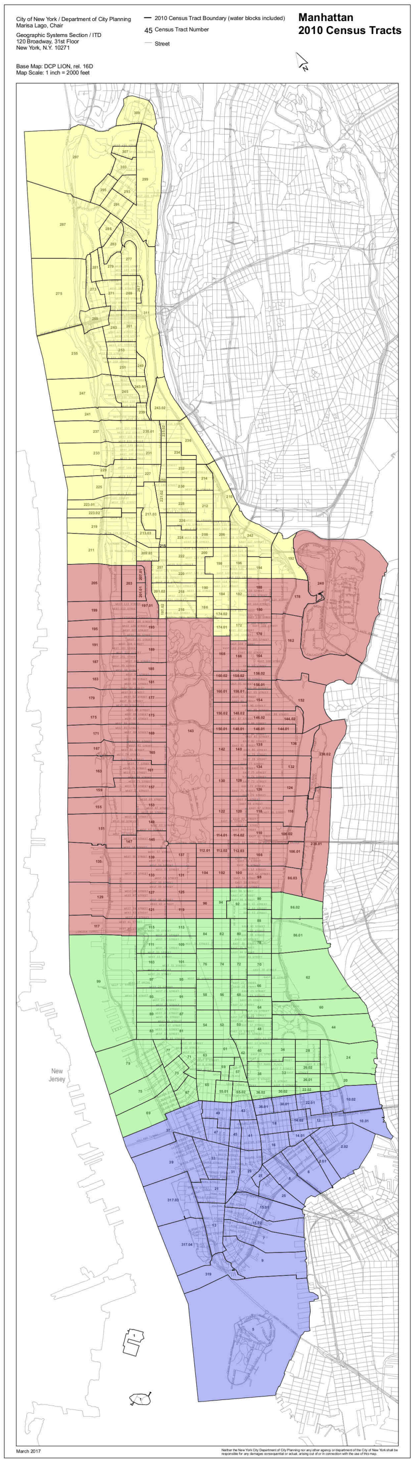
(a) 50 ACT areas, 50% of population has access to spectrum

(b) 25 ACT areas, 70% of population has access to spectrum

Figure 7.9: Gradual aggregation: 50- and 25-ACT area case



(a) 8 ACT areas, 90% of population has access to spectrum



(b) 4 ACT areas, 95% of population has access to spectrum

Figure 7.10: Gradual aggregation: 8- and 4- ACT area case

7.4.2 *Implementation details*

The metric guiding the algorithm, as described in the previous section has the form

$$M_{AB} = \frac{P_{AB} + P_{BA}}{(N_A + N_B)^n} \tag{7.4}$$

where the P_{AB} is the population in the strip of ACT area A that would be liberated if merged with ACT area B and P_{BA} defined in an analogous manner. N_A and N_B represent the number of census tracts contained in ACT areas A and B, while n is the power parameter controlling how important keeping areas the same size is for us. The difficult part in this expression is the P_{AB}, which asks for (1) knowledge of the exact area being liberated by a merge, S_{AB} and S_{BA} and (2) the exact population distribution in that area $\rho_A(x, y)$ and $\rho_B(x, y)$. Then,

$$P_{AB} + P_{BA} = \iint_{S_{AB}} \rho_A \mathrm{d}xy + \iint_{S_{BA}} \rho_B \mathrm{d}xy \tag{7.5}$$

However, the computation of the exact area S_{AB} is a tiresome process, as we have seen before (section 7.2.3)–and we might have a simple approximation that would be just enough. In favour of the approximate reasoning goes also the fact that our ρ_A is constant over every census tract contained in A since that is the level of granularity we have data for: $\rho_a = \frac{P_a}{S_a}$ where P_a is the population of ath census tract and S_a its area. Hence, we discretise the equation 7.5:

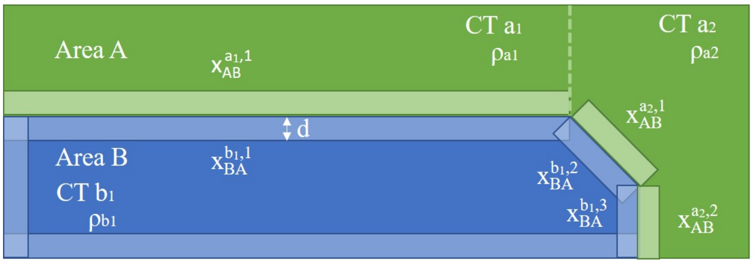
$$P_{AB} + P_{BA} \approx \sum_{a \in A} \sum_{x_i \in G(a) \cap G(B)} x_i d\rho_a + \sum_{b \in B} \sum_{x_j \in G(b) \cap G(A)} x_j d\rho_b \tag{7.6}$$

where $G(A)$ is the border of ACT A, $G(a)$ the border of the census tract a and values $x_i \in G(a) \cap G(B)$ then represent line segments that comprise the border between census tract a and ACT B. Summing is performed over all census tracts in A and B respectively. This approximation is particularly useful in our case, where we do not have reliable information on demand distribution finer than census tract level. If we had a better resolution of data in terms of demand[51] that would take us back to a variable density $\rho_A(x, y)$ which could again be integrated numerically in 7.5 or 7.6. The way the algorithm works on census tracts and the principles of our approach presented here are illustrated in Fig. 7.11

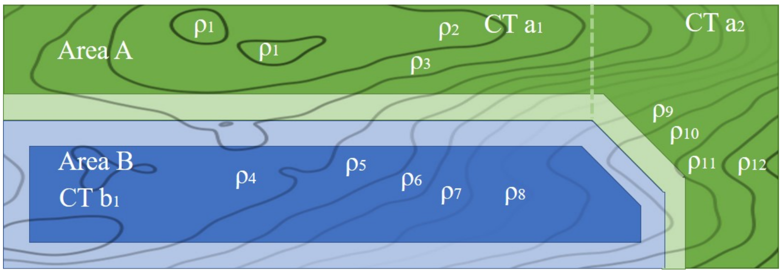
Fig. 7.11(a) illustrates the equation 7.6, i.e. the approximate metric calculation used in our implementation. Fig.7.11(b) shows what the realistic situation with detailed population densities would look like (where the exact metric 7.5 is relevant).

At this point we note that if the area is given the central position instead of the population, the metric M then features S_{AB} and S_{BA} instead of P_{AB} and P_{BA}.

[51] This data could be gathered through a measuremet campaign or user metadata history in other bands. See: Google collects Android users' locations even when location services are disabled (Keith Collins, Nov 21, 2017), available at `https://qz.com/1131515/google-collects-android-users-locations-even-when-location-services-are-disabled/` (last accessed on Nov 23, 2017)



(a) The approximate metric calculation



(b) The variable density case

Figure 7.11: Algorithm illustration

The stopping criterion of the algorithm can again be either the measure of area or population effects, corresponding to previously introduced ALP and PCTAS metrics. We call these *global ALP* and *global PCTAS* as they correspond to the whole area of interest (in our showcase, the borough of Manhattan). The global ALP is the ratio between all the grey space area and the area of all census tracts, while the global PCTAS is the sum of PCTAS for all ACT areas divided by the total population of all census tracts. In our case we chose the global PCTAS as our stopping metric (Fig. 7.8 shows the evolution of the metric's value through the iterations of the algorithm) since we use population-based metric 7.4 for sorting as well.

7.4.3 *Discussion about the Implications*

Innovation comes at a price. Fostering competition as well. Serving public interest, providing connection to everyone in Manhattan as well. These are all regulatory objectives of the CBRS framework.

Between the hammer of inefficient, tight census tracts and the anvil of big alternatives (traditional nationwide licenses of exclusively licensed spectrum bands) which would take whole New York City and more into a licensing area, any of the stages of our algorithm's journey is better. This kind of trade-off in making the right policy decision has to be considered. As our Figures 7.9 and 7.10 show, there are choices to make when thinking about fostering competition and innovation. Let us observe the extreme cases depicted there as archetypes: the 50-ACT area solution as the archetypal competition heaven, potentially allowing dozens of operators operating in proximity, in a very granular, small-cell way. The 4-ACT area solution is public interest's promised land, one with happy 95% of citizens. Neither the perfect competition nor the perfectly served public interest are a realistic option, so we seek the solution somewhere in the middle, as the regulator would.

Let us consider the two transitional cases, 25-ACT area and 8-ACT area one in terms of real CBRS rules existing at the moment. In the 3.5 GHz band, up to 7 PAL licenses for 10 MHz channels can be issued per census tract. In addition, a carrier cannot obtain more than 4 of those. The 25 area case yields $7\frac{PAL}{ACT} \cdot 25ACT = 175$ potential PALs (compared to $7\frac{PAL}{CT} \cdot 288CT = 2016$ potential PALs in the original CT division, a tenfold decrease). While decreasing the auction complexity (for 74,000 census tracts in the US, that is 518,000 PALs in the auction)[52], we maintain competition, decrease precluded population figures and spectrum waste over the area. If aiming to please the big carriers by offering them larger license areas and not preclude more than 10% of end users and area of Manhattan, there is an option to divide Manhattan into 8 ACTs. We do not get a significant decrease in auction complexity compared to the 25-area case (10-fold decrease when going down from 288 CTs to 25 ACTs is unmatched by the 3-fold decrease from 25 to 8 ACTs).

From the sub-leasing viewpoint, there is also a trade-off to account for: (1) The license area should be big enough for the licensee to have a non-trivially large area that can potentially be subleased while the licensee operates in the rest of the ACT (2) The area should be small enough for the lessee to maneuver with leasing from different carriers in different areas and aggregating a shape of their own.

7.5 CHAPTER SUMMARY

In this chapter, we have observed in depth the development of the CBRS licensing model based on census tracts geographic license areas. After diagnosing the issues with census tracts by performing geospatial analysis, we devised an optimisation procedure to offer a solution in the form of aggregated census tracts (ACT). In the meantime, the events in the CBRS rulemaking have shown FCC's shift over final rules towards the big carriers and their own vision of licensing areas. We expressed our concerns in direct communication with the FCC: the large licensing areas favoured by the pundits of traditional business models disrupt the balance between competition and affordability in smaller units. In the next chapter, we continue with our endeavour in exploring the reasons why the balance in the CBRS rulemaking was such an impossible regulatory objective to achieve.

[52]The argument of stakeholders advocating for license areas of the size of counties, EAs and CMAs was that the complexity of such auction model is extremely high. The auction expert, Paul Milgrom disagreed in his letter filing to the FCC:
https://ecfsapi.fcc.gov/file/108082392228281/CBRS%20Auction%20Filing_Milgrom_FINAL.pdf

Part IV

THE BALANCE OF THE FORCES

The Tower of Babel: Building Act of 2018 AD

"Look, since this whole thing is hypothetical,
I'll bite: why don't you make a pyramid?"

Audio version at: `https://www.youtube.com/watch?v=lBrtNzD3eTQ`

8 PATHETIC DOT THEORY FOR CBRS

The regulation of behaviour is the foundation of the regulatory framework design process. When regulating behaviour, the regulator has a goal: in the case of CBRS, the regulatory goal was establishing a functional sharing system in a band aligned with PCAST recommendations to utilise underutilised spectrum. Fulfilling this goal was to serve public interest and respond to the pressure of constantly growing spectrum demands. The overall goal is to get to a state where we are using spectrum more efficiently. The behaviour to be regulated behind these regulatory objectives is the behaviour of sharing spectrum.

Spectrum sharing is not taking off. The notion of spectrum sharing does not have a good name among the big carriers, as they are led by traditional norms and traditional business models. Sharing is associated with lack of protection, which is a barrier for them and something they would leave to the unlicensed bands and their users. This does not mean that the world is divided in two halves: licensed carriers and users of unlicensed bands. The unlicensed bands are not a sharing utopia in which every user shows good attitude towards sharing and in which the sharing behaviour does not need to be regulated. However, succumbing to the bipolar world vision has a tremendous effect on the culture of sharing. This mirroring of coded language has kept us away from regulating sharing behaviour, all while the sharing models were emerging. Now that the regulatory efforts are made towards sharing models implementation, they are about regulating behaviour of using spectrum, and not about behaviour of sharing spectrum–that is not on the agenda.

Once design of a framework starts, it is very important for the system to be designed to incentivise the users that will share spectrum, and if it promotes innovation, does it foster competition. The PCAST report proposed that we need to make spectrum sharing a norm. For that to happen, the framework needs to be designed with the goal of building trust.

We need to look at this problem through a lens that permits us to take a wide perspective on how behavior is regulated. We adopt the approach taken by Lessig, which looks at the regulation of behavior through constraints of architecture, market, law and norms. This approach recognises the behavioral change is driven by multiple factors and understands how incentives or disincentives to change can be embedded in the technical design choices of the system.

8.1 THINGS THAT REGULATE - CHICAGO SCHOOLS

The regulator and its *law* are not the only force of regulation which can constrain or enable certain behaviour, e.g. the *market* is another. This is the initial point at which both Chicago schools agree: the "old" one championed by Coase, R. Posner, M. Friedman (to name a few) and the "new" one, as presented by Lessig in the eponymous essay[1]. The key difference is in interpreting what the existence of other forces means for the law force.

The old Chicago school of law and economics promotes a neo-classical microeconomic approach to regulation, based on free market principles and advocates for removing the state from the regulation: out with the law. Lessig identifies two additional *departments* of Chicago school that do not replace the law with *market*, but with forces of *norm* and *architecture.* The new school does not displace law, but advocates for activism, for the state to do more. The law force in Lessig's theory not only regulates behavior directly, but also indirectly, through the other three forces (recognizing these are not the only constraints). Law directs behavior in certain ways; it threatens sanctions ex post if those orders are not obeyed. Social norms create social conventions people feel compelled to follow in business or daily life. Markets regulate through the device of price. And architecture constrains based on the limits of behavior it structurally imposes.

Law, market and social norm as constraints on behavior can be intuitively understood. However "architecture as constraint" requires a longer introduction. Architecture can be understood in its traditional meaning as relating to physical form and structural design. There are numerous examples of the effects of architectural choice. A few simple ones are given here as examples. Robert Moses built bridges on Long Island to block buses, so that African Americans, who depended primarily on public transportation, could not easily get to public beaches[2]. The Camden Bench is a street bench, which as authors of the book point out, was designed to constrain 28 forms of anti social behavior (e.g. graffiti, skate boarding, sleeping, stealing) and support one behavior, namely sitting[3].

Of course, architecture can also be understood in the digital world. Lessig was particularly interested in the architecture of the Internet and the behaviors specific architectural choices enable or constrain within that domain. He expanded these ideas further on this topic in his book Code and Other Laws of Cyberspace[4]. In this book he talks about 'architecting' or 'coding' cyberspace to enable or prevent certain behaviors.

[1] Lessig, L. 1998. The New Chicago School. The Journal of Legal Studies, 27(S2), pp.661-691.

[2] Robert A. Caro, The Power Broker: Robert Moses and the Fall of New York, Alfred A. Knopf, New York, p.318., 1974.

[3] G. Savicic and S. Savic, Unpleasant Design. Designing Out Unwanted Behavior., 5th STS Italia Conference, A Matter of Design: Making Society Through Science and Technology, June 2014.

[4] Lessig, L. Code 2.0, 2006. and Code and Other Laws of Cyberspace, 1999

So for example an architecture which encodes location and identity within supports commerce while it can potentially limit certain freedoms around anonymity. It is from this work that the phrase, 'Code is law', has emerged.

8.2 pathetic dot theory

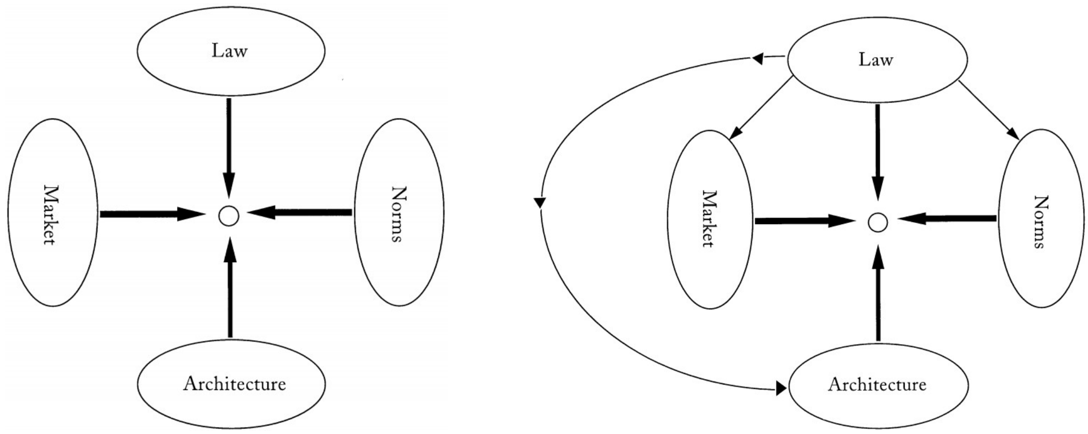
Each of the forces constrains or enables a certain type of behavior and the behavior changes accordingly. The forces put tension on the dot in the center, the entity or a thing being regulated - whose behavior will change as a result of suffering, being constrained. Lessig dubs it the pathetic dot. He lays out the pathetic dot theory through several examples, the five of which he puts more emphasis on: smoking, seat belts, discrimination against disabled people, drugs, and abortion. The example we take is the wearing of seat belts in cars. We can make individuals wear seat belts through rules (law). We can make it a stigma not to wear a seat belt through education (norms). Insurance companies can offer lower premiums for those who wear them (market). Car manufacturers can build cars that lock the ignition unless the seat belt is on (architecture). These forces can come together to achieve the desired behavior if all the individual stakeholders in this picture are aligned. Of course the stakeholders may not be aligned and the modalities of regulation may be in opposition. The Fig. 8.1(a) captures the modalities of regulation.

What does "coming together" mean? This is a question of the effectiveness of regulation. There is no single solution to the problem of regulating to achieve satisfying outcome and there exist several combinations of forces which can lead to desired behavior. However, the common thread in all of them is balance, as lack of a component or an excessive intensity of another leads the dot from out of stability[5].

The forces do not act independently. In the above example, the changes on architecture, norms or market could be imposed by law and that is how the desired behavior is achieved by net effect of all forces coming together through the law. As Lessig points out, "Each constraint is subject to law—not perfectly, not completely, and not in any obvious way, but nonetheless, each itself an object of law's regulation". Hence in the above example laws can also be enacted that drive the education programme, oblige the insurance companies to have suitable policies and enforce a specific type of manufacturing. The Fig. 8.1(b) captures this idea of law regulating directly but also indirectly through the effect on other forces.

Lessig is giving a meta-role to the law, as he is primarily a legal scholar, making a point that the law can constrain behavior directly and indirectly, through constraining other three structures of constraint. However, he notices that "there is an equally important story about the market, for example, affecting other constraints, or norms or architecture as well. And with these other stories, there would be another range of

[5]This assumption, as explained in Chapter 1, stems from the thought that if a component is not included in the support of the desired behaviour change, it will necessarily work against it (in the case of spectrum, no norms means all existing norms will actively work on pushing the dot out of wherever you're trying to steer it).



(a) Modalities of regulation acting on to change the dot's behavior

(b) Law regulates directly and indirectly

Figure 8.1: Pathetic Dot Theory

arrows representing influence one way or the other." This is the direction which we will explore more.

8.3 INTRODUCING PATHETIC DOT THEORY TO THE CBRS SHARING

The regulatory goal was to create an effective framework that will govern the sharing in CBRS band. As we have seen in Chapter 6, the CBRS is the landscape in which different stakeholders live: the prospective PAs and GAAs (and the SAS providers and the equipment vendors). One approach to pathetic dot analysis would be to place just one of these inside the dot and observe the effects of the forces on their sharing behaviour. The path we have chosen is one of unification, where the whole stakeholder community is placed within the dot[6].

Why do we find pathetic dot theory appropriate for CBRS? First, it comes from Lawrence Lessig, the theorist of commons, Internet, spectrum, content - the digital world of interplay between the state, the FCC, copyright, IP etc. He is the leading theorist of modern communications network regulation. He writes about the issues of digital culture and the regulator behind it, but also about what issues in particular they regulate. This is a perspective wide enough to deal with the causes and symptoms of these issues in a meaningful way to comprehend and describe the impact these issues have on society globally. We see spectrum regulation as such issue. Second, we recognised the striking resemblance between Lessig's forces and the components of our NTBRS framework. This suggests a relationship between the pathetic dot theory and sharing economies and its applicability to a spectrum sharing model. Third, let us return to Chapter 6. There we examined the interplay of the regulator and the stakeholders coming from different positions. Some of them had strictly technical

[6]Our argument for "all-in-one" dot is the following. As we have seen in Chapter 6, in the original idea of PCAST and CBRS NPRM there was no place for the cellular market in PA tier. They were all supposed to fall into GAA tier. Placing all of the commercial stakeholders within the dot aligns with the purpose of the thesis.

character, some had an economic one, some were a blend. And there was the regulator encompassing all of their standpoints in the rulemaking. This is analogous to what we have seen in Fig. 8.1(b). Here we align with Lessig in the choice of the law being the force driving all other forces to a desired behaviour outcome. Our motivation comes from the nature of CBRS structure and rulemaking. It is a new world built from scratch with all of its architecture (SAS), its markets (auctions of licenses, CBSDs, SAS markets) and norms (sharing as a norm from PCAST). All brought by the FCC rules - the law.

8.3.1 *Research questions*

For the work presented in this chapter, the research question is: **How to regulate the sharing behavior in order to build the culture of sharing?** While answering this question we will in particular look at the relationship between the sharing behavior enablers of the NTBRS framework and Lessig's forces acting on a CBRS pathetic dot (the NTBRS is the context of the thesis we work within).

Balance between the forces (the right mix of modalities) leads to the desired behavior. Imbalance can lead to temporarily satisfying behavior, but in the long run it has undesired consequences and fails to achieve the regulatory goal. This is why we investigate the existence of balance and the potential of achieving it. Therefore, similarly to what we did in Chapter 6, to answer the main question for this chapter we gradually ask the following:

1. **Is there a balance in the CBRS rules?** These rules are the initial conditions of the new CBRS ecosystem which we interpret through Lessig's modalities first. In the temporarily static combination of forces, the initial balance would be an important feature and a good sign for the evolution of the framework (and the band). The laws have put the initial conditions to it and now it needs to blossom.

2. **If there is no balance, why not?** While the calculation of the net effect of the forces and exact mathematical operations are unfeasible, this question is answerable if the contribution of a force or more of them is negligible. This transforms the question into: **What is the weakest link in the combination of forces?**

3. **Can a balance be reached in the future?** Lessig's framework is inherently dynamic, as it regulates future behavior and *change*. This is why the initial balance is a good sign for the evolution, but does not guarantee success - as *the thing and the forces surrounding it constantly change*. Once we find the weakest link in the initial state, this question transforms into: **Can the weakest link grow strong?** Here we note the importance of interconnections between the forces, as we promised. While the law is omnipresent and had its effect in creating the band rules and shaping them, the interplay of the other forces will be the one leading it to the future. Hence, we ask: **Which forces are feeding into the weakest link and is their effect strong enough to see it grow?**

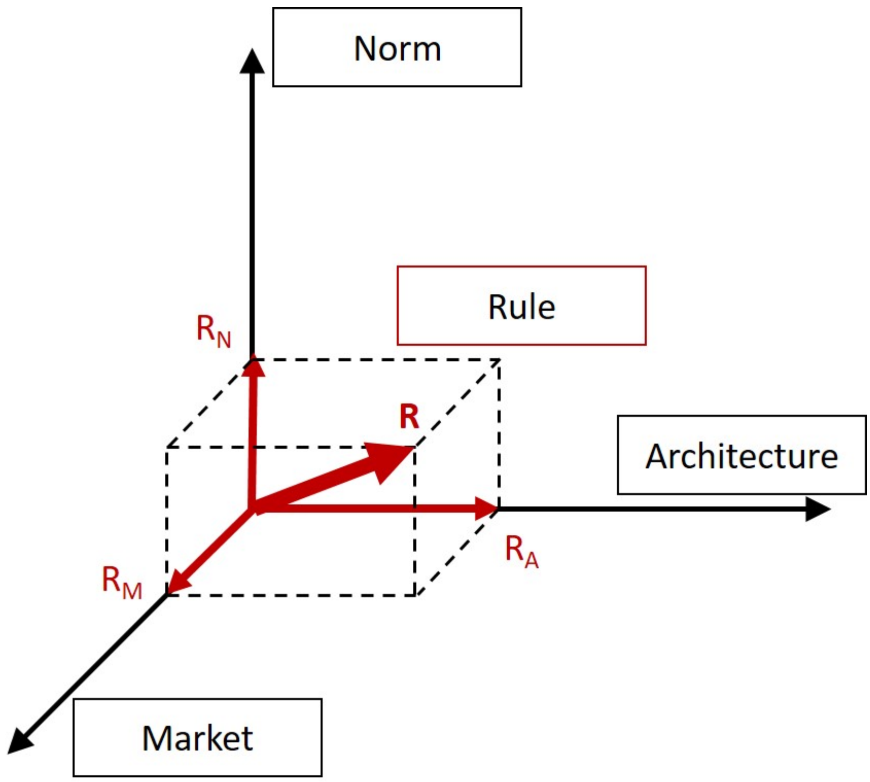


Figure 8.2: Decomposition of a rule into force components

8.4 ANALYSIS: THE FUZZY SPACE OF THE FORCES

Going back to the content analysis fundamentals, to understand the framework and the effects of forces, we need representative material describing it. In this case it is the rules of CBRS, as they describe the initial conditions of the band. Chapter 6 already told the tale how they were reached from the process perspective, and now we change the perspective to capture a broad picture of the forces shaping the framework and to find the last missing piece for the thesis puzzle.

It is rarely the case that a rule in such a complex system is defined by a single force: the rules are necessarily a combination of forces contributing components of different magnitudes. This corresponds to the traditional vector analysis which naturally suits the story of forces. An example of such an interpretation is shown in Fig. 8.2.

Here a sample rule R is decomposed into its architecture, market and norm components R_A, R_M and R_N, respectively. There are two reasons why we do not show a law component here, the trivial one being impossibility of proper representation of 4-dimensional space graphically. The other reason however is the fundamental one: we are analysing rules here, and they are components of law by definition.

It is impossible to meaningfully assign 'crisp' numerical values to the components akin to those shown in Fig. 8.2, but there is certainly a sense of relative magnitude we can attach to them. This will be performed in a fuzzy logic manner, assigning fuzzy values 'high' (H), 'medium' (M), 'low' (L) or 'zero' (blank) for the magnitude of a particular component of a rule. For example, every rule is going to have a 'high' law component as explained earlier, but a rule about license terms will have no relation to architecture and hence not even a 'low' component.

Now once we have established the answers, we need the questions as well: what exactly are we looking for? Merely observing what a rule *is* gives the initial conditions for the CBRS in terms of the forces, but says nothing about the big picture, what brought the framework to that state or where it might go from there. Hence, we need to do more.

The analysis from Chapter 6 inspires us to ask which forces *shaped* a certain rule and how. This approach is going to help us determine the origins of (im)balance and trace back the rules from their final state. Finally, after investigating the past and the present, we turn to future as well looking for the effects the forces, channeled through the rules, are going to have. In particular, we are interested in the interconnections between the forces (stemming from the interconnections of the rules) as this introduces dynamics to the otherwise static model of forces and tells us whether the dot may reach the state of balance from an initial imbalance, or succumb to imbalance after the temporary balance at the beginning.

When looking for components in the *shaping* stage, we pose the following three questions: (1) how dominant was the regulator in holding the upper hand in the rule-making process for that specific rule? (2) were the arguments made by stakeholders from a viewpoint of a CFO, CTO, both or neither? (3) What would an NYC taxi driver say about the spirit of the rule? Answers to the first two questions follow from the proceeding analysis in Chapter 6, while the third question is a thought experiment designed to ensure the conformance with the prevalent entrepreneurial capitalist norms: a small entrepreneur from the big city, endangered by Uber, our imaginary friend is the authority on how things are done in America.

We proceed by tabulating the rules of CBRS from Report and Order and the Second FNPRM amended in the Order on Reconsideration and Second Report and Order and grouping them in three major groups: CBRS, CBSDs, and SAS & ESC rules. To make the material readable, we further group the rules into meaningful standalone items for analysis and to link it to original text, we put references to the exact rules as laid out in the FCC amended Part 96 of the Part 47 of the Code of Federal Regulations (CFR).

8.4.1 *CBRS Rules*

1. **Based on the rule 96.25(b)(1) and definition 96.3, each PAL consists of a single License Area which is a Census Tract.**
   Law: being a rule, one of its dominant force components is the law. It was also dominantly shaped by the law, as the regulator had a leading role in adopting it.
   Market: as it defines what is being sold, it has a market force component. It aims to significantly change the market by the change of business models, but it was not shaped by the market.

Table 8.1: CBRS Rules, legend: fuzzy set L=low, M=medium, H=high, 0=blank

No.	**Rule**	**IS**				**Affecting**				**Shaped by**			
		L	**M**	**A**	**N**	**L**	**M**	**A**	**N**	**L**	**M**	**A**	**N**
1	PA license area unit is a census tract	H	M	H			H	L	M	H		H	
2	Channels of 10MHz dynamically assigned by the SAS to PALs	H		H			H		M	H		M	
3	Band plan for PAs and GAAs	H	H	M			H		H		M	M	M
4	PAL is a 3-year, non-renewable license, but two consecutive terms	H	M				H		M	M	M		M
5	GAA access to PAL channels allowed when spectrum is free - outside PAL Protection Area	H	M	H			H		H	M	M		
6	Contiguous geography and channels assignments by the SAS to PALs	H	M	H			H		H	H			
7	Allocation = Auction for PAL,Competitive bidding	H	H				H			M	M		H
8	PAL aggregation	H	H	M			H			M	H		L
9	Secondary market allowed	H	H	M			H	H		M	H	M	M
10	Reg status: Both tiers can operate on a non-common and/or common carrier basis	H	H				M		M	H		M	
11	Both tiers must register with the SAS and operate as per instructions	H		H					M	H			
12	GAA status within the SAS-managed band	H	M	M			H		H	H	M	M	
13	More cooperation required for GAAs in category B	H		M	H		L			H			

Architecture: the geographic division of the US into census tracts is a given architectural condition, making the architecture force dominant. It loops back into affecting the architecture somewhat, by the effect of equipment adaptation to new licensing areas. However, this effect is not big as the designated use, small cells, is already tailored for small areas. Finally, it was shaped by the architecture as the considered arguments (both pro and contra) came from measurements and statistical bureaus .
Norms: While not being based on any existing norm (as the prevalent traditional norm is one of large license areas) the only relationship this rule has with the norm force is its attempt to affect it and change it to making smaller, granular license areas acceptable under exclusively shared licensing models.

2. **96.13(a) and 96.25(b)(2) To PAs SAS determines and assigns permissible channels 96.53(b). Each PAL consists of 10 MHz channel within frequency range 3550-3650 MHz by definition in 96.11(a)(2). A PA may request particular channels, but is not guaranteed to get those.**
Law: being a rule, one of its dominant force components is the law. It was also dominantly shaped by the law, as the regulator had a leading role in adopting it.
Market: this rule is not about how big are the channels and what is being sold as much as it is about the dynamic assignments and reassignments of channels to PAs in an unpredictable way, controlled by the SAS. It aims to change the market however, because it leads to more efficient use of spectrum and ability to pack more different users in the band which boosts spectrum ecosystem in terms of access points, handsets and other equipment. It is not shaped by the market: the representatives of the market wanted to see a completely opposite rule (Chapter 6, NPRM issue 5 and related issues).
Architecture: the existing technology makes it possible, and the rule itself is an architectural feature of CBRS. Ten megahertz blocks of spectrum, standardised by LTE provide enough spectrum for different operations and the architecture of SAS, being, among other its features, a dynamic responsive database based on cloud computing enables it to perform these assignments dynamically. Such SAS can be considered as given, as presented by the Google with their prototype, so the rule is not going to result in architectural change. At the same time, the prototype had some effect on shaping the rule.
Norms: Again, relationship of this rule with the norm is one of going against the flow. The existing norms of fixed assignments are to be affected by it and have not participated in shaping it.

3. **96.13(a)(1) Maximum of 7 PALs can be assigned in any given license area at any given time. This implicitly means that the remaining 80 MHz of the band is always available for GAA shared use and also, if there are no PALs assigned, it means potentially entire 150 MHz for GAA use based on 96.11(a)(1). Also, GAA frequencies are available on a shared basis 96.35(b) and GAA users may**

operate in the entire band 3550-3700 MHz according to Section 96.11(a)(2)
Law: being a rule, one of its dominant force components is the law.
Market: it is highly market because it again defines what is being offered on the market (not necessarily what is to be bought– that holds for PALs but GAAs do not pay a price directly but through their other costs of operation). It defines the grounds of a trade-off: either pay for protection or suffer interference - this affects the cost of a PAL, combined with the knowledge of the exact quantity of PALs offered. At the same time, the size of the band portion reserved for GAA, the size of GAA pool, directly affects the overall degree of competition enabled in CBRS. GAA pool is 80MHz when all 7 PALs are assigned (70MHz), while when none of 7 PALs is assigned, GAA have potentially whole band for themselves (150MHz). If the GAA pool size were smaller, for example 30MHz, then the demand on PALs would be much higher and competition for PALs in the competitive bidding procedures, which would put a high price on spectrum. This is because in this case prospective GAAs would have to seek other options as the pool is too small to accommodate everyone. When GAA pool is of reasonable size, i.e. large enough to accommodate the demand, then the competition for PALs is lower, as the right to buy protection is less attractive. It is also highly affecting the markets as a game changer for the CBRS markets; what it can lead to at this point is hard to predict.
Architecture: It is a moderate architecture force, because of the size of census tracts, the size of channel blocks - the building blocks. There is no significant effect on architecture by this rule (it is not going to change technology or band plans), and the rule itself was mostly shaped by market arguments, not architectural ones.
Norms: Affecting the norm moderately, because the big carriers traditional ones that obey according to old norm still have an opportunity to continue obeying it as enough spectrum is left for them under exclusive model and they don't have to consider GAA options to operate in the band. However, they can and it is an additional degree of freedom (additional dimension in which you can move) and a potential norm changer.

4. **96.25(b)(3) PAL will be issued a license for three years, non-renewable. According to 96.27(b) PAL may apply for two consecutive terms within the first application window (accepted every three years, 96.27(a)).**
Law: being a rule, one of its dominant force components is the law. It was also somewhat shaped by the law, as the regulator had to make a compromise with the stakeholders while adopting it (the regulator first proposed 1-year license terms with 5-year cap.)
Market: the market component is predominant in this rule because it solely defines what is being sold and constrains the planning in terms of business models Hence it is also changing the business models. At the same time, it was the influence of market stakeholders clinging on the longer-term license proposals that

made the regulator eventually adopt a middle ground solution (Chapter 6, PN issue 5, FNPRM issue 8).
Architecture: Compared to the role of other forces, architecture force did not have any weight in this rule because the nature and technology of CBRS environment had no effect on short term license adoption.
Norms: Again, relationship of this rule with the norm is one of going against the flow. However, the traditional licensing norms have had it its part in shaping it through the voice of the big carriers asking for a compromise. It continues with an attempt to change that norm by making the stakeholders accept the short timespans.

5. **96.25(c) Unused PAL channels available for GAA use outside PAL protection areas. By definition 96.3 PAL Protection Area is the area within PAL's default protection contour calculated by the SAS in accordance with section 96.25 or smaller, self-reported protection contour in accordance with section 96.41(d) ("aggregate received signal strength for all locations within PAL protection area of any co-channel PAL shall not exceed an average (RMS) power level of -80 dBm in any direction when integrated over 10 MHz reference bandwidth with the measurement antenna placed at a height of 1.5 m above ground level, unless the affected PAL licensees agree to an alternative limit and communicate that to the SAS.")**
Law: being a rule, one of its dominant force components is the law. It was also somewhat shaped by the law, as the regulator resisted the initiatives from the part of the market to prevent use of assigned channels.
Market: as this rule describes part of the "package" a potential GAA user is getting, it is partially market in nature. In the long run, it aims to change the market's nature and it was shaped by the market: this time it was not the big carrier component of the market getting what they wanted, but the newcomers.
Architecture: this is a fundamentally architectural rule, as it describes the venue of tier existence in physical spectrum space. It does not affect the future of architecture and is not dominantly shaped by the architecture pundits.
Norm: this rule was adopted against the usual non-sharing norm, so we do not say it is shaped by norm. It aims to change the prevalent norm and make sharing accepted, hence it is affecting the norm.

6. **Contiguous geographic areas 96.25(b)(1)(i) and contiguous channels 96.25(2)(i): An SAS must assign geographically contiguous PALs held by the same licensee to the same channels in each geographic area to the extent feasible. An SAS must assign multiple channels held by the same licensee to contiguous channels in the same license area, to the extent feasible.**
Law: being a rule, one of its dominant force components is the law. It is exclusively shaped by the law, as the regulator initiated it and insisted on it.
Market: This rule is going to affect the market in the terms of acquirement planning. It already has its fundamental market component through enabling extend-

ing deployment to adjacent space and frequency.
Architecture: this is a dominantly architectural rule, as it bonds the continuous nature of the space and spectrum with the database architecture of SAS. It does not affect the future of architecture and is not shaped by it.
Norm: this rule goes along the lines of making sharing a norm, hence its enforcement affects the norm force.

7. **96.29(a) When mutual exclusivity for PAL applications is detected, PALs will be issued via auctions as subject to competitive bidding procedures; 96.29(b) PALs are mutually exclusive when they seek more PALs than the number of PALs available in that geographic area; 96.29(c) When there are two ore more accepted applications for PALs in a given license area, the FCC will make available one less PAL than the total number of PALs in that license area for which all applicants have applied, up to a maximum of seven; 96.29(d) except in rural areas, when there is only one application for PAL in license area, no PAL will be assigned for that license area: the auction will be canceled, and spectrum assigned to GAA until the next application window. In rural areas, when there is only one application for a PAL in the license area, that applicant will be granted the PAL.**
Law: being a rule, one of its dominant force components is the law. It is moderately shaped by the law, as the regulator's frame was kept throughout the process.
Market: This rule is defining the market and hence has a large market force component. It will keep on affecting the market somewhat, and the market stakeholders participated in shaping it (one example is the exemption of rural areas which came through stakeholder action.).
Architecture: the role of architecture in this case is merely an enabling one.
Norm: this rule was dominantly shaped by the traditional norm, and it does not change it nor aims at changing it in the future.

8. **96.31(a) PA licensees may aggregate up to four PAL channels in any license areas at any given time. Partial ownership and attributions of interest are defined according to 47 CFR § 20.22(b) - Rules governing mobile spectrum holdings, attribution of interests and subject to the same aggregation cap.**
Law: being a rule, one of its dominant force components is the law. It was also somewhat shaped by the law, as the regulator had to make a compromise with the stakeholders while adopting it.
Market: this rule is about how much you can buy, so the market is the predominant force in this case. It aims to change the market as it will enable secondary market options in addition. The market stakeholder community shaped it by their demands for unlimited aggregation and supporting 40 MHz as a larger limit from what the FCC originally proposed (30MHz.).
Architecture: this aggregation rule is somewhat architectural as it manipulates the standardised building blocks, 10 MHz LTE channels. It is not attempting to

change the architecture, nor was it shaped by it.
Norms: The effect of the old, no-cap, no-sharing norms of traditionally privileged spectrum users had its role in putting the tension in the rulemaking process, so it affected the final middle ground of the regulatory position. The rule itself does not have a role in changing this norm.

9. **96.32(a)-(c) PALs may transfer or assign their licenses via leasing arrangements. They may not partition or disaggregate or enter leasing arrangement for a portion of their licenses. The leasing is permitted only for areas outside their protection areas, but within service areas.**
Law: being a rule, one of its dominant force components is the law. It is moderately shaped by the law, as the regulator's existing general rules (20.22) was kept throughout the process.
Market: This rule is defining another market variant and hence has a large market force component. It will keep on affecting the market somewhat, and the market stakeholders participated in shaping it.
Architecture: while bringing in a new line of markets, it also brings a new line of architectural setup, as it enables changes in borders between users and different spectral arrangements. It will be affecting the architecture during its implementation and saw the influence of architecture in its shaping.
Norm: this rule was moderately shaped by the existing norm, similar to the case of auctions. Being aligned with the existing norm, it does not aim at affecting it.

10. **96.9 PA, GAA users and lessees can all operate on a non-common and/or common carrier basis.**
Law: being a rule, one of its dominant force components is the law, and this rule in particular is all about regulatory status of CBRS users. It is dominantly shaped by the law, as the regulator's standard approach from other licensed services was kept throughout the process.
Market: This rule sets the eligibility for the market of CBRS and hence has a high market force component. It continues to influence the market through reinforcing the additional degree of freedom given to common carriers to be able to participate as GAAs.
Architecture: the role of architecture in this case comes as a shaper, as allowing GAAs to operate as common carriers is justified by the universality of CBSDs and their interchangeability.
Norm: enabling the operation of GAAs as common carriers, this rule is also enabling a change in the norm (as in Rule 3).

11. **96.23(b) and 96.33(b) Both CBRS tiers must register with an SAS and comply with technical rules for CBSDs as set in 96.39.**
Law: being a rule, one of its dominant force components is the law. It is dominantly shaped by the law, as this is the epitome of regulation.
Market: This rule does not have significant market component.

Architecture: the role of architecture is dominant as it is about tagging and controlling environment, as all CBSDs have to register with the SAS, comply with the same rules and be managed by the SAS when they operate in the band. Technical details of the architecture also shaped the rule.
Norm: As one of the rules making the users to get used to the SAS "bot" regulating the band, it is changing the accepted norm.

12. **96.35(c) and 96.35(d) GAA have no expectation of interference protection from other GAA users, must not cause interference to PA licensees and incumbent users and must accept interference from them. SAS determines and assigns them few permissible frequencies 96.53(b) without channelisation on an opportunistic basis.**
Law: being a rule, one of its dominant force components is the law. It was also dominantly shaped by the law, as the regulator resisted the initiatives from the part of the market to prevent opportunistic use.
Market: as this rule describes the "package" a potential GAA user is getting, it is moderately market in nature. In the long run, it aims to change the market's nature and it was shaped by the market: this time it was not the big carrier component of the market getting what they wanted, but the newcomers citing the success of Wi-Fi from the market viewpoint.
Architecture: this is an architectural rule as well, as it describes the SAS relationship with GAA users, opts for frequencies rather than channels and describes other architectural aspects of the tier. It does not affect the future of architecture and is somewhat shaped by the architecture referring to the state of the art in dynamic spectrum access and geolocation-database-driven spectrum sharing.
Norm: this rule was adopted against the usual non-sharing norm, so we do not say it is shaped by norm. It aims to change the prevalent norm and make sharing accepted, hence it is highly affecting the norm.

13. **96.35(e) GAA users operating outdoors in category B have to cooperate and coordinate with an SAS in the selection and use of available frequencies in order to minimise interference and maximise effective use of spectrum.**
Law: being a rule, one of its dominant force components is the law.This is one of the rules where the FCC is sending a strong message and it is exclusively shaped by the regulator.
Market: the message of the regulator is a time capsule ready to influence markets in the future of the band: if an operator desires to operate outdoors within category B (higher power), they should opt for a PAL, as a GAA status will ask for a lot of "cooperation", i.e. nuisance.
Architecture: this is a moderately architectural rule, as it implicitly deals with interference.
Norm: the regulator sets the norm here, inviting the outdoor GAA users (higher power) to be cooperative and patient with the dynamic reassignments which will occur often as they represent source of greater interference.

Table 8.2: CBSD RULES legend: fuzzy set L=low, M=medium, H=high, 0=blank

No.	Rule	IS				Affecting				Shaped by			
		L	M	A	N	L	M	A	N	L	M	A	N
1	Scaling from PA to GAA interchangeability	H	H	M	L		H		H	H			
2	CBSDs submit their information to the SAS	H		H					H	H		H	
3	Power limits and categories	H		H			M	H		M		H	

8.4.2 *CBSD Rules*

1. **By definition 96.3 CBSDs are fixed stations or networks of such stations that operate on PA or GAA basis in the CBRS band. Based on the interpretation of CBRS rules as a whole, this means that PA and GAA users are interchangeable in the framework. The decision on whether you as an operator choose to operate as a PA or a GAA is based on whether or not you need to buy protection as all CBSDs are the same.**
   Law: being a rule, one of its dominant force components is the law. It was also exclusively shaped by the law, as the regulator led the initiative and had the major impact on making it a rule.
   Market: it is a highly market related rule as it defines the possible transition between the players in the market and a possibility of a relatively quick change in the operating business model. It is going to affect the markets highly because of the players using this possibility in foreseeable and unforeseeable ways.
   Architecture: It is moderately architectural because the implementation of this rule is made possible by the CBSD equipment interoperability.
   Norm: this rule has a norm component as well because the FCC is saying "we have not prohibited this interchangeability, so why don't you make the best of it?", promoting sharing in a way. It has the potential of influencing the overall norm in the future as well, similar to other rules allowing the big players to act as GAA.

2. **96.39(a) CBSDs must have geolocation and reporting capability to determine and report their geographic coordinates to the SAS at the time of the first activation from power-off condition. 96.39(c) All CBSDs must register with an SAS prior to transmission with the following information: geographic location, antenna height above ground level, CBSD class (category A or B), requested authorisation status (PA or GAA), FCC ID number, call sign, user contact information, air interface technology, unique manufacturer's serial number, sensing capabilities (if supported) and additional deployment information (category A must inform will they be operated indoors or outdoors 96.43(b), while category B, limited to outdoor operations must submit: antenna**

gain, beamwidth, azimuth, downtilt angle and antenna height above ground level 96.45(c)-(d).) If any of the information changes, CBSD must update SAS within 60 seconds of such change. 96.39(c)(2) CBSD response time to SAS instructions is 60 seconds (to cease transmission, move to another frequency range or change its power level). 96.39(d) CBSDs must report on received signal strength and interference metrics (e.g. packet error rates) for itself and the associated end user devices to an SAS.
Law: being a set of rules, one of its dominant force components is the law. It was also dominantly shaped by the law, as the regulator had the imperative to make the data instrumental for sharing available in real time.
Market: it is not directly related to the market force.
Architecture: It is highly related to the architecture in its essence as it deals with architectural information and the SAS. It was also shaped by the architectural practice.
Norm: this set of rules has the potential to change the norm when it comes to data, trust and making sharing possible.

3. **96.41(b) Power limits are specified as follows (1) CBSD (category A) maximum EIRP 30dBm/10MHz, maximum PSD 20dBm/MHz; (2) CBSD (category B) maximum EIRP 47dBm/10MHz, maximum PSD 37dBm/MHz (3) end user device maximum EIRP 23dBm/10MHz.**
Law: being a rule, one of its dominant force components is the law. It was moderately shaped by the law, as the regulator adopted a middle ground solution based on architectural claims.
Market: it is affecting both the future equipment markets and the service providers' market as the power levels will determine feasibility of their deployment plans and business models.
Architecture: It is highly related to the architecture as it sets a standard for the equipment and deployments. As such it was instrumental in the shaping of the rule and has the potential for a long-term influence on the architecture.
Norm: this rule has no relation to the norm force.

8.4.3 *SAS and ESC Rules*

1. **96.53(a)-(o) SAS takes over the regulatory role, determines and provides information on channels, equipment, users, protects incumbent users and PA users from interference, ensures enforcement of policies, facilitates coordination and conflict resolution, regulates power levels for CBSDs, as CBSD must operate at or below maximum power level authorised by SAS 96.39(c)(1). 96.57(a) SAS must register, authenticate and authorise all CBSD operations. Also, 96.66(a)-(b) SAS is responsible for management of PAL spectrum leasing. In addition, 96.61 SAS must deploy secure protocols and procedures as a measure against policy violations.**

Table 8.3: SAS & ESC RULES legend: fuzzy set L=low, M=medium, H=high, 0 = blank

No.	**Rule**	**IS**				**Affecting**				**Shaped by**			
		L	**M**	**A**	**N**	**L**	**M**	**A**	**N**	**L**	**M**	**A**	**N**
1	SAS takes over the regulatory role	H		H			M	H	H	H		H	
2	SAS information gathering and retention	H		H					M	H			
3	Inter-SAS coordination	H		H	H		H	M	H	H		H	
4	Domain proxy for information exchange possible	H		H				H				H	
5	Dynamic zones based on ESC-SAS interaction	H		H	M			H		H		H	
6	SAS enforces default protection areas on PALs	H		H	L		H	M	M	H		H	
7	FCC, CBSD, ESC-to-SAS communication	H		H								H	
8	SAS operators can be PAL or GAA operator also	H	H				H		M	H	H		
9	Multiple SAS administrators nationwide	H	H				H			H		M	L
10	SAS licensing and business model	H	H				H			H			L
11	ESC is non-governmental sensing entity	H		H				H		M		H	

Law: being set of rules, one of its dominant force components is the law. It was strongly shaped by the law, as the regulator pursued the vision of the SAS-based regulation.
Market: this set of rules has no direct relation to the cellular carriers market. However, it is going to have an effect on the creation and evolution of the new SAS market
Architecture: It is highly related to the architecture as it sets a standard for the machine-enabled regulation. As such it was instrumental in the shaping of the rule and has the potential for a long-term influence on the architecture on both SAS and user side.
Norm: this set of rules has the potential to change the norm and make machine-enabled regulation a widely accepted concept for sharing.

2. **96.55(a)(3) Duty of SAS administrators is to make obfuscated CBSD registration information available to the general public. Also, according to Section 96.55(b) SAS shall keep records on all transmissions for at least 60 months. Exception to this are the transmissions of incumbents, whose retention is is governed through the ESC, 96.55(c).**
Law: being a rule, one of its dominant force components is the law. It was dominantly shaped by the law, as the regulator followed the vision of relevant data-keeping and protection of national security.
Market: it is not directly related to markets, not even to the SAS market as everyone will have to obey the same rule.
Architecture: It is highly related to the architecture as it sets a standard for data gathering and protection. As such it was instrumental in the shaping of the rule.
Norm: this rule has the potential to moderately affect the data protection and privacy perception norms.

3. **96.55(a)(2) Inter-SAS coordination, SAS administrators must make all CBSD information required to coordinate their operations available to all other SAS administrators.**
Law: being a rule, one of its dominant force components is the law. It was dominantly shaped by the law, as one of the most controversial rules that can make or break CBRS. Aware of its necessity, the regulator pushed for it.
Market: it is affecting the markets as the spread of "common knowledge" and open information will ask for a change of business plans and strategies. It will also make changes to the SAS market because of the sensitive information availability to all SASs nationwide who can also act as PAs and GAAs.
Architecture: It is highly related to the architecture as information exchange is a mean of architecture as much as the exchange of energy or matter. The changes it will impose on architecture relate to the questions of secrecy, privacy, reliability (e.g. implementation of blockchain). The role of the architecture in shaping the rule was fundamental as it described the minimum of information needed for spectrum sharing.

Norm: this rule is a norm in itself, as it prescribes information sharing. It is also affecting the future norms by liberalising the information perception, currently perceived as in need of protection and secrecy to guarantee security.

4. **96.57(b) information exchange between a network of CBSDs and an SAS does not have to be direct, as it may employ a sort of a domain proxy, a subsystem through which this communication will happen.**
   Law: being a rule, one of its dominant force components is the law.
   Market: no direct relation to the market.
   Architecture: It is highly related to the architecture as it stems from topology considerations and can greatly simplify the architecture for sharing through proposing a hub to collect and store CBSD information for forwarding to SAS instead of many CBSD-SAS direct links. As such it was instrumental in the shaping of the rule and has the potential for a long-term influence on the architecture through new design.
   Norm: this rule has no relation to the norm force.

5. **96.57(d) An SAS cannot authorise CBSD operation within Protection Zones without a confirmation of incumbent non-presence by sensing from an ESC. This is the concept of dynamic zones protecting the incumbents replacing initial static Exclusion Zones by facilitating ESC and SAS communication and coordination so that the most accurate data on spectrum availability within the CBRS band is maintained.**
   Law: being a rule, one of its dominant force components is the law. In a tour-de-force as the regulator, the FCC coordinated the interests of the state and the stakeholders and played a vital role in the rulemaking process making this particular discussion a great example of effective and successful policy making.
   Market: it is not directly related to the market, as it is an interaction between non-market incumbents and rest of CBRS.
   Architecture: It is highly related to the architecture as it lies in the foundation of spatial definition for the CBRS. The transition from static to dynamic zoning is the process of the future which will evolve with the CBRS and the effect on architecture will be significant. The influence the architecture had on shaping the rule is vital, as it was in the heart of the initiative to reduce the static exclusion zones geographically precluding 60% of population.
   Norm: this rule has somewhat of a norm in its nature, as it stimulates cooperation necessary for successful sharing and building trust in such a diverse stakeholders community: the military incumbents, the FCC and all three other clusters identified.

6. **96.57(e) SAS calculates and enforces PAL protection areas and this process is consistent across all the SASs according to section 96.25.**
   Law: being a rule, one of its dominant force components is the law. It was moderately shaped by the law, as the regulator aimed to find the compromise solution

around the challenge how to define PAL frequencies in actual use (where the engineering definition of 'in use' is adopted) allowing the users to self-report, but leaving the authority to SAS to enforce the default protection contour on them to prevent policy violations and discourage untruthful reporting.
Market: a reason for a user to faithfully report the protection area boundaries is that of secondary markets: it pays off to keep only the area actually "in use". This in turn means that this will influence these markets, but also the primary markets and deployments through a trade-off: faithful reporting for leasing purposes would allow the competition to deploy in proximity where they could not based on the default contour, but allows for leasing profit (and vice versa). We will discuss this trade-off in more detail later.
Architecture: This is an architectural question, in past, present and future meaning of it. As the shaper of the rule, architectural issues brought it to the table and suggested solutions. As the part of the rule itself lies the architecture of propagation, interference protection and coverage. Finally, in the future the rule will affect the architectural technical solutions in interference mitigation.
Norm: this rule is normative in its core as it calls for truthfulness and cooperation. It has potential to change the norms as well through the evolution of trust.

7. **96.59(a) Based on the information from CBSDs, ESC and other SASs, SAS determines the available and appropriate channels/frequencies and performs assignment. The FCC gets information on reassignment and shutting down of CBSDs based on ESC sensing upon FCC's request, and both the FCC and the CBSDs may request information about frequency availability, 96.59(a)(1)-(2). In the other direction of communication, SAS may request from the CBSD a confirmation which channels/frequencies will it utilise, in case the SAS had offered a range to select from. This may happen where the competition is not high (e.g. rural census tracts)**.
Law: being a rule, one of its dominant force components is the law. The regulator shaped the rule as an architect and not the lawmaker.
Market: it is not directly related to the markets.
Architecture: It is highly related to the architecture as it dictates the protocol design on the defined interfaces for the whole CBRS system and builds on regulatory architecture (the established ways of such information exchange). As such it was instrumental in the shaping of the rule.
Norm: this rule has no relation to the norm force.

8. **96.59(a) It is not prohibited for an SAS administrator to hold a PAL license, lease PA spectrum or act as a GAA user in the CBRS band as long as they behave in non-discriminatory manner.**
Law: being a rule, one of its dominant force components is the law. It was pushed by the regulator claiming that the public interest is not threatened by such an option.
Market: this is a market rule, as it defines the intersection of roles in the CBRS

market, akin to interchangeability rules. It is changing the future markets by opening prospects for potential multi-portfolio business plans. Market force highly shaped the rule with the future participants of SAS market playing the lead role.
Architecture: this rule is not directly related to architecture.
Norm: this rule has the potential to change the norms by making acceptable the diversity in the CBRS market.

9. **96.63 The FCC authorises multiple SAS administrators, nation-wide. Protocols and methods to authorise, assign and manage interference protection within CBRS are left to the FCC-qualified SAS administrators to establish and develop (e.g. which interference mitigation algorithms will they use, how will they design secure protocols and procedures for the database to ensure reliable communication and coordination in the CBRS band), 96.63(a)-(n).**
Law: being a rule, one of its dominant force components is the law. It was pushed by the regulator keeping the nationwide requirement despite the requests for regional (which would bring more competition, as the stakeholders claimed).
Market: this is a market rule, as it defines the SAS market. As such, it will continue affecting this emerging market.
Architecture: this rule was partially shaped by the architecture through the stakeholders (existence of WinnForum).
Norm: this rule is somewhat motivated by the anti-monopoly norm.

10. **96.63(e) License term for SAS administrator is five years, and it may be renewed. 96.65(a)-(b) SAS administrator can charge CBRS users for its service and collect reasonable fees approved by the FCC.**
Law: being a rule, one of its dominant force components is the law. It was pushed by the regulator despite motions from stakeholders asking for different charging mechanisms (e.g. charging GAAs only).
Market: this is a market rule, as it defines the SAS business model and what the player in SAS market gets. The emerging SAS market will change under the influence of it.
Architecture: this rule has no direct relation with architecture.
Norm: Unlike the previous rule, this one is not at all motivated by the norm orthogonal to the anti-monopoly norm from previous rule: it is shaped by the traditionalist long-term licensing norm.

11. **96.67(a)-(d) ESC is a database-aided sensing entity that has to be operated by a non-governmental provider and will be deployed close to Exclusion and Protection Zones to accurate detect incumbent transmissions and inform the SASs.**
Law: being a rule, one of its dominant force components is the law. It was supported by the regulator.
Market: this rule is not related to market force.

Architecture: this rule was shaped by the architectural demands, it is architectural in its foundation as it adds the sensing component and dynamics to sharing architecture and hence has the potential to change it in the future through novel design.
Norm: this rule is not related to the norm force.

8.5 DISCUSSION: BALANCE OF THE FORCES AND THE IMPLICATIONS

The tables 8.1, 8.2, 8.3 from the previous section can be interpreted in a timeline. The rulemaking process is the past, the history of different forces *shaping* the rules. The present is the *identity* such rules shaped in the past have now in the present: they join the forces (could be components of all 4 forces, or 1 dominant one etc.) and become one with them. From that point onward, we speak only of forces, while the rules still exist they became the medium through which the forces act (on the dot). This is the future in which the forces interact and catalyse the change in dot's behavior but also in the intensity of the forces. This is when we speak of forces *affecting* other forces. This is the context in which the discussion should be understood.

After assembling the tables we proceed by searching for patterns in them. We use the machine learning tools described in Chapter 6 (EM algorithm for clusterisation in Weka). While the motivation for this choice has been discussed earlier in Chapter 6, let us repeat the details relevant to this chapter. Weka implementation of EM clustering has the ability to identify the number of clusters on its own from the data using cross validation. Compared to alternatives such as k-means clustering, EM has a more generalised approach and allows observing an rule with its probability of belonging to a cluster. With fluid, multi-faceted rules this is instrumental. After all, what we were looking for are the sets formed at the intersections (e.g. rules that are highly shaped by norms and low in affecting the architecture) which is much more informative than two clusters "market rules" and "architecture rules". It is important that the algorithm recognises these non-trivial clusters as it helps further analysis.

The first, naive approach can be to cluster the rules based on what they ARE (their identity with respect to forces, the first super column of the tables). Doing so results in three groups (clusters): 11 market, 13 architecture and 3 norms representatives. If we proceed by adding the other columns (the forces a rule affects, the second super column and the shapers of a rule, the third super column) to the attribute space and continue clustering, the result is somewhat different. Namely, the three clusters we get are not the three distinct forces anymore.

The clusters can be described as: (1) market rules (nine of them[7]), (2) architectural rules that will affect the market (five of them) and (3) architectural rules that will NOT affect the market (thirteen of them) as shown in Table 8.5. The difference between the two subsets of architectural rules is not only in that one aspect, whether they are affecting the market or not. The other difference is their relationship with norms: the architectural rules that affect the market also highly affect the future norms (the effect on the future norms of other architecture rules is low). This bears even larger significance when we note that the market rules themselves only moderately shape the future norms.

Further analysis of the clusters represented in Table 8.4and Fig.8.3, gives us even more insight. The fuzzy variables have been converted to crisp ones for a showcase: H is replaced with a ten, M is a five, L is a two, and the blank is zero. This allows us to get a feeling of what an average element of a cluster looks like. We proceed with the analysis of the table, recognising the characteristic values differentiating the clusters (written in bold in the Table).

The effect of law force on shaping these rules ranges from moderate for markets to high for the architecture. This is a direct consequence of two underlying principles: (1) in our interpretation, regulation is a zero sum game for market-based stakeholders and (2) the exact nature of architecture. The zero sum game in this case denotes the fact that the regulator wins whenever market stakeholders lose the game (the game being shaping the rules). Conceding to a compromise is "the defeat" of the regulator, while market objections being ignored is "the defeat" of the market stakeholders. The case of architecture is different as the architecture pundits and the regulator can be on the same side and iteratively improve the rule. This is why an architectural rule is shaped by both, the law and the architecture in a significant way. It helps that the questions of architecture usually have a definitive answer while those of the market may not have it. **This is the first important point we find**: the force of law adds to the one of architecture but subtracts from the one of the market.

The architecture affecting the market is a bridge and we will refer to it as such, but stay assured it is in its essence architecture. The market component of it is low (the market component of the other architectural rules, those not affecting the market, is non-existent). However, the effect this bridge has on markets is equal to that of the markets on themselves, very high. **This is the second finding**: there is a powerful component of architecture creating the future of markets. Market rules are moderately shaped by market (cf. discussion in the previous paragraph), while the effect of market force on the architecture rules there is low to non-existent.

[7]The rule CBRS 9 has been excluded in initial process of clusterisation, as it is substantially different from all others. As we will see later, there are architectural rules with a high effect on the market but only one market rule with a high effect on the architecture: CBRS 9. This makes it an antipodal point to the architecture-market bridge, the lone representative of the market-architecture bridge. This rule was subsequently included in the market cluster by the algorithm itself (given its attribute values). The rule was excluded initially as it prevented the cross validation procedure in making more than a single cluster.

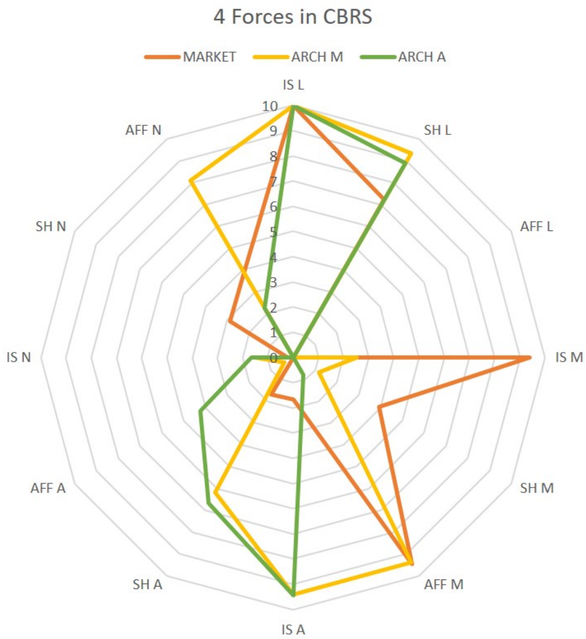


Figure 8.3: Four Forces in CBRS

The architecture component of the market rules cluster is low: combined with the finding of low market component in the architecture, this tells us that the two clusters are rather disjoint in this sense. Architecture force also had a low participation in shaping the market rules with a significantly larger influence in shaping the architectural rules. Finally, the market and the architecture related to the market are not going to affect the architecture, while the market-independent architecture has significant potential there.

Market rules are shaped at least to some extent by norms. Here we mean the traditional norms, existing at the time of the rules creation. These norms embody the capitalist spirit and the habits of the stakeholders. When it comes to the future norms, the market-independent architecture and the market have a low to medium potential in affecting them, but the architecture affecting the markets highly affects the norms as well. **This is the third finding.** Finally, market rules themselves do not have normative component at all, while both types of architectural rules do have a low degree of normative character.

Returning to the timeline of the forces, we depict the findings in Figure 8.4.

While the law has its part in shaping all the rules, the devil in the details is to be sought in the interaction between the other three forces. The architecture-market interaction is asymmetrical as the architectural input was participating in market rule-making more than the opposite. The market relied on shaping itself, while fighting the input from the law and getting support from traditional Norms. Norms themselves remained slim.

That is what we see in the present as well with the imbalanced forces stemming from the all encompassing Law. While the imbalance of the present should be quali-

Table 8.4: Clustering results

Cluster		Market rules	Architectural rules affecting the Market	Architectural rules NOT affecting the Market
L	IS the Law	10	10	10
	Shaped by the Law	7.23	9.37	8.9
	Affecting the Law	0	0	0
M	IS the Market	9.39	2.54	0
	Shaped by the Market	3.93	1.2	0
	Affecting the Market	9.45	**9.39**	0.8
A	IS the Architecture	1.68	9.39	9.45
	Shaped by the Architecture	1.7	6.2	6.68
	Affecting the Architecture	0	0.4	**4.23**
N	IS the Norm	0.2	1.53	1.66
	Shaped by the Norm	**2.88**	0	0
	Affecting the Norm	3.9	**8.1**	2.25

Table 8.5: Clusters and Rules

No.	Market Rules	Architectural rules affecting the Market	Architectural rules NOT affecting the Market
1	CBRS 3	CBRS 1	CBRS 2
2	CBRS 4	CBRS 5	CBRS 11
3	CBRS 7	CBRS 6	CBRS 13
4	CBRS 8	CBRS 12	CBSD 2
5	CBRS 9	CBSD 1	CBSD 3
6	CBRS 10		SAS 1
7	SAS 8		SAS 2
8	SAS 9		SAS 3
9	SAS 10		SAS 4
10			SAS 5
11			SAS 6
12			SAS 7
13			SAS 11

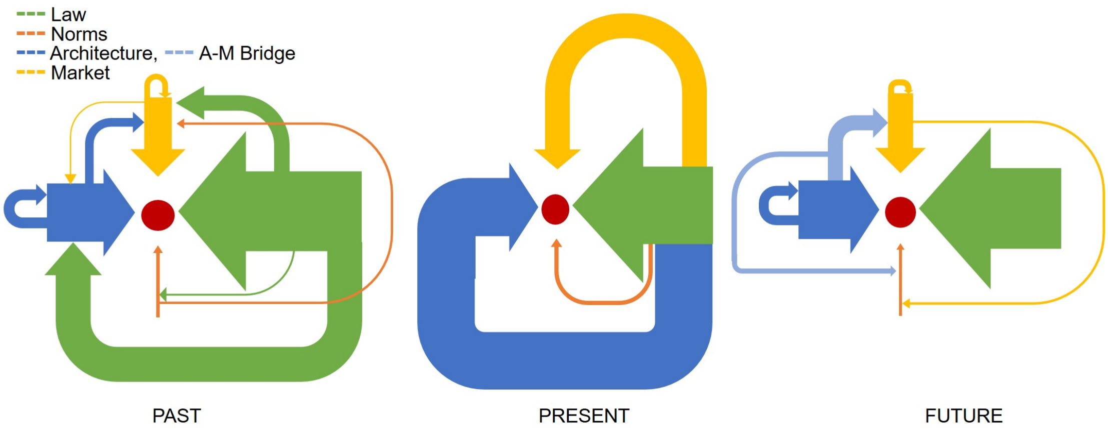


Figure 8.4: Past (Shaped by), Present (The identity), and the Future (The effects) of the forces

tatively obvious from everything we have seen so far, it deserves to be addressed at this point as it answers two of the questions we started with. The balance does not necessarily mean equal distribution of the forces (i.e. the thickness of the arrows), as a few strong rules can bring order or chaos, depending on the arrangement. However, non-existence of a force or its significant under representation does necessarily mean imbalance. This is the case here where the Norm is represented by comparatively weak rules, small in numbers and effects. To rephrase it as the answer to first two research questions: Yes, there is imbalance in the CBRS force distribution and the cause is the lack of norms. With this in mind, we proceed to the future.

The future bears some similarities with the past, namely the circular nature of architecture and the markets. However, it brings us an important new feature: the effects of market and the architecture on the norm. The nature of this effect is described in the previous section whenever the relationship with future norms is diagnosed. What we note is the more significant role of the architecture force in this reinforcement of norms and the fact that it's a particular component of the architectural force doing all the work. As this deserves more attention, we will address it in a dedicated subsection.

8.5.1 *NTBRS and Pathetic Dot Theory*

The reader may have noticed similarities between the NTBRS components and the forces in Lessig's theory. The shaping of the rules by the forces is analogous to the effects of NTBRS on the issues we saw in Chapter 6. Let us compare the vision of the separation points through the lens of NTBRS and how the final rules stemming from them were shaped by the forces.

> Short term licenses and small licensing areas were deemed crucial for innovation: however, the inclusion of mobile operators in the PA tier shifted the attention from the innovativeness of the CBRS band to the question of revenues and profit. The deviation from traditional long-term, renewable licenses was not seen as a profitable option.

> The approach in which the new band is extra food for old, traditional consumers is not a fertile ground for sharing. In the view of NTBRS, this is a failure of regulation, as it leaves the door open for reversion to old models that have proven to work for the old conditions of non-sharing. For the big carriers, there will always be a reason why to give up sharing, if that option is on the table. This again necessarily corresponds to the necessity of societal, cultural change.

This sentiment is captured in the story of shaping the license term rule as well:

> 96.25(b)(3) PAL will be issued a license for three years, non-renewable. According to 96.27(b) PAL may apply for two consecutive terms within the first application window (accepted every three years, 96.27(a)).
> *Law*: being a rule, one of its dominant force components is the law. It was also **somewhat shaped by the law, as the regulator had to make a compromise with the stakeholders while adopting it** (the regulator first proposed 1-year license terms with 5-year cap.)
> *Market*: the market component is predominant in this rule because it solely defines what is being sold and constrains the planning in terms of business models Hence it is also changing the business models. At the same time, **it was the influence of market stakeholders clinging onto the longer-term license proposals that made the regulator eventually adopt a middle ground solution.**
> *Architecture*: Compared to the role of other forces, architecture force did not have any weight in this rule because the nature and technology of CBRS environment had no effect on short term license adoption.
> *Norms*: Again, relationship of this rule with the norm is one of going against the flow. However, **the traditional licensing norms have had its part in shaping it** through the voice of the big carriers asking for a compromise. It continues with an attempt to change that norm by making the stakeholders accept the short time-spans.

Is having five components of NTBRS redundant when Lessig's theory works with four, conveniently merging the natural laws and the artificial technology under the single umbrella of architecture force? If we observe the Fig. 8.4 or Table 8.4 we note that the two clusters of architecture have substantially different character, hence different colouring in the "future" part of the figure. When we read the rules that are classified under market-independent architecture tag from Table 8.5, they are dealing with the technology: the artificial constructs of SAS, CBSDs, small cells power levels, ESC, while the bridge consists of rules related to the nature of spectrum space: geography, frequencies, time - radio environment. Here we recognise the two components of NTBRS emerging from the unified Architecture - Nature and Technology may be appropriately bundled in Lessig's theory for general considerations, but in our case the force splits. The fundamental reason why we cannot ignore the existence of the two components and observe them as one lies in the core of this thesis.

8.5.2 *Norms and Culture of Sharing*

How can Culture of Sharing make Sharing a Norm? By building trust. The trust can be built by explaining, reasoning and communicating - and having this conversation in the language of incentives. Just like Lessig speaks of seat belt education campaigns, so do we. The first type of conversations is about the value of spectrum in the sense that the privileged users in spectrum bands need to start considering sharing as an opportunity to build new business models and not continue to see sharing as a concept hindering their revenue generation. The second type of conversations, once the value of sharing is disseminated, is about the need for protection. The technology we have today is more robust to interference than ever before. Once the coexistence is a normative imperative, the innovation efforts would be turned to an enabler of coexistence. Once the users are incentivised to innovate to be able to operate and coexist in the bands, as the norm is sharing as predominant way to access spectrum, the technology will fit in the puzzle. This is when the third type of conversations comes in, talking about the right to access spectrum and not the right to own spectrum anymore.

Culture of sharing is important part in sharing economies, where the resource is not necessarily owned to provide service or be serviced. It found its place in our NT-BRS framework within the Society and we have seen calls for the discourse change: replacing sharing economies with sharing cultures. This corresponds to a change in Lessig's norms-markets relationship: when it comes to sharing, norms have to be more powerful than markets in order to overcome the burden of legacy. In our concrete example of pathetic dot analysis, we have seen another link between norms and markets. The same part of architecture - the nature - affects both, norms and markets. The link exists.

Important to note here is the distinction between the future norm and the present one. When we speak of norms in positive sense that is not the norms that have been shaping the framework because those norms have nothing to do with norms we wanted to see in CBRS. Their nature is different: the current have negative influence on sharing and the future norms have a positive one. The current norms, as mentioned few times, are those encountered in traditional band managements, represented via very particular mindset of a cellular licensed carrier.

We did not forget the gaping open question of why we need to distinct architecture force components in our consideration of CBRS. A superficial approach to correlation between affecting markets and affecting norms might result in wrong conclusion that if we push hard enough on the markets, we are going to change the norms. However, the findings we started the discussion with contradict this: Fig. 8.4 and Table 8.4. Our results show that the bridge, or as we now call it - the nature (architecture) - affects norms a lot. They also show that the nature affects markets a lot (as much as the markets themselves do). Even though the market reinforces itself, there is still fresh source of change coming from the architecture force, so this means that the market can be changed. They also show that when markets affect the norms it is not as powerful as when the nature does it. And yet the technology, in the way it is encoded in the rules, in either case has no effect. So the nature has to change the markets and norms simultaneously. This means that the way to build the culture of sharing in spectrum sharing systems is to act on the architecture force (its nature component) to make the nature change markets and norms simultaneously.

This is the main finding of the thesis as it goes to prove our claim that the spectrum is a resource like no other and if we want sharing to become a norm, it has to come from the Nature of the resource.

8.6 Chapter summary

The socio-economic theory of regulation, introduced by Lawrence Lessig, was the natural choice for the analysis of CBRS framework as it captures technology, economics, policy and politics of CBRS model. Pathetic dot theory stems from the tradition of the Chicago school recognising different modalities of regulation, that act as forces on the behavior of a regulatee placed in the pathetic dot. These forces are law, architecture, norms, and market and their net effect has the ability to change the behaviour and to regulate it to the desired end. Therefore, we introduced old and new Chicago schools, in particular their difference in perception of the law force and the role of the regulator. The concept of law always regulating directly but also indirectly by acting upon other structures of behavioral constraints (architecture, norms, and markets) is the one that Lessig adopts and so do we. We extend it by looking for other important interconnections between the remaining three forces.

In this chapter, we introduced old and new Chicago schools, in particular their difference in perception of the law force and the role of the regulator. The concept of law always regulating directly but also indirectly by acting upon other structures of behavioral constraints (architecture, norms, and markets) is the one that Lessig adopts and so do we. We extend it by looking for other important interconnections between the remaining three forces.

Our investigation is led by three research questions which we answered successively. Based on fuzzification of relationship between CBRS rules and the forces, we observed this relationship throughout the process: from the rulemaking process analysed in Chapter 6, to the announcement of final rules and beyond. We detect the imbalance in the rules and diagnose that the norms are the weakest link. In the most challenging part of the discussion we examine what is going to happen with the norms as the time progresses and the ecosystem evolves. We discover that the group of rules corresponding to the architecture is not homogeneous. The separation in this cluster is with respect to the effect these rules have on markets. As it turns out, rules related to the nature of the resource and the spectrum space have a significant effect on the markets. The rules about the technology do not. This extends to the norms as well, as we note that the effect of nature on norms is greater than the effect of the markets (on norms). Here we conclude that this relationship has to be put to use to achieve spectrum sharing. A particular component of the architectural force, the one of nature in the NTBRS framework is responsible, we found, for building the norms of sharing. This established NTBRS as the superior model for regulation analysis in case of spectrum sharing and opened the space for the discussion on the details of culture building. Namely, we use this argument to support our claim of the importance culture of sharing has on shaping the behavior and start the roadmap on achieving it. The roadmap will be set out in the next chapter.

Slaying the Dragons

"With great power limits comes a great responsibility of using power wisely, Charlie."

Audio version at: `https://www.youtube.com/watch?v=_FihMauWXUM`

Manifesto

"You're the right person to read it, you might find a new slogan in there. "

Audio version at: `https://www.youtube.com/watch?v=kdynPA4negU`

9 THE FUTURE OF DYNAMIC SPECTRUM SHARING

To draw a final line, in this chapter we conclude with: a summary of the work in Section 9.1, an outline of a way forward by proposing SPECTRUMISM as the underlying philosophy of spectrum sharing economy in Section 9.2, and a preview of our future work in Section 9.4.

9.1 SUMMARY OF THE THESIS

PART I aimed to introduce the problem in its wide context, the one which culture of sharing asks for. With reviewing the current radio spectrum affairs, we offered an uncommon approach of connecting the domains (physics, economics, engineering, and law) found within a complex spectrum ecosystem.

PART II starts by showing that the problem was not in something we found in asking why spectrum sharing is not sustainable, but the problem was in something we did not find. Chapter 3 recognised the important role of nature, technology, business and regulation we extensively surveyed in the previous chapter. However, the critical component was missing: the culture of sharing. Without it, sharing does not have a chance, our NTBRS framework suggests. The NTBRS framework was just the first in the set of heterogeneous research tools and methods we employed to explore this problem. Devising the methodology in Chapter 4 was a challenge on its own, as we needed to capture the rich and diverse ecosystem. As spectrum is social issue per se, we found it appropriate to introduce social science research methods to engineering, while relying on engineering methods as well.

PART III is where the case study of CBRS sharing model is conducted. We aim to learn from the destination and the journey and to understand the events that have led to the present state of the CBRS model. Chapter 5 showed how an attempt of paradigm shift in spectrum policy came after a century of legacy ballast, as its compelling evidence of regulations never being able to catch up with technologies is presented. Chapter 5 also shows whose shoulders are to carry the responsibility of the spectrum paradigm shift, as it introduces the reader with the regulator and its complex organisational structure and rulemaking process. We study the behaviour of the stakeholders in Chapter 6 to learn more about them and the spectrum band they are to inhabit as we are interested in how it is different from non-sharing, traditional spectrum bands. Through a rigorous content analysis of an entire CBRS proceeding under the docket 12-354, we encounter the domains of NTBRS framework mirrored in the ten separation points of CBRS band and a non-sharing/traditional one. Chapter 7 dealt with the question of licensing areas in CBRS, the one issue for which the regulator did not seek a middle-ground solution. We investigated the issues with the proposed solution of census tracts and the ways to bring the balance into it, aggregating census tracts to increase their usability while retaining small licensing areas available to all market players.

Part IV is where the search for balance intensified. In Chapter 8 we observed the interplay of modalities of regulation shaping the behaviour in the CBRS band. We applied Lessig's pathetic dot theory which observes the behaviour of a pathetic dot with the four forces of market, law, norms, and architecture acting on it to produce different behavioural effects. We extended Lessig's approach to examine the effects of modalities of regulation interacting with each other, not just acting on the regulatee. A particular component of the architectural force, the one of nature in the NTBRS framework is responsible, we found, for building the norms of sharing. This established NTBRS as the superior model for regulation analysis in case of spectrum sharing and opened the space for the discussion on the details of culture building. In Chapter 9, we free the spectrum resource from all of the constraints and boundaries encountered in CBRS case study and the pre-CBRS historiographic exposure. We use the findings of previous eight chapters and the ideas hidden in plain sight to: (1) announce the discovery of the dimension of data in spectrum space, (2) propose licensing scheme that is uniquely tailored to spectrum nature, (3) recognise the link to incentivisation, and (4) further explore culture of sharing as the component of norm force which is now getting a concrete shape. Along with the ideas around spectrum uniqueness, these four concepts distributed in the five domains of NTBRS framework constitute our proposed philosophy of SPECTRUMISM.

9.2 A WAY FORWARD

Efficient, optimal spectrum use must be the primary regulatory objective. If we do not have efficient, optimal spectrum use, we will not have spectrum at all, we will have the biggest spectrum crunch to-day. All of the components of spectrum sharing model have to contribute to this goal: the interference protection framework, the licensing model, the band plan, technical specifications etc. What follows is a precise portrait of a way forward envisioned in spectrumism and discussion of its potential implications on dynamic spectrum sharing of the future.

9.2.1 *Why the need for a vision?*

The spectrumism implements the concepts laid out in thesis introduction, as vision of dynamic spectrum sharing in which culture of sharing can thrive.

Chapters 5, 6, 7, and 8 analysed the issues through a CBRS case study using different methodologies to expose them. We started by presenting the vision of PCAST report and aimed to see if the vision is implemented in the CBRS sharing model. The case study saw the PCAST concepts mapped into the CBRS band, to an extent - it has been a tale of scaling down.

As a response to PCAST's call to identify the bands in which military spectrum could be shared with other users, one of the two bands identified by the NTIA was the 3.5GHz band. The FCC initiated the creation of CBRS with the NPRM and this was the first step towards creating one lane in the superhighway: from the initial 100MHz, CBRS became 150MHz. The three tier model is adopted for the CBRS band, but not as diverse in users and in license terms as it was envisioned by PCAST. As we have seen in Chapter 6, the PA tier was overtaken by the big carriers, with the license model tailored to fit their needs. The critical mission users envisioned by PCAST are not left with much choice but to compete in expensive auctions for the licenses. The SAS as the sharing architecture is adopted for the CBRS, but not performing[1] dynamic allocation and assignment to the extent that the PCAST envisioned. The test city as envisioned by PCAST, is not a part of the FCC policy on CBRS, but the substantial effort towards testing is evident within the stakeholders community (in particular WinnForum and CBRS Alliance, as trials and prototypes and some experimentation are happening, as described in Chapter 6). There has been a great deal of work on incentive mechanisms for the incumbents to share their spectrum[2,3], but the spectrum currency concept envisioned by PCAST is not addressed actively, at least not at this time. An attempt from the regulator to standardise a new spectrum effectiveness metric as proposed in PCAST, is not observed. The PCAST concept of receiver regulation has not been adopted either.

In summary, the elements of a multi-tiered access model adopted for CBRS are significantly different from what PCAST proposed. Here is the opinion of Preston Marshall about a particular part of multi-tiered access model adopted for CBRS, the

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[1]Wireless Innovation Forum Webinar Series #21 Originally presented on 22 February 2018 (slides are available at: `http://www.wirelessinnovation.org/assets/Webinar_Slides/winnforum%20cbrs%20baseline%20standards%20webinar.pdf` video at: `https://www.youtube.com/watch?v=pWqSpF69CtI`)

[2]Lenard, T. & White, L., 2006. Digital Age Communications Act: Report from the New Spectrum Policy Working Group, Tech. Policy Inst. 1, 20. Available at: `http://www.techpolicyinstitute.org/files/9.pdf`

[3]Robyn, D., 2015. Making Waves: Alternative Paths to Flexible Use Spectrum. Available at: `http://www.aspeninstitute.org/sites/default/files/content/docs/pubs/Making-Waves.pdf`

PA tier. He is one of the leading figures in the process of CBRS framework design, initiator of CBRS Alliance, consultant for a PCAST report and the representative of the Google Inc., a dominant stakeholder in the 3.5GHz public record proceeding[4]:

> The proposed PCAST mechanism for acquiring PA status was not adopted by the FCC, but was interesting, and very flexible. Some of its attributes include:
> 1. Auctions were continuous, and were triggered based on mutually exclusive requests for rights. Devices or networks would request to acquire spectrum rights, and bid against any other users whose protection requests would conflict with theirs. This framework resembled the structure of Internet advertising, where extremely rapid auctions determine the placement of advertisements in search results, or placement on web pages.
> 2. Protection criteria and emission characteristics were specified by the user, rather than by regulators. Requests for excessive power or receiver protection would cause more conflicts with other users, and likely raise the cost of acquiring protection. The level of the requested protection in these requests would be left to market forces to balance.
> 3. Receiver characteristics, such as adjacent band and channel protection requirements, were included in the request for protection. Rather than impose receiver standards, poor receivers would conflict with potential users over a greater area, and again, raise the likely cost of obtaining protection of poorly performing devices. This would continually incentivise improvements in receiver performance through market forces, rather than static, regulatory decision-making.

The PCAST report gave us the wide, general principles of future spectrum sharing policies. The FCC action on PCAST recommendations narrowed down the general principles to focus on a specific band. The result of these efforts is a very extensive public record which served as a case study in order to propose a set of principles that are narrow enough to be implemented as a bundle of ideas and solve the spectrum conundrum if thinking long-term. Spectrumism is an attempt to encompass both, the PCAST vision and the FCC realisation of it, in order to propose a way forward.

9.2.2 *A Futuristic Scenario: Key Ideas and Principles of Spectrumism*

In Fig. 9.1we illustrate the key ideas behind the vision. This is a futuristic scenario of a spectrum sharing economy, which we termed SPECTRUMISM. As a sample of spectrumist future, the scenario envisions the future where: (1) the uniqueness of the resource is the topic appreciated in the boardrooms of stakeholders companies ($\exists!$, exists only one)[5]; based on our findings, this also means meaningful incentivisation and building

[4]Marshall, P., 2017. Three-tier Shared Spectrum, Shared Infrastructure, and a Path to 5G. Cambridge University Press

[5]It is not the similarities with other resources the strategies are based on, but the unique aspects of it instead.

of culture of sharing, (2) licensing and on-the-fly regulation is performed by machines, both on the distributed regulator and spectrum user side, (3) the data flowing through this management chain reveals both the physical reality of a distributed dynamic spectrum sharing system and the plans devised in the boardrooms, (4) short-term, small-space modular licenses as building blocks in all spectrum dimensions (time, space, frequency, and data), (5) users are aware of spectrum importance and spectrum sharing necessity, (6) mix of mobile base stations (drones) with very dynamic licensing demands coexist with the fixed ones which have a role in wide deployment strategies.

These principles are embedded in an architecture with two telecom operators (grey and blue) operating in an area and communicating their spectrum needs to a branch of the distributed regulator network. The grey operator has an intelligent computing hub (domain proxy) aggregating inputs from the management and data from static and mobile equipment deployed in space, so all communication with the machine regulator is done by the operator's own machine. With the small and short licenses this device also takes on itself the responsibility of renewing licenses, applying for new ones and planning future bidding, while the distributed regulator takes on itself the role of the license granting body as well, performing fast auctions locally. The blue operator has no such hub and their equipment is connected directly to the regulator. In this intelligent machine to machine interaction, this implies a level of intelligence at the equipment level as well, so the blue operator's equipment runs and licenses itself autonomously, on an autopilot mode. This can be a fairly simple system where the operator sets a fixed threshold of relevant parameters (number of users, QoS, profit gains over the license cost, etc.) for a base station within a license period. As long as the parameters are within the defined limits, the base station reapplies for the license, but once they are not, the base station stops reapplying and ceases its operation.

9.2.2.1 *Uniqueness*

This thesis introduced and throughout the chapters 2 and 5 reinforced the idea of spectrum uniqueness. What makes spectrum a unique resource compared to other *natural* resources is the combination of its following features:

- shareability and instant renewability,
- spectrum is a sociopolitical resource, and
- spectrum does not exist until technology puts it to use.

Spectrum is not the only shareable resource but the way in which spectrum shareability is different to shareability of other resources is in its physics and metaphysics: spectrum is a fluid, fast cleansing natural resource. It is a "public" resource, like water, gas, land or minerals, but unlike these resources, spectrum is instantaneously renewable (like wind and solar power). In addition, it is perfectly renewable, as it retains the same functionality throughout infinitely many uses. It is recyclable because technology can reuse the frequencies. All of these are interchangeable terms that can describe spectrum nature.

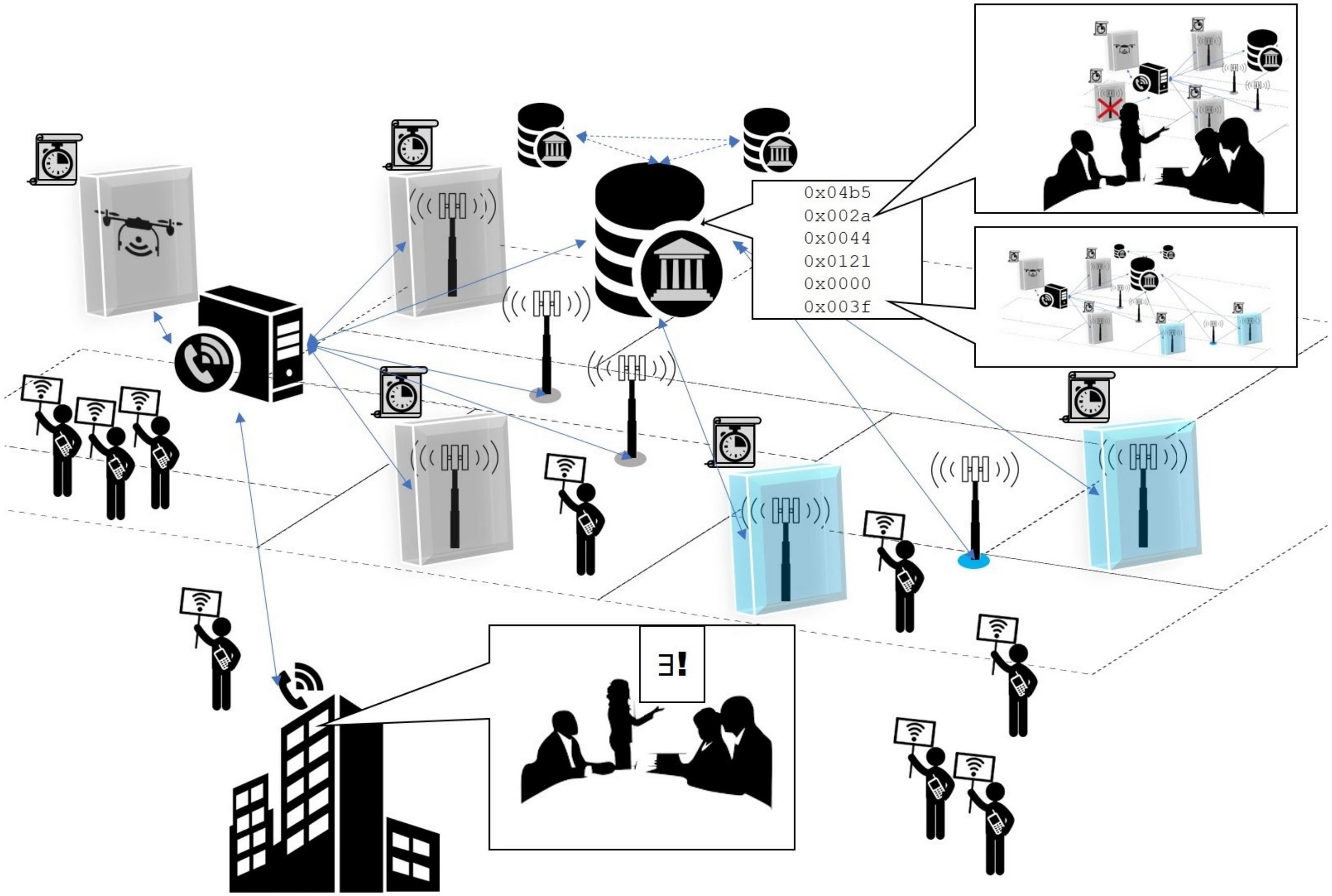

Figure 9.1: Spectrumism in a future scenario

For a sustainable consumption of spectrum, these properties need to be put to use. It is not the only shareable resource which is currently not being shared and is underutilised. However, the additional natural features of spectrum obviously call for putting it in an optimal, efficient cycle of use in order to avoid the great imbalance of high unsustainable density of use in some points of spectrum space and then the desert of unused spectrum space surrounding it.

The relationship of spectrum with the communications, (free) speech, the government, the broadcasters and the telecom operators is a unique property of spectrum that makes it a sociopolitical resource. Each of these relationships drives the historical dimension of people and spectrum relationship and asks to add social science research methods into the spectrum analysis toolbox for devising a unique policy. At the same time, the spectrum resource consumption inevitably relies on economics and technology. The mix of social science, economic analysis and technical science research tools is necessary for a design of spectrum policy so that it is uniquely tailored to spectrum resource.

Spectrum resource exists only when put to use by technology, i.e. the stakeholders make it real. Hence, the relationship of spectrum and stakeholders/spectrum users is tighter than that relationship with other resources. Because of that, the effects of incentivisation and norms within stakeholders' community are stronger than it is the case with other resources.

In the figure we see the acknowledgment and appreciation of spectrum uniqueness in spectrum sharing ecosystem (stakeholders boardrooms). Implicitly, the same can be stated for the regulator and the citizens.

9.2.2.2 *Data dimension*

The current representation of spectrum in the electrospace shows erratic discontinuities, the jumps from one time instant to the other, one frequency to the other or one point in space to the other. This seemingly random behaviour could be explained and joined in a regular structure if another dimension was added. Assume a figurative dimension (without a unit) describing the operators' decisions on deployment and operation. It joins all the dispersed points in the electrospace and shows where the new ones will appear. This dimension is not impossible to reconstruct: while it seems to ask for mind-reading at first, reading the historic data may suffice as data science shows. Hence, this dimension is the dimension of data. It is an extrapolation from the data points in old electrospace, but also from other data sources. This thesis has shown a lot of data sources that complement the raw deployment information: e.g. the rulemaking proceeding is one of them, census data the other. It is not just a linear combination of the existing electrospace coordinates, as it brings new information, the one about stakeholders' decision mechanism. Hence, the dimension of data stems from the unique property of spectrum only to appear when in use by the stakeholder, when the transmitter is on.

In this consideration, the data dimension is taken figuratively, without putting a unit on the axis (bits?). However, one may think of quantitative metrics, such as valuing data according to the information entropy of it (data bringing surprising results being more valuable than the monotone repeating information).

The dimension of data has not been observed "in the wild" as the traditional users are segregated in all other dimensions of spectrum space. The further the two users are, less they care about the neighbouring use and the intentions of the other users (the plans, the strategies). The (spectrum) crunch shrinks most dimensions, the users are brought into coexistence in space, time, frequency. The importance of intentions of the neighbours grows - the ability to complement them and anticipate them. It is no coincidence that the amount of real-time data associated with successful, efficient use of spectrum in such conditions grows as well[6] - as the data embodies the intentions. The sharing needs to be dynamic for the data to achieve its full potential, which is why this is different from the data dimension in the provisionally available spectrum models, LSA and SAS data. In the most dynamic sharing envisioned so far, type of information the spectrum users need to reveal to the band manager like the SAS is: their network deployments, intentions to operate and on which locations, exact times and frequencies they are active or when they cease the operation, power levels they use and other specifications. Based on this information, the SAS builds the spectrum dimension of data - having the most accurate information about spectrum usage based on real-time radio environment conditions. This is the instant effect of data, short-term, in real time. But there is the long-term effect of the information built as described. If this information is made accessible to the other inhabitants of the band, they may plan their operation and organise their deployments and coverage accordingly, so that they are able to coexist while achieving strategic goals. The short term effect is mostly for the functional real-time band manager and for spectrum sharing to work, but the long term effect is for the entire CBRS ecosystem.

In the figure we see the bits of data telling two stories. One is the story of the current deployments, while the other gives an insight into the boardrooms and the process of decision-making through the evolution of deployment and use.

9.2.2.3 *Machine-enabled regulation*

The perspective of an artificially intelligent network taking over control is a notorious one in the general public, often resulting in citing Skynet and other Sci-Fi concepts with dystopian results. In technological communities the perception tends to be different, as confidence and awareness of the technical capabilities of the machines grows. If spectrum world was a purely technical one, automation of regulation and management would be a cause for celebration. As we have seen in Chapter 6, however, for some of the powerful stakeholders the powerful dynamic SAS was an unwanted guest.

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[6] Suddenly, the need to track interference from neighbouring use becomes higher. The need for sensing grows, as well as the need to coordinate. All of this generates more data.

In the spectrumist perspective, the machine is the natural choice for the regulator. It has the ability to handle vast amounts of data autonomously, to seamlessly integrate with fellow machinery doing sensing and communication and it can learn. Allowing the digital regulator to learn and adapt opens the space for flexible regulation and decisions on the go, quick integration of new technology and adaptation to new conditions. As the timescale of changes in the system goes down to seconds, the switchboard operator has to be replaced with the automated one, but this comes with a twist. We call not just for the automaton in the middle, but also the automata at the ends of the sharing chain. In the current loop, the request for spectrum in a company would come from the engineers to the traders of spectrum who would acquire what is needed through strategising, black magic of sorts and techniques the engineer asking for spectrum would find illogical. What if the spectrum trader in residence was also a machine like the regulator, giving the engineer a button to demand the spectrum they need, or, even better, predict what they need? This scheme is not unlike the machine traders at the stock markets or the devices coordinating the smart grid.

Automation of regulation also means automation of trust, as the trustworthiness of a player would be dynamically assessed based on the feedback left by other players and the objective measures (sensing). This is emphasised in the case of very short, very localised licenses where fusion of this data has to be performed in real time. There is another component of short, small licenses where the fast machines at all ends of the net come to rescue: the complexity. No matter how many licenses are to be managed, the vast network of trading and regulating devices can handle it. In the end, the line between the regulator and trader devices can be blurred by enabling distributed regulation in a blockchain-like fashion.

The caveat in building AI for all this is not in its own sinister plans, but the prejudices and biases we program them with. The machine does not care about the burden of legacy or the ways we regulated land for millennia, but its programmer probably does. As we know all too well today with the algorithms shaping our lives, the biases are contagious and can go from a human to a device.

In the figure the regulator is a database, and it interacts with other devices, domain proxies and base stations directly.

9.2.2.4 *Dynamic coexistence, right to access and DDL*

Mobile base station floating on drone captures what we mean by building spectrum licensing on the rights to access spectrum, instead of on static, ownership rights. The same licensing framework applies to both mobile and fixed base stations[7], the framework is technology neutral (in terms of choice of deployment) and accommodates diverse spectrum usage. For diverse spectrum users to coexist, the interference protection framework would be designed by the machine-enabled regulation, based on the data dimension of dynamic spectrum sharing as described above. Based on real-time data and actual spectrum use, the interference protection framework is calculated so

[7] Fixed base station is a special case of a mobile base station with zero velocity.

that enables issuing of spectrum rights to access seamlessly and as continuous and contiguous as possible. Such interference protection and licensing frameworks eliminate the problem with spectrum underutilisation, as the users are incentivised to use spectrum more efficiently due to dynamic nature of spectrum and spectrum policy tailored to account for spectrum uniqueness.

Short term licenses reflect the true nature of spectrum, the fast-cleansing resource readily available nanoseconds after its last use. They also capture the spirit of the market better, as they leave more space for the invisible hand to act. In long term licensing models, whatever happens in the industry and among the operators within the 10 years of the license term does not show on the price, as long as it does not happen just before the license expires. A war could start and end within that decade, and the chances are that effects of it would not be noticed if it was right in the middle of the license term. This effect corresponds to the common engineering problem of sampling: how fast should samples of a varying quantity be taken so that nothing important is missed? The rule of thumb is that the sampling has to be at least two times faster than the frequency (dynamics) of the quantity being sampled (Nyquist criterion). Mapping it back to the story of licenses, it is hard to believe that the market changes only every 20 years, so that 10 year licenses would suffice. The market of spectrum, after all, is closely linked to very vibrant markets around it: equipment market, UE market, database market (and the future SAS market), content market, service market, whole internet economy the spectrum is relying upon. They are all technology-enabled, and we have repeatedly shown throughout the thesis how fast the technology is.

This pace of technology and markets needs regulations to start catching up by enabling faster and less administratively burdensome way to get access to spectrum. This is the point we wanted to make with this subsection: as the right to access spectrum is a more natural way to manage spectrum than seeing it as a property and issuing ownership rights over it - spectrum does not exist unless it is put to use.

To design a licensing framework based on rights to access spectrum, we propose here a concept of *digital dynamic license (DDL) for spectrum sharing*[8]. We envision dynamic spectrum sharing which is not based on exclusivity and it is not based on the ownership rights that allow to exclude other spectrum users from using the resource even when the "owner" is not using it. This is the concept that can enable more efficient spectrum use, as it does not allow spectrum to lie fallow.

Digital dynamic license reflects the nature of the spectrum resource: non-depletable, reusable, renewable, natural, fluid. These licenses would be issued in real time and based on real demand and availability via on-the-spot auctions. Like a digital birth certificate which tells you how old you are at which point in time, the digital dynamic license would be issued on the spot, to tell the user which frequencies are usable for that amount of time (duration of license) in a given area. It is, figuratively speaking, a

[8] Chapin, J.M. and Lehr, W.H., 2007, April. Time-limited leases for innovative radios. In 2007 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (pp. 606-619). IEEE.

birth certificate of a hertz, on a square meter, in a second (Hz/m^2/s) and is expressed in bits, the data. They are a measure of a state of hertz, so the DDL is the elementary particle of localised, modular, granular dynamic spectrum sharing. The DDL licenses are not renewable, each time an operator wishes to operate, new DDL is assigned. They are relaxed from the administrative burden and costs, as they are granted locally, ad hoc and based on real demand via tiny auctions similar to eBay auctions, but more automated and much faster.

The concept of *licensing to use* allows the spectrum needs to be matched exactly by the spectrum taken. If the market offers a large number of small license packets: small area, small time period, small frequency chunk, the operators big and small can bid for as many as they need, with a SAS-like entity packing it for them in as-contiguous-and-continuous-as-possible sets. The change in needs of an operator of any size results in them simply not bidding for a license packet they have been using so far or bidding for a new one, continuously matching their needs with what they take from the pool. Spectrum does not lie unused within their ownership, and the high granularity of the license atoms allows them to precisely tailor the quantities they need.

As it goes with auction design, untruthful bidding has to be prevented in order to ensure that the resource is sold at least for what it is objectively worth. It has been shown[9] that these fast auctions can avoid the untruthful and dishonest bidding through appropriate models.

In the figure, the geographic space is divided into area units, and the base stations are symbolically enclosed in 3-dimensional modular shapes, tailored for their own size and with a timer indicating short term licensing. The mobile base station coexists with fixed ones, base stations appear and disappear (as extracted from the data).

9.2.2.5 *Citizens awareness of sharing necessity*

The average person in the world, or even the average end user of the spectrum (these two categories are converging to one another rapidly) does not think about the spectrum, or care about it. When our phone loses connectivity, we do not think about it in technical terms, we are worried about our needs for connectivity and everything that stems from it.

Why should we care? Let us explain this by looking at Maslow's pyramid (Fig. 9.2). When the Internet entered the life of an average citizen of the developed world with the sound of a phone modem in the nineties, it was not more than an addition to their self-actualisation, a new hobby. Building personal internet presence, a chance to take more active roles on bulletin board systems, forums, chat rooms led to complementing the offline sense of esteem, and once the social networks and messaging applications came into play, Internet ticked the love and friendship box as well. This came with the increase in access speeds which allowed richer content and real time audio and video over the Internet. At the same time, Internet was losing its wire re-

[9] Zhou, X., Gandhi, S., Suri, S. and Zheng, H., 2008, September. eBay in the sky: Strategy-proof wireless spectrum auctions. In Proceedings of the 14th ACM international conference on Mobile computing and networking (pp. 2-13). ACM.

Figure 9.2: Maslow's hierarchy of needs

straints as the users got a chance to take their social life with them, on their phones and laptops. The wireless connectivity would allow them to be online most of the time, thanks to spectrum, the invisible hero. The fact that (almost) everyone has a phone with an internet connection (which is, in turn, a result of the 3G-4G progress) allowed the development of mobile services related to health, property, personal security, resource management. This coincides with the sharing economy boom as well. Finally, the phone is not enough: thousands of other devices want to go online too to take care of human everyday needs, including the physiological ones. The IoT, the promises 5G made and the new perspectives on machine autonomy through learning allowed (and will allow) a pervasive network of sensors, actuators, interfaces and computing resources to bring sensing and automation to the lowest rung of the pyramid. This journey Internet took, from the top to the very bottom of the Maslow hierarchy of needs was enabled by the halfway change of medium: without the freedom wireless brought, it would be hard to imagine the development of personal services and mobility of users. The joke-sketch of Maslow's pyramid extended with Wi-Fi at the base often seen online is not wrong: wireless communications became the enabler of every layer in the hierarchy.

The need for spectrum is real: with the descent down the pyramid comes the increase in demand. That we see from the pyramid even if we do not look at it through the spectrum perspective: the most important needs are most in demand as well. Everyone is looking for those essentials from the bottom, and those who find them get a chance to go up and improve their quality of living. Unfortunately, the bottom layer is strongly tied with inequality and imbalance in resource distribution. It is not a global scarcity: the food thrown in garbage bins in Europe could feed Africa, and the water reserves in the North could supply the South. It is the management, and an ancient one, as we had the same needs from the very origin. No wonder we learned to share by sharing water, food, shelter or air. Bringing spectrum in the equation again, we see how sharing it could have been a viable approach while it was the toy of the few. With the proliferation of wireless technology and the growth of the ecosystem full of IoT devices and phones outnumbering humans, sharing becomes a necessity.

The citizen with an idea of how spectrum is important, how it drives the modern civilisation and runs in its bloodlines also recognises the wisdom (or lack of it) in spectrum regulation and distribution. Once the user moves from observing the platforms (the providers of content, interactive interfaces of the connected world) and looks under the hood at the pipes (the supporting industry bringing the bits and hertz together), they assume the forgotten role of stakeholders. When the platforms warned them about the potential change in the pipes which could affect their lives (Net Neutrality), millions reacted by writing to the FCC and putting pressure on the ISPs and enterprises built on Internet. If the net neutrality activist could recognise the mistakes in spectrum management, a similar effect could be observed in spectrum-related dockets. Furthermore, if the average person is faced with the dilemma of sharing a resource or losing it altogether, they would opt for sharing: and they would tell that to their congressperson or their cellular provider. Going back to the personalisation of enterprises and the rebranding processes of our time where the big companies try to lose the image of anti-social profit-driven empires, the effect such a movement would have on a CEO of a cellular provider and consequently, the company could be significant.

When the FCC or the Congress are about to make a regulatory step against technological progress, the first to react are activists from the tech community organised around ideas of free software, open access and free knowledge, the likes of R. M. Stallman or Aaron Swartz. These activists have what we actively looked for in this thesis: culture of sharing.

In the figure the citizens have their spectrum protest signs: they are activists, aware of spectrum importance and the necessity of sharing. Implicitly, the other stakeholders are aware as well–the boardroom talk on uniqueness has that as a consequence.

9.2.2.6 *Invisible mechanism 1: Incentivisation*

What we do not see in the figure are the hidden mechanisms discovered in Chapter 8 which enable the sustainability of the culture of sharing in this scenario.

We have seen the link between nature, business and society which was put to side because of the direct powerful link between nature and society we made a point about. Now we return to this indirect link and give it a name. The relationship which shows how to put value on a certain behavior with respect to a certain resource is what we refer to as *incentivisation* in this work. This tool of regulation can introduce previously unobserved links between the three elements (nature, business and society) to devise a reward mechanism for (sharing) behaviour. Once the effects are sustainable, the scaffold of incentives can be changed or removed, leaving a Pavlovian reflex. Incentives do not need to be there to stay, but are an initial driving force necessary to have sharing behaviour built (and sustainable) - thanks to the culture of sharing. As once you are in the loop, you will be hooked. The regulator determines how long the incentives mechanism will last and at which magnitude based on how much the stakeholder values its effort needed to accept and participate in sharing framework.

Incentivisation gives an opportunity to the stakeholder to put its behaviour in a spreadsheet. If there is a mathematical way to calculate your wins and losses it helps. The origin of the incentives however should be in the regulator's larger spreadsheet. The incentives, as motivations to sharing behaviour have not been a part of the regulatory language. Based on our findings in the thesis, we can suggest to the regulator how to make an incentives spreadsheet. **The idea is to link the qualitative realms of nature of the resource and the realms of the stakeholders community with the market as a quantifier.** The nature of the resource gives ideas on what aspects of it could serve as a building block of an incentive or what related resources or services might be a part of the incentives deal. The assessment of the stakeholders community results in an estimate of incentivisation magnitude and versatility, as it needs to accommodate for different stakeholders. Finally, the market puts a price tag on these inputs and allows a comparison between their effects and other components within the regulation spreadsheet (opportunity costs, transaction costs, etc.). This is why we put so much attention on understanding spectrum (Ch 2, 5, 7, 8) and those who use it (Ch 5, 6, 7, 8). At this point we need to remember that we have already seen this link as a possible norm (society)-affecting tool in Chapter 8: while the strongest effect on norms was the one of the nature directly affecting them, there was also the indirect link from the nature to norms through the markets. Here we gave it an interpretation and explained how to put it to use.

The incentives we discussed so far are *extrinsic*. They are separable from the game but stimulating for the players to join. The CBRS rules themselves have *intrinsic* incentives embedded. The rules cannot be neutral with respect whether the stakeholder will decide to participate in sharing the band or not, as they define the operation in the band - the rules of the game. The intrinsic incentives of the CBRS rules are therefore inseparable from the game, the rules being incentives on their own, unlike the extrinsic incentives such as reward mechanisms that can be removed from the framework without defying the purpose and the motivation of CBRS sharing.

The incentives have to be balanced. Too few would keep the stakeholders out, while too many would lead to the stakeholders gaming the system and using it only for the benefits (defying the purpose of sharing). This thesis proposes that decision on where the balance is should be made with the culture of sharing as a goal. The point we make in this subsection is that the extrinsic incentives need to exist to encourage sharing and need to be devised sensibly. We proposed a way to design an incentive mechanism with the culture of sharing in mind, by putting the link of nature of spectrum, the stakeholders and market to use.

9.2.2.7 *Invisible mechanism 2: Culture of sharing and the norms*

For a culture of sharing the resource to exist, there needs to be: (1) a positive perception on sharing in a community around that resource consumption (stakeholders) and (2) the wide adoption of sharing behavior, its implementations in practice. We aimed to explore the culture of sharing and what really motivates the users to share spectrum and we argued that the culture of sharing is the enabler of sharing that is missing in spectrum sharing world. If there was a culture of spectrum sharing, we would have spectrum sharing economy and therefore examples of successful spectrum sharing. There are no sustainable dynamic spectrum sharing models today and we are not seeing real world implementations, even with the existence of sharing frameworks and mature technology for sharing.

Culture of sharing is a component of social norms, tightly related to the positive perception of sharing in a community. The positive perception of sharing behaviour in a community is necessary but not sufficient. For example, donating blood is a type of sharing behaviour that has a positive perception in a community, but it is not widely accepted, i.e. culture of sharing is restricted to a small group of practising donors. Different example is code sharing, which is a type of sharing behaviour that has both, positive perception in a community and is a widely accepted behaviour, i.e. culture of code sharing is not restricted to a small group of practicing coders. When it comes to culture of spectrum sharing, we neither have a positive perception on sharing (as shown in Ch 6) nor the wide acceptance of spectrum sharing (as seen in incidental implementations of LSA and the hammered progress towards CBRS implementations).

Why is this so and what can we learn from the above examples? We do not share blood because: (1) it asks for initial step out of the comfort zone, (2) we have the perception that a small donor community covers the needs of the whole society, (3) while nominally supporting it, we often do not comprehend its importance fully, as majority of people do not need blood donation. On the other hand, we share code because: (1) we give back to the community from which we daily take code snippets and solutions to our problems, recognising that another coder might face the same problem as we did, (2) we use code sharing as a feedback tool for bug reports, feature requests and suggestions, (3) we offer transparency to end users and build trust. *Both of these lists of reasons stem from the nature of the resource being shared.*

What if we wanted to build the culture of sharing blood? We would have to tap into the nature of blood, to see what we can offer to the donor as a perk. When compared to code sharing, we cannot offer the same effect of building trust with end users, but we might do something about feedback. If we note that once a person donates blood we can use small sample of it for tests and hence provide health information to the donor, we have an incentive to offer. If you take a look at real blood donation campaigns, you will notice the few tools for attracting new donors: (1) health care subventions, making regular health care cheaper for the donors, (2) educational campaigns informing the donors about the blood renewal cycle, (3) the above mentioned tests feedback. We have seen these already in one of the previous sections: the extrinsic incentives. Code sharing is not immune to incentivisation either. GitHub is a portfolio, coders promote their work, have an opportunity to offer a showcase to an employer or a client, and in return... they share. Every behaviour of sharing is incentivised. *The takeaway point here* *is that if we want to build the culture of sharing, there are two ingredients: (1) understanding of the the link: nature of the resource - norms, and (2) understanding of the link nature-market-norms, i.e., incentivisation.*

As noted, culture of sharing is not the only component of norm force observed. In the vector of norm, as one of the forces which shape the behaviour of sharing, we can find other components: *norm of cooperation*, *norm of privacy protection* and the driver in the opposite direction - the *norm of entitlement*. When we talk about the traditional norms in this thesis, we have in mind the norm of entitlement that can be observed in the mindset and the attitude of big carriers towards sharing (desire for long term licenses, QoS protection guarantees, nationwide licenses and infinitely renewable). While this component runs opposite to the idea of sharing, it has to be taken into account as it represents the current state of norms and it has been seen as a shaper of CBRS rules. We find the norms of cooperation and privacy protection in the rules as well, but only in future tense (Chapter 6 and 8). These are more aligned with sharing, as the example of code sharing might show. There, the shareability of the resource is enhanced by the cooperation norm (coders work on big projects together $\rightarrow$ they document and write readable code $\rightarrow$ code is shareable and reusable) and shaped by the norm of privacy protection (coders obfuscate or do not share privacy sensitive content, sharing platforms care about user privacy).

The main difference between the norms of cooperation and privacy protection on one side and the culture of sharing on the other can be seen going back to the rules clusters in Chapter 8. Both are affected by Lessig's force of architecture, but while the culture of sharing is affected by the nature component - it is the technology that drives cooperation and privacy protection. For example, privacy protection is about the interaction with the artificial entity of SAS, while culture of sharing is built through rules that recognise instantaneous renewability of spectrum and its spatial features (e.g. GAAs accessing unused PA spectrum). The particular example of privacy protection and SAS (technology) relationship resonates with what we have said about data: the privacy is cherished for the information that might be hidden in the data, and it is inherently connected with the data-handling technology.

9.2.3 *A Roadmap*

We have presented a futuristic spectrum sharing economy scenario in which culture of spectrum sharing exists. Here we give our outlook on how to get to the spectrum sharing future in which sharing the spectrum is widely accepted behaviour and the ecosystem is built on the awareness about the necessity of sharing.

The multipliers that 5G promises in throughput, speed, connectivity and latency are motivated by the explosion of wireless demands. Billions of new devices are entering the arena yearly. 5G is an attempt to avoid the user feeling the effect of the overload, a way to mitigate the effects of spectrum crunch. Spectrum sharing needs to become a predominant way of spectrum usage to serve the demands. As we have seen, spectrum policy needs a paradigm shift. An attempt has been made with the CBRS band but as we have shown the results did not meet the expectations. Paradigm shift is not an autocratic task of the regulator and everyone can play a role.

Academia has an active position to take in the rulemaking process and act as a stakeholder in spectrum sharing ecosystem by responding to the regulatory consultations on designing sharing rules, stating a policy position driven by research findings and advocating for a change more actively. The research practices and methods used have mostly been focused on technical science research methodologies, but there is a need for interdisciplinary design of methodologies that take into account the understanding of policy, context and rules.

The *regulator*'s role in designing sharing rules needs to change so that the designs clearly reflect an interplay of technology, economics, law and social issues of spectrum sharing. Most importantly, the regulator has to pay more attention to incentivisation of sharing, communicating clearly the costs and benefits for each of the stakeholders to participate in sharing. The regulator also has to envision future spectrum uses, follow progress in academia on spectrum sharing issues and abandon decision making practices on band-by-band or service-by-service basis. In terms of communication with the stakeholders, the FCC can serve as an example to the other regulators worldwide, as the relevant information is becoming public and accessible to every stakeholder within the industry, academia and general public.

The *industrial stakeholders* are a critical mass in spectrum sharing ecosystem which drives the paradigm shift in policy towards more sharing oriented future, as they are direct spectrum users. Each of the stakeholders, the established licensed carriers, the newcomers and smaller players, the equipment vendors, have to orient their business models to include the analysis of the spectrum resource which by the use of their technologies needs to be put into an optimal, efficient cycle of use (an analysis that will work on the things that make it different, not the things that make it the same). The newcomers should drive spectrum sharing by acting as early adopters and catalysts of the culture of sharing. This kind of role is critical, as for the reinforcement of culture of sharing there needs to exist a critical mass of early adopters. The equipment vendors need to drive the innovation and work towards developing technologies that can enable decision making based on nothing else but technological data. This would help build the trust in spectrum sharing, by designing robust feedback mechanisms which clearly reflect that it is harder to lobby a computer.

The *citizens* will soon start to talk about connectivity as their human right. Activism has a long history in both fighting for resources and fighting for technological freedom. The spectrum is in the crux of both.

9.2.4 *Recommendations*

We believe that the dissertation findings could serve the regulator in developing the policies for sharing in the other bands, as regulator is currently addressing these issues within wide sharing initiatives. In this section, we offer a set of actionable recommendations. Their adoption, we believe, can lead to sustainable dynamic spectrum sharing systems in the future.

Recommendations towards spectrum sharing policy paradigm shift are centered around technology as an enabler and philosophy as the driver and can be framed through the following concepts of future regulations: (1) sharing as a norm, (2) sensible incentivisation, (3) citizen activism, (4) democratisation of the markets, (5) evidence-informed policies, and (6) bringing the culture of sharing home. Our motto for the regulator is *be smart*, i.e. do not go for the obvious (tedious) solutions and be flexible in the rules enforcement, as “smart” in the 21st century also means “machines with intelligence”. The goal is to relieve the regulator of the hard work and make the society take the burden; this will create the culture.

We seek for the natural behaviour of the systems under spectrum sharing policy. Like the water takes the shape of a vessel, we want the usage of spectrum to take the shape of available spectrum, current radio environment conditions, actual use, i.e. context awareness instead of binary, over-prescriptive rules. Currently, we have spectrum policy systems in which each possible path and option is defined, a brute force one. Intelligence in the systems comes with the defined goal, not the rules, but the principles. Those principles for example, ensure that the users can use the equipment considering what its specifications are, not prescribing the noise margin on equipment. It also means diversity in technologies and regulations not based on poor receivers but on the receivers currently deployed, i.e. technology-context awareness. What can enable this kind of flexible, adaptable policy making are the databases storing and maintaining information about: spectrum ownership, actual use and availability, interference incidents etc. and making this information available in a spectrum sharing ecosystem. This can help raise awareness of how spectrum is being used and make social norms an enforcement mechanism with the goal of reasonable, efficient and smart spectrum use. These kinds of incentive mechanisms bear a cost, but they also represent investments worth taking within long-term thinking about the future in which sustainable sharing systems are designed under spectrum welfare criteria.

9.2.4.1 *Recommendation 1*

Make efficient, optimal spectrum use the primary regulatory objective. An example we cited earlier about energy efficiency efforts in China mirrors this need: it is understandable that at earlier stages of adoption efficiency is not a primary goal. This change comes from the top (the regulator) but to be sustainable, it needs to be taken forward by the participants, once it is clear it is either an efficiency game, or no game at all.

9.2.4.2 *Recommendation 2*

Support regulation automation, by proposing (regulator), designing (industry) and lobbying (operators) for autonomous, dynamic, responsive systems like the SAS and the ESC.

9.2.4.3 *Recommendation 3*

Academics, start clean slate reform discussions. If you were to design a wireless communications system on Mars, how would you do it? This is not a thought experiment, but an important question of future space colonisation, and yet it can have straightforward applications on our planet as well. It is closely linked to a question we mentioned before: how different would be the world of spectrum today if we started from a different fundamental dimension of it: space, time, power, etc. and not frequency (wavelength). This discussion is a proxy for the vital question of nature of spectrum. We urge the academics to begin, and hope for other stakeholders to join.

9.2.4.4 *Recommendation 4*

Entrepreneurs, start developing data solutions for telecommunications services handling it ethically. There are two independent concerns about data privacy in spectrum (sharing) management: the protection of users (metadata can be deanonymised and abused by the authorities, cf. E. Snowden's findings) and the protection of business interests. Solutions based on AI coupled with encription could provide a toolchain for black box handling of it, and could be tested at a varying scale before becoming the standard. It also opens a new business niche.

9.2.4.5 *Recommendation 5*

Activists, start outreach activity on spectrum. The likes of Electronic Frontiers Foundation (EFF) whose outreach coordinator C. Doctorow has penned numerous comments to the FCC have the responsibility of educating its members, supporters and the members of the general public about the essentials of radio spectrum. We live in the time where the information about spectrum comes from the academics, major market stakeholders with vested interests, and from conspiracy theorists. This needs to change, especially with the government structures (EU, US) seeking opinion from the taxpayers and non-governmental sector as well.

9.2.4.6 *Recommendation 6*

Regulator, start nudging. The nudging approach is inexpensive, easy to implement and its failure does not affect the system. Make sharing default behaviour in new bands, which asks for opting out instead opting in. Normalise sharing.

9.3 REBUTTALS

Conclusions and the methodology of this thesis could be challenged by different groups of theorists and practitioners alike. In this section, we briefly address some of the questions that may be raised.

The contemporary critics of AI are alarmed by the number of applications in which AI solutions are requested without (1) the need for it, (2) ways to implement it (in a way that is both technically feasible and ethical) and may consider a lot of these applications to be the consequence of the current hype cycle stage. The idea to give a major real-time decision-making role to a black box is controversial in their vision, and we have mentioned some of their concerns in our proposal of AI-powered regulation. However, we do want to point out the arguments voiced in favour of such approaches[10] which in fact cover other technical ethics concerns as well, for example that of the data privacy (operators would share data with trusted machines, not humans). And once again we repeat that this is a regulation of machines: giving the machines the power to perform it is not unnatural.

The property rights advocates traditionally ask for licenses large in every electrospace dimension justifying it with long term investments and large scale operations. However, the 21st century economy is not the economy in which Bell Telephone Company had the leeway for two-decade plans. Every technological market is ready for fast actions, except for spectrum.

The engineering community will find the language of the thesis strange and uncommon. The colliding worlds of policy and engineering are also colliding worlds of evidence and advocacy. If those strongly in favour of evidence label this thesis as advocacy, they are not completely wrong; but advocacy is not grounds for dismissal when being a part of evidence-informed policymaking process. If the question of the thesis is "how to build the culture of sharing?" it is natural to be motivated by the quest for it and to advocate for building it in the end. We did not start this research from the premise that the culture of sharing is the special ingredient that is missing. We discovered that while comparing the success stories with the failures.

The supporters of incremental solutions might disagree with our radically different vision and departure from the current positions in spectrum sharing. They are inclined to support the slow developments in the regulatory domain, embodied in frameworks like the LSA. For them we presented the shortcomings of LSA in Chapter 2, revealing the non-existence of true sharing in the framework. It is our belief that settling for these options is even more dangerous than opposing them, as it creates a false feeling of preparing a spectrum sharing future, while none of the sort is really happening.

The flexible use of the term spectrum sharing, even in its dynamical variant is something we addressed in this thesis in an attempt to avoid the no true Scotsman fallacy of vacuously defining "true spectrum sharing" and moving the goalposts in the process. Insisting on dynamical spectrum sharing being simultaneously small and modular

[10] E. A. Holm (2019) In defense of the black box, Science, Vol. 364, Issue 6435, pp. 26-27

in space, time and frequency, we have moved from most contemporary and historical types of sharing. However, the question of "what about Wi-Fi" persists and we need to re-address it here. It is our belief, as seen in the SPTF report, that the principle of Wi-Fi does not scale to other bands as a permanent solution, and while it is undoubtedly a success story, the bands we analyse in this thesis ask for different business models.

The assumptions made in this thesis are open for discussion. For instance, the assumption of sharing meaning more efficient use may be confronted by claim that exclusive cellular licenses are functioning efficiently. This argument originates from the current state of affairs, before mass 5G and IoT deployments and as such, it has limited relevance. Chapter 2 of this thesis has a purpose of reminding the reader of many cases where a simple non-flexible solution worked well until a point in time where the technological progress and the increased demand broke it.

There is a long chain of *ifs* in the reasoning this thesis is built on, as we seek sufficient conditions for building the culture of sharing, and consequently the sharing itself. This inevitably opens the space for a question about the alternatives: are there other ways to build the culture, without the causal links we discovered? Are there other ways to build sharing, without the sharing economy establishment? These questions, while interesting, are not within our scope, and while we expect the answer to be affirmative, we leave the investigations to others. As long as we reach the same paradigm-shifting goal of spectrum welfare through sharing, the road we take is of secondary interest. Here we found one such path.

9.4 FUTURE WORK

The interdisciplinary approach we took in research design did not have an alternative. The research question of how to build the culture of spectrum sharing is an abstract interdisciplinary question which asked for tools from different domains that reflect complexities of spectrum sharing ecosystem. This work was an exhaustive dive into the multidimensional ocean of spectrum resource, its regulation, technology, economics, legal and political issues. Our experiences from different stages of multi-domain analysis performed on an example of a spectrum sharing model are at the same time our recommendation to policy makers on how to design spectrum policy for future dynamic spectrum sharing models.

We hope that this work opens an interesting research field. As a stakeholder from academia, we list some of the topics left to explore and research directions which could further verify spectrumism and lead to the development of spectrum sharing economy.

Our next steps following directly from this dissertation are:

- Modelling of incentive relationships between the stakeholders in a spectrum sharing ecosystem with the goal to set the stage for spectrum sharing economy. The results and insights of Chapters 6, 7, and 8 can be used with the agent based modelling (ABM) tool, as the observed behaviour in the output ABM model feeds the decision making process. In addition, our idea is to use promise theory of Mark Burgess as a policy-based management tool as it matches the sharing nature of spectrum use since it is not based on obligations and forcing, but on promises that carry value.

- Designing a full spectrum sharing licensing scheme applicable for future spectrum sharing scenarios.
  We will use the insights from Chapter 3 and results of the analyses performed in Chapters 6, 7, 8 and 9 for: the design of interference protection mechanism for spectrum sharing systems coexistence, the use of market mechanisms to assign the licenses, setting the technical parameters to encourage sharing and creating policies in which culture of sharing can evolve. These five chapters can serve as a set of guiding principles for designing policy to encourage spectrum sharing.

- Designing an auction model for dynamic digital licenses.

- Evaluation of distributed responsive dynamic automated regulation.

At this stage, we can identify two wider research directions that stem from this work and ask for interdisciplinary research methods for the issues of engineering spectrum sharing ecosystem. Both research questions owe their interdisciplinary nature to building on top of the interconnections presented in this work:

- A researcher from economics background could study markets of the CBRS ecosystem.

- A researcher from engineering background could study how to determine the value of shared spectrum.

The data dimension of spectrum sharing which we have introduced in this dissertation is not just another bullet in the list above, as it is a crucial ingredient in dynamic spectrum sharing ecosystem which has been overlooked. Data manipulation has to be fast, secure and aimed at decision-making and prediction of supply, demand and events in the near future requiring adaptation and responsiveness. While it is similar to the character of data in other areas of technology, in particular resource management, the rapidly recycling spectrum asks for the most rapid processing and decision making.

The frameworks for spectrum sharing are currently very important. The goal of this thesis was to analyse a sharing framework. In the process, we have also engaged with the regulators by answering to the specific points of consultation and shared some of the results of our analysis with the Ofcom and the FCC already. As these conclusions are being written, the CBRS proceeding has been re-opened by the FCC. It was motivated by the petitions for reconsideration from the big carriers who are determined to tailor the CBRS band sharing to their established business models and prevent the newcomers from finding their place in spectrum markets. There is little doubt that the events to follow will confirm the findings of our work, unfortunately not those about the means of building the culture of sharing but those about its nonexistence.

However, we plan to engage with Ofcom in subsequent rounds of consultations and share the findings of the thesis, as the final decisions on whether or not the 3.8-4.2 GHz band would be released under sharing rules are not reached yet.

In such a time, the importance of a constructive plan with a forward looking ideas is crucial. This dissertation aimed to serve as an example of that.

Part V

APPENDICES

A RESULTS OF ANALYSIS IN CHAPTER 6

A.1 NPRM

Table A.1: ISSUE 1 - How should the rights be assigned among PA and GAA tier?

Stakeholder	3-tier	2-tier/transitional*
API	X	
AT&T	X	
BliNQ	X	
Cambium Networks	X	
Cantor	X	
Edison	X	
Ericsson	X	
Exelon	X	
Google	X	
InterDigital	X	
Microsoft	X	
Motorola Solutions	X	
OTI/PK	X	
PISC	X	
Spectrum Bridge	X	
Vanu Inc.	X	
WISPA	X	
WSA	X	
WiFi Alliance	X	
Verizon		X*
CTIA		X
4G Americas		X
PCIA		X
ITI Council		X
T-Mobile		X
NSN		X
Qualcomm		X

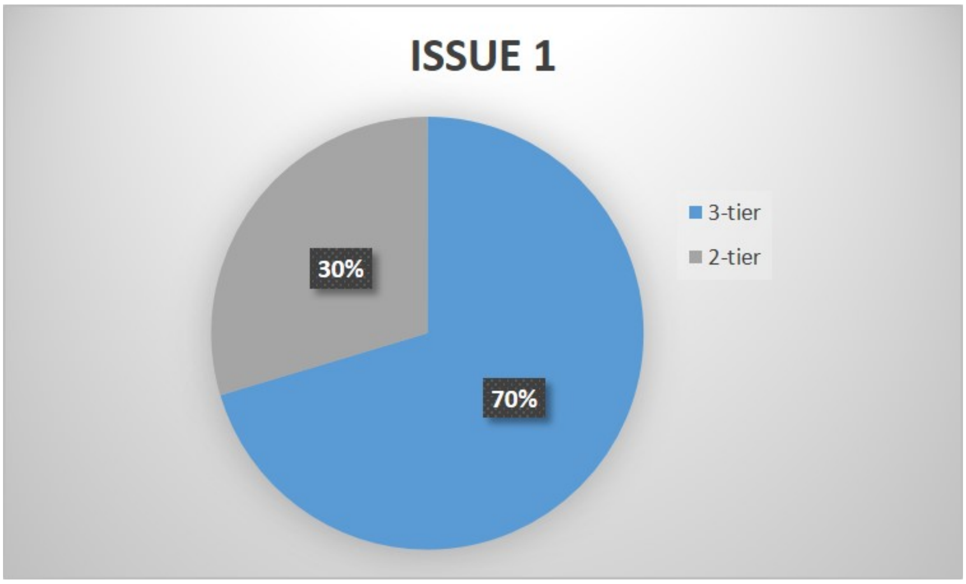

Figure A.1: How should the rights be assigned among PA and GAA tier?

Table A.2: ISSUE 2 - Should CBRS (both tiers) be licensed-by-rule?

Stakeholder	Agree	Oppose
InterDigital	X	
SITA	X	
WISPA	X	
WiMAX Forum	X	
Great River Energy	X	
PISC	X	
Exelon	X	
WiFi Alliance	X	
Spectrum Bridge		X
TIA		X
T-Mobile		X
AT&T		X
4G Americas		X
Xchange Telecom Corp.		X
Microsoft		X

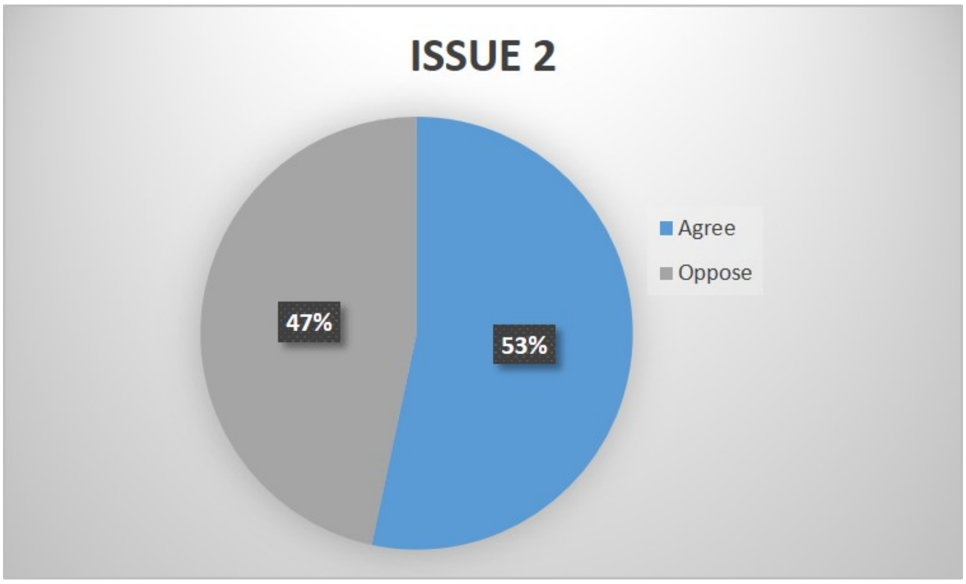

Figure A.2: Should CBRS (both tiers) be licensed-by-rule?

Table A.3: ISSUE 3 - What is the right methodology for PA tier?

Stakeholder	Broader PA tier	Critical users
Alcatel-Lucent	X	
AT&T	X	
BliNQ	X	
4G Americas	X	
WISPA	X	
NSN	X	
InterDigital	X	
Ericsson	X	
Google	X	
ITI Council	X	
PCIA	X	
CEA	X	
CCA	X	
Mobile Future	X	
Cambium Networks	X	
T-Mobile	X	
Verizon	X	
Motorola Solutions		X
OTI/PK		X
Spectrum Bridge		X
EEI		X
UTC		X
NRECA		X
API		X
Exelon		X
Harris Corp.		X
Rajant		X
Edison		X

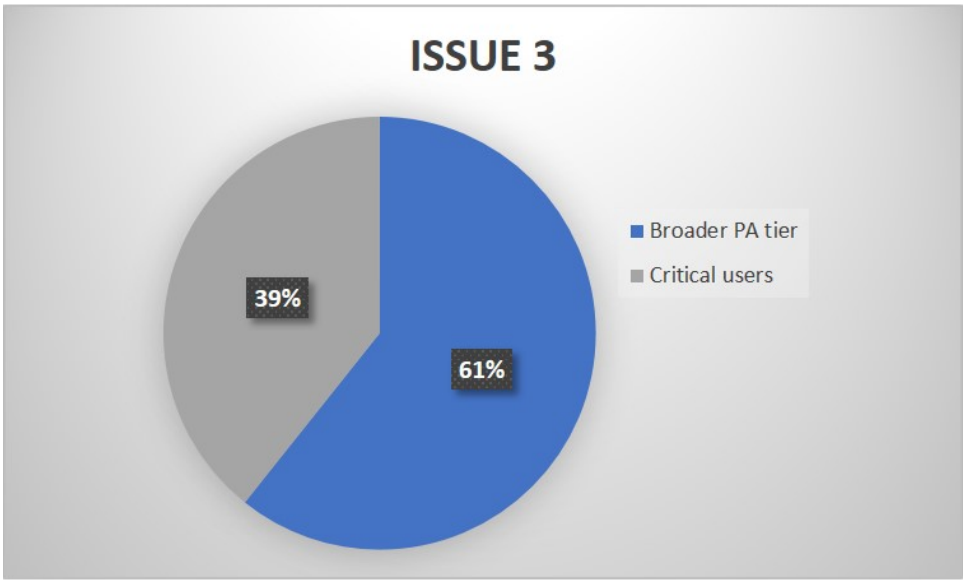

Figure A.3: What is the right methodology for PA tier?

Table A.4: ISSUE 4 - Should the adjacent 50MHz be added to the CBRS band?

Stakeholder	Agree	Oppose
Interdigital	X	
Ericsson	X	
ITI Council	X	
Google	X	
Motorola Solutions	X	
Spectrum Bridge	X	
UTC	X	
WISPA	X	
KanOKla		X
SIA		X
WiFi Alliance		X
Neptuno Networks		X

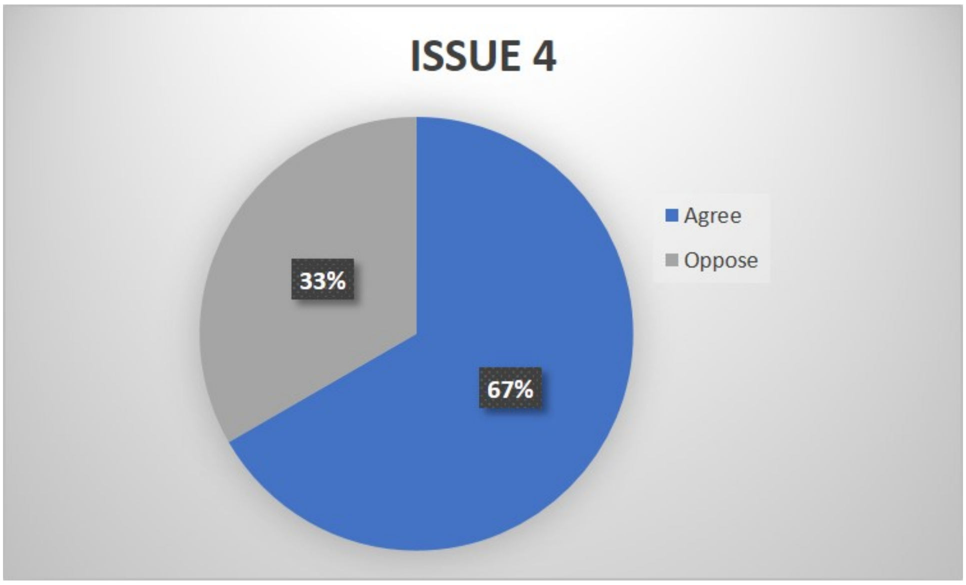

Figure A.4: Should CBRS (both tiers) be licensed-by-rule?

Table A.5: ISSUE 5 - GAA throughout the band: dynamic vs. static assignment?

Stakeholder	Agree	Oppose
Google	X	
Microsoft	X	
PISC	X	
Spectrum Bridge	X	
WISPA	X	
EEI		X
Motorola Solutions		X
NRECA		X
T-Mobile		X
UTC		X

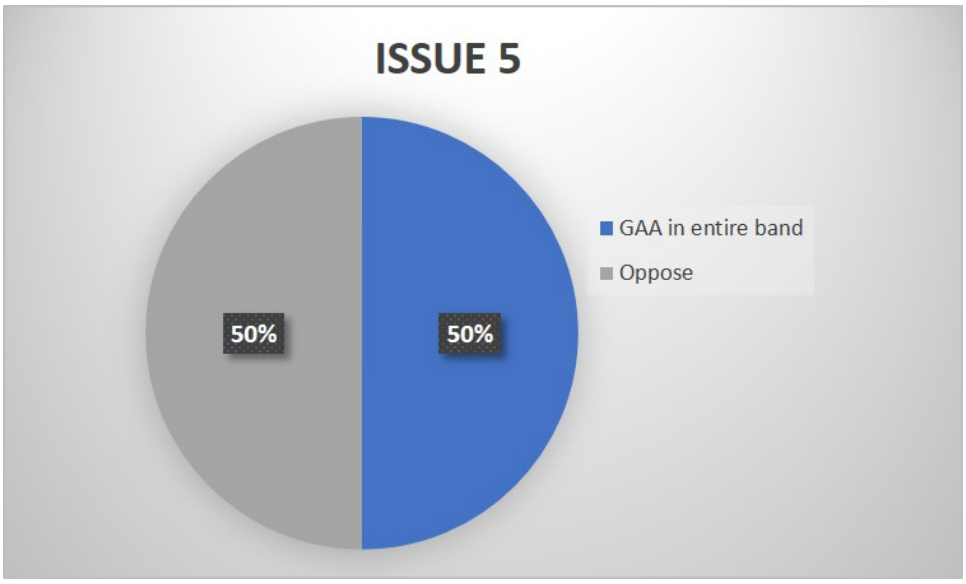

Figure A.5: Should CBRS (both tiers) be licensed-by-rule?

A.2 LICENSING PN

Table A.6: ISSUE 1 - 3-tier or 2-tier and transitional approach?

Stakeholder	3-tier	2-tier/Transitional
AT&T	X	
BliNQ	X	
CEA	X	
Federated Wireless	X	
Google	X	
OTI/PK	X	
Cambium Networks	X	
CTIA		X
Motorola Solutions	X	
Motorola Mobility	X	
Microsoft	X	
NSN		X
T-Mobile		X
Qualcomm		X
Spectrum Bridge	X	
WISPA	X	
UTC	X	
KanOkla		X*
Ericsson		X*
CTIA		X
NSN		X
Verizon		X*

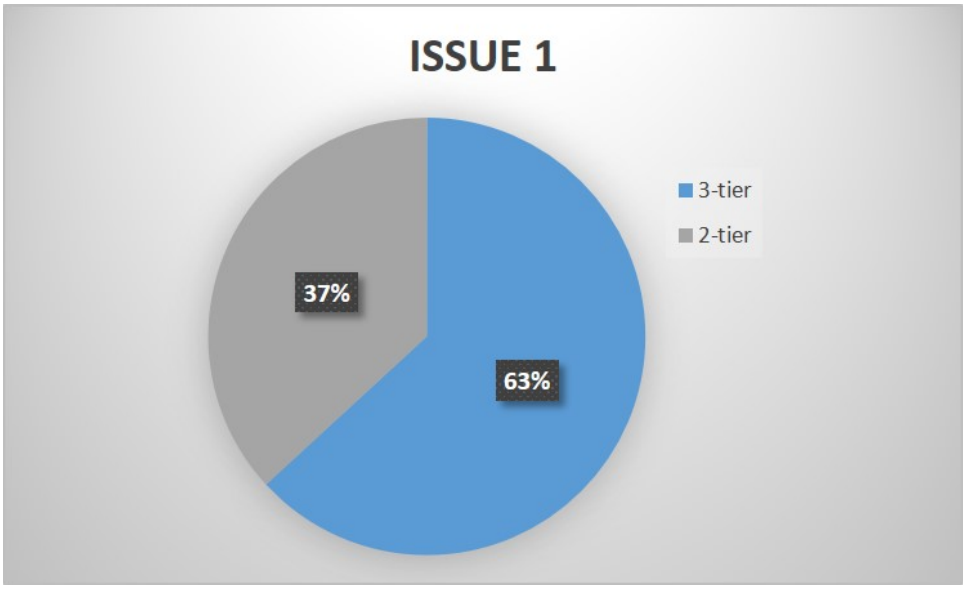

Figure A.6: 3-tier or 2-tier or transitional approach?

Table A.7: ISSUE 2 - Census tracts as license areas?

Stakeholder	Yes	No, issues.	Census blocks[1]	EAs, CMAs[2]
WISPA	X			
Spectrum Bridge	X			
Neptuno Networks	X			
Alcatel Lucent				X
AT&T	X			
Verizon				X
Google		X		
CTIA				X
T-Mobile				X
NSN				X
Qualcomm				X
PCIA				X
OTI/PK			X	
Motorola Solutions			X	
Microsoft			X	
Federated Wireless			X	

[1] smaller than census tracts, definition here
[2] economic areas, cellular market areas

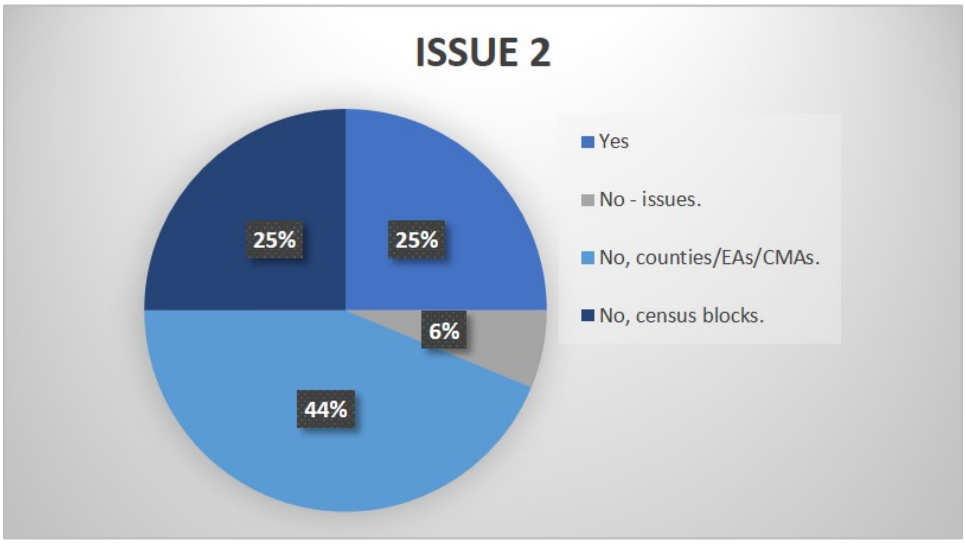

Figure A.7: Census tracts as license areas?

Table A.8: ISSUE 3 - Open eligibility for PA tier?

Stakeholder	Broader PA tier	Critical users
AT&T	X	
Alcatel Lucent	X	
API		X
BliNQ	X	
CTIA	X	
CEA	X	
Ericsson	X	
Google	X	
OTI/PK	X	
Microsoft		X
Motorola Solutions		X
Motorola Mobility	X	
PCIA	X	
NSN	X	
T-Mobile	X	
Qualcomm	X	
Spectrum Bridge	X	
WISPA	X	
UTC		X
Verizon	X	

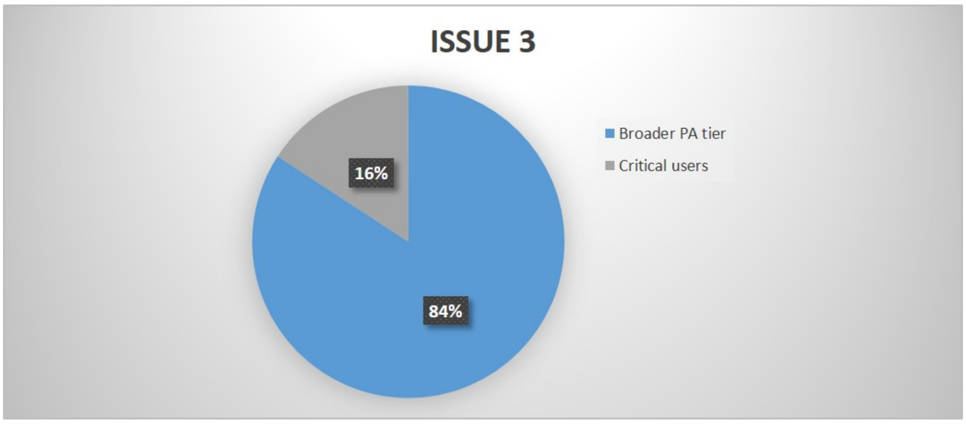

Figure A.8: 3-tier or 2-tier or transitional approach?

Table A.9: ISSUE 4 - Supplemental proposal: extend Part 96 rules to 3650-3700MHz?

Stakeholder	Yes	No
Google	X	
Cambium Networks	X	
ITI Council	X	
Motorola Mobility	X	
Motorola Solutions	X	
OTI/PK	X	
T-Mobile	X	
WiMAX Forum	X	
Verizon	X	
Qualcomm	X	
Neptuno Networks		X
NAB		X
API		X
UTC		X
KanOkla Communications		X
SIA		X
WISPA	X	

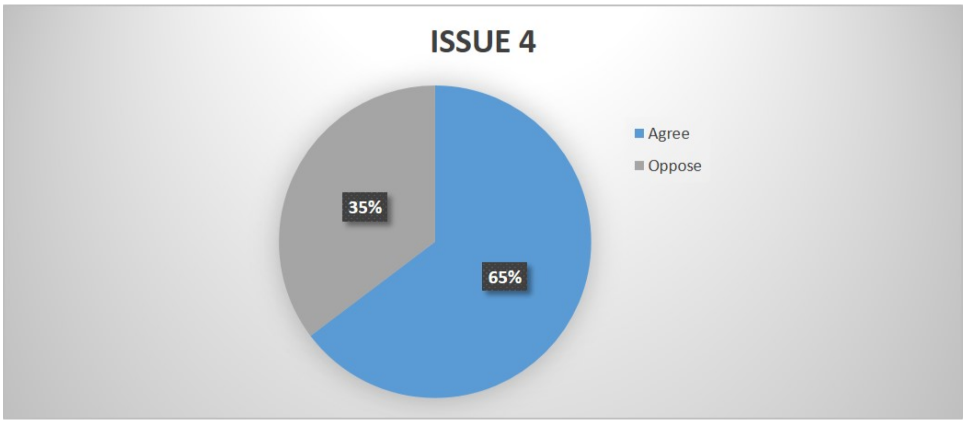

Figure A.9: Supplemental proposal: extend Part 96 rules to 3650-3700MHz?

Table A.10: ISSUE 5 - The license term of 1 year with up to 5 years aggregation cap ?

Stakeholder	1y+multiple cap	less than 1y	1y & no aggregation	1-15 years
WISPA[3]	X			
OTI/PK[4]	X			
Spectrum Bridge	X			
AT&T	X			
Federated Wireless	X			
Motorola Solutions		X		
Microsoft			X	
NSN				X
Qualcomm				X
Ericsson				X
4G Americas				X
Google				X
Alcatel-Lucent				X
CTIA				X
T-Mobile				X

[3] 4y aggregation cap
[4] 3y aggregation cap

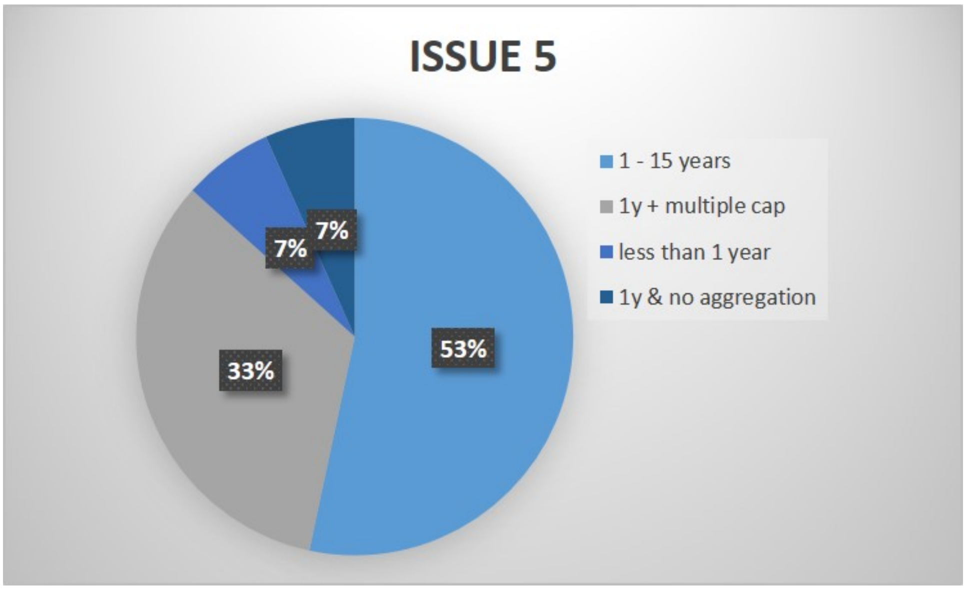

Figure A.10: What is the appropriate license term and temporal aggregation cap?

Table A.11: ISSUE 6 - Non-renewable licenses.

Stakeholder	Agree	Oppose
Federated Wireless	X	
WISPA	X	
AT&T		X
CTIA		X
Google		X
OTI/PK		X
PCIA		X
Qualcomm		X
Spectrum Bridge		X
T-Mobile		X

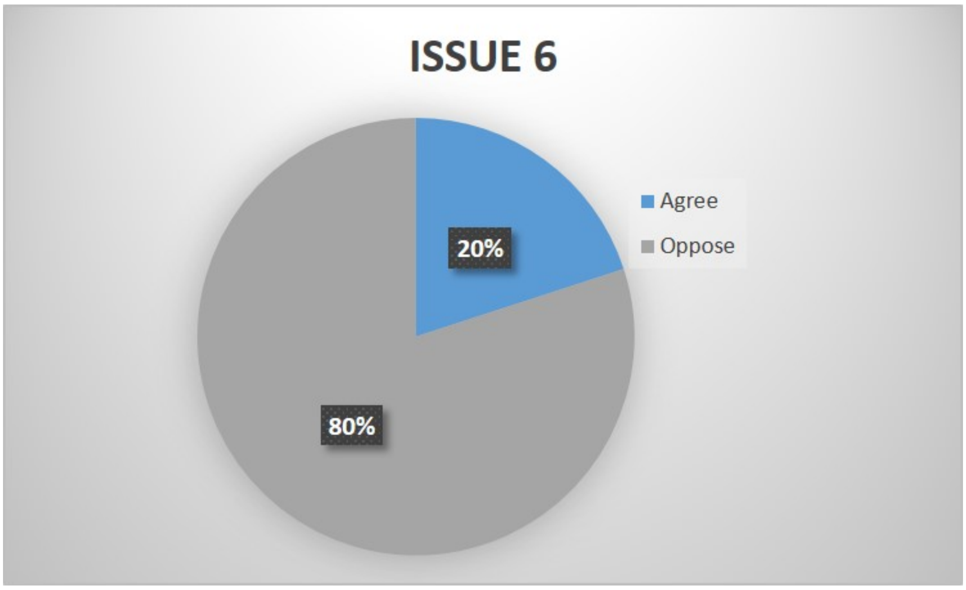

Figure A.11: Non-renewable licenses.

Table A.12: ISSUE 7 - GAA to access 'unused' PAL channels?

Stakeholder	to unassigned ch. only	NO GAA acc. to PA ch.	to ch. not in 'actual' use
AT&T	X		
T-Mobile	X		
OTI/PK			X
Federated Wireless			X
Google			X
Spectrum Bridge			X
CEA			X
WISPA			X
CTIA		X	
Ericsson		X	
NSN		X	
Verizon		X	

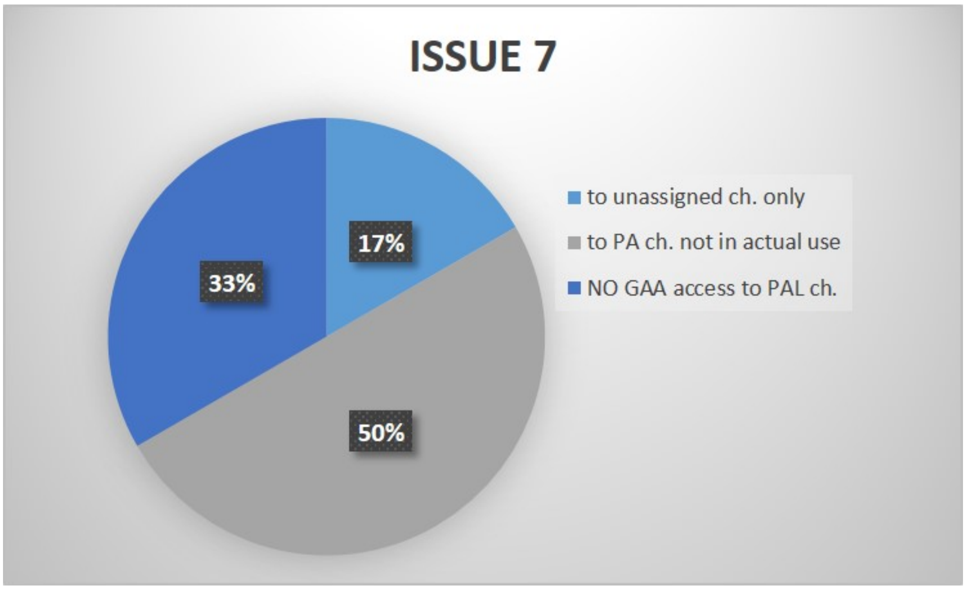

Figure A.12: GAA to access 'unused' PAL channels?

Table A.13: ISSUE 8 - Proportional assignment of GAA and PA frequencies?

Stakeholder	Reject GAA	More of fixed PA freq.	GAA "floor"/throughout 3.5GHz
Microsoft			X
OTI/PK			X
Federated Wireless			X
Google			X
Spectrum Bridge			X
WISPA			X
Qualcomm	X		
CTIA	X		
Ericsson		X	
AT&T		X	
NSN		X	

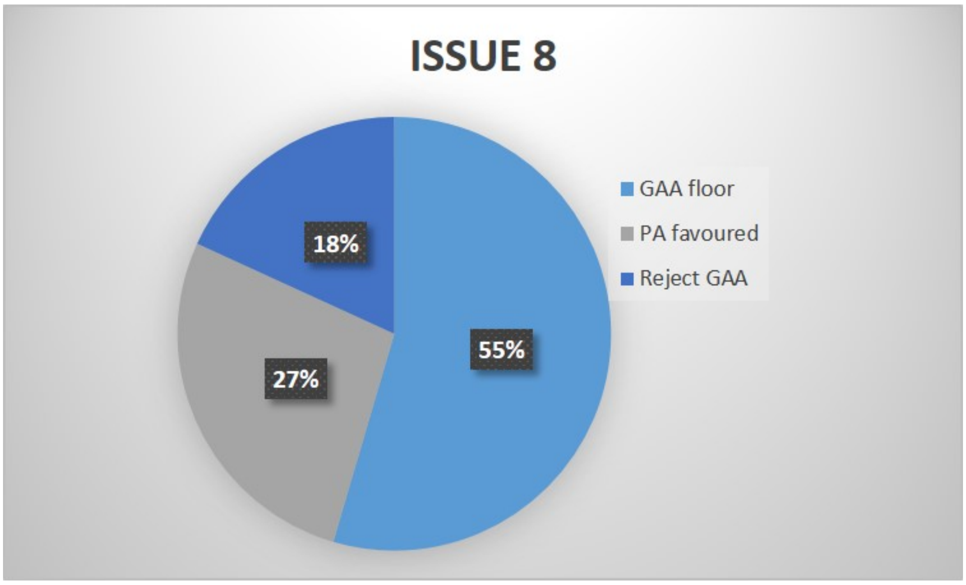

Figure A.13: Proportional assignment of GAA and PA frequencies?

Table A.14: ISSUE 9 - The SAS - dynamic or static and more restrictive?

Stakeholder	Static	Dynamic
AT&T	X	
T-Mobile	X	
Ericsson	X	
Qualcomm	X	
NSN	X	
UTC	X	
Alcatel Lucent		X
Spectrum Bridge		X
Shared Spectrum		X
OTI/PK		X
Motorola Mobility		X
Google		X
WISPA		X
BliNQ		X

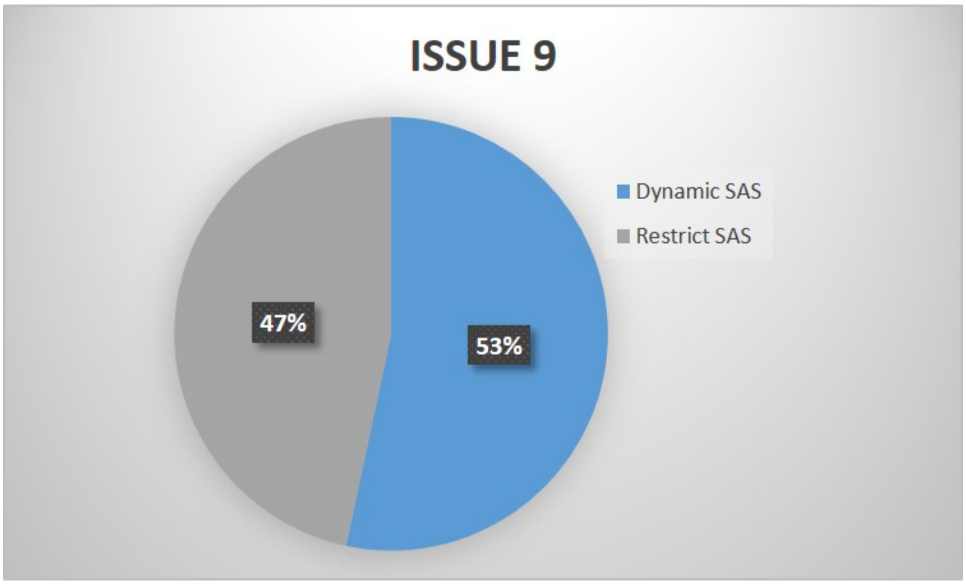

Figure A.14: What is the SAS purpose and functionality?

Table A.15: ISSUE 10 - Static vs. dynamic frequency assignment?

Stakeholder	Static	Dynamic
AT&T	X	
T-Mobile	X	
CTIA	X	
Ericsson	X	
NSN	X	
Verizon	X	
Alcatel-Lucent		X
Google		X
Motorola Mobility		X
Motorola Solutions		X
OTI/PK		X
WISPA		X

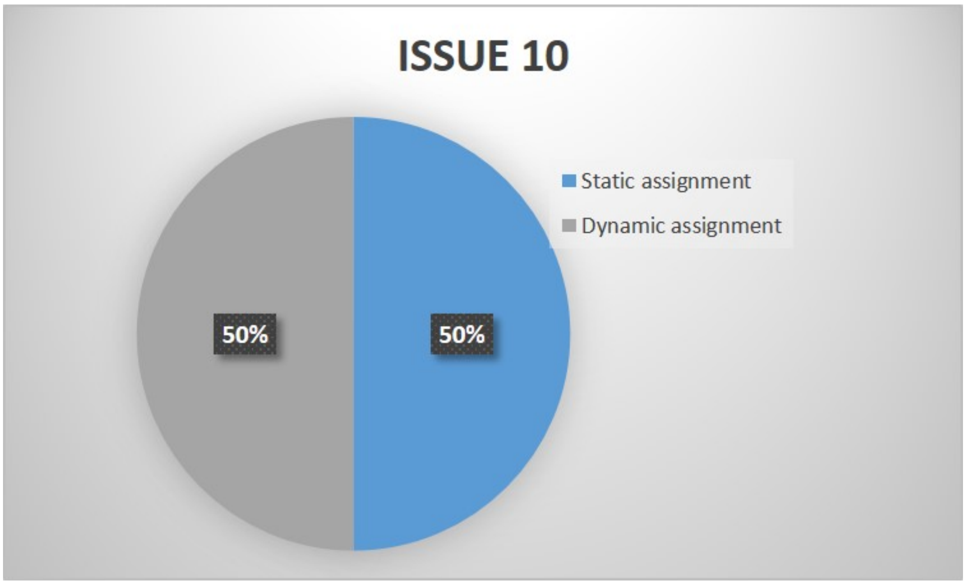

Figure A.15: Static vs. dynamic frequency assignment?

A.3 FNPRM

Table A.16: ISSUE 1 - Multi-tiered access model

Stakeholder	3-tier	2-tier/Transitional
Alcatel-Lucent		X
AT&T		X
Verizon		X
CTIA		X
PCIA		X
Qualcomm		X
Mobile Future		X
NSN		X
Ericsson		X
4G Americas		X
SIA		X
Telecordia		X
Google	X	
WISPA	X	
WinnForum	X	
WSA	X	
PISC	X	
Motorola Mobility	X	
Interdigital	X	
BLiNQ	X	
DSA	X	
Federated Wireless	X	
Spectrum Bridge	X	
WiFi Alliance	X	
Shared Spectrum	X	
Microsoft	X	

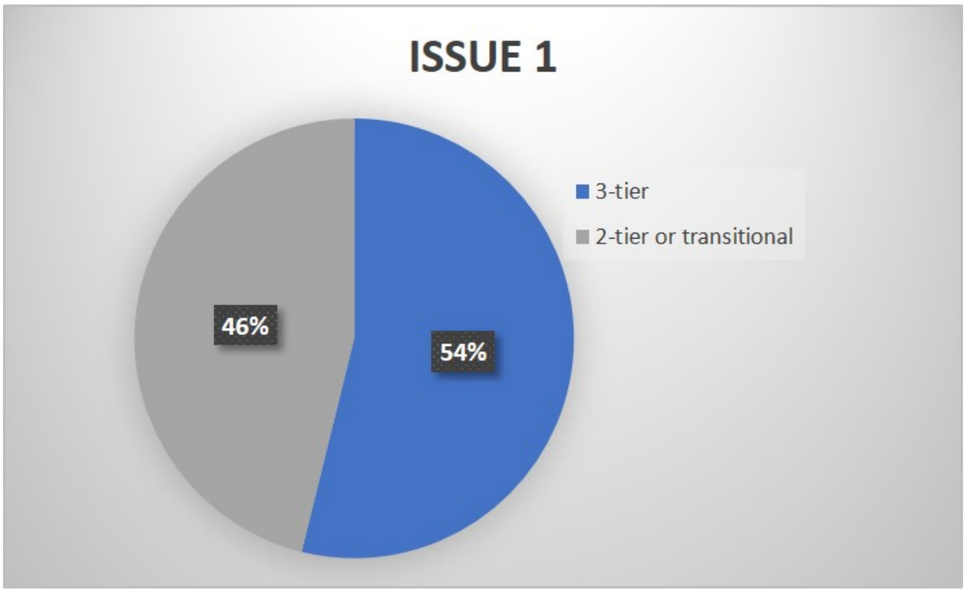

Figure A.16: Multi-tiered access model

Table A.17: ISSUE 2 - Census tracts as license areas?

Stakeholder	Yes	No, CT issues	Larger areas[5]
WISPA	X		
AT&T	X		
Cantor Telecom	X		
ENTELEC	X		
Neptuno Networks	X		
PISC	X		
Southern Company	X		
API		X	
Google		X	
NCTA		X	
CTIA			X
T-Mobile			X
Verizon			X
NSN			X
Qualcomm			X
Ericsson			X
HKT Limited			X
PCIA			X
SIEMENS Industries			X
WiMAX Forum			X
UTC			X
Mobile Future			X
XCEL Energy			X

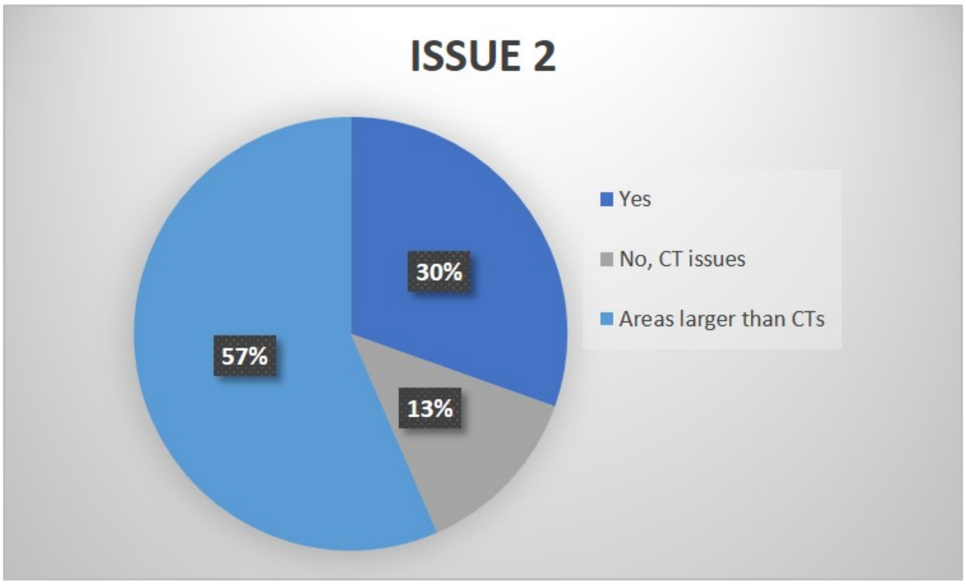

Figure A.17: Census tracts as license areas?

[5] economic areas, cellular market areas

Table A.18: ISSUE 3 - Supplemental proposal: extend Part 96 rules to 3650-3700MHz?

Stakeholder	Yes	No
Google	X	
AT&T	X	
ENTELEC	X	
Microsoft	X	
Motorola Solutions	X	
PISC	X	
WSA	X	
WiFi Alliance	X	
InterDigital	X	
AIRSPAN Networks		X
API		X
Ameren Services		X
BLOOSTON Coalition		X
BliNQ		X
Exelon		X
FWCC		X
Great River Energy		X
Iberdola USA Networks		X
Neptuno Networks		X
Oncor		X
UTC		X
Sprint		X
Telrad Networks		X
SIA		X
SIEMENS Industry		X
Sacred Wind Communications		X
WiMAX Forum		X
XCEL Energy		X
Cloud Alliance		X
WISPA		X

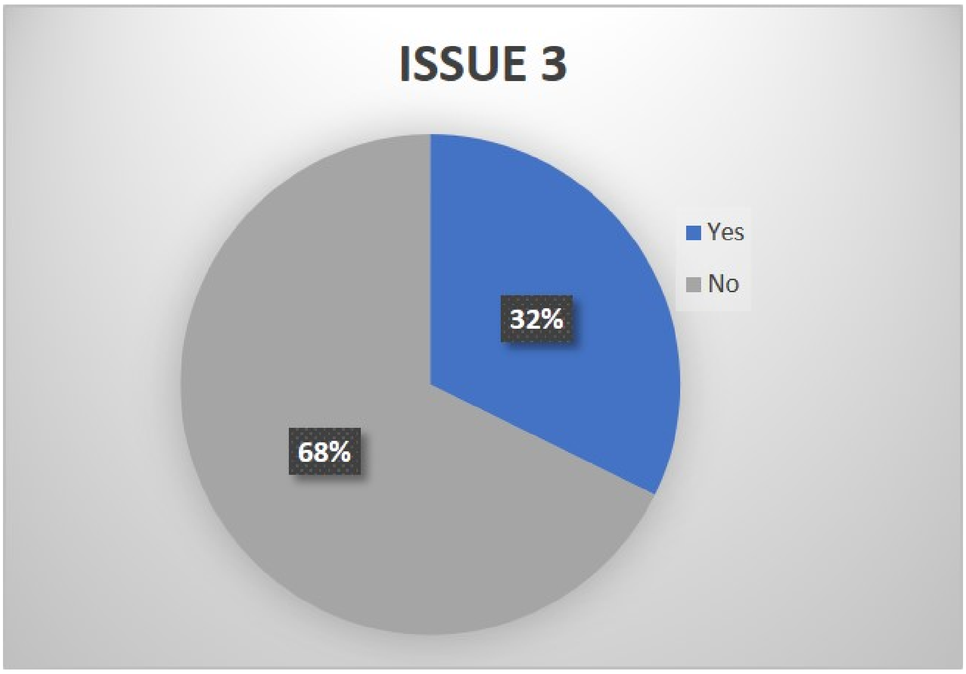

Figure A.18: Supplemental proposal: extend Part 96 rules to 3650-3700MHz?

Table A.19: ISSUE 4 - Dynamic frequency assignment by the SAS?

Stakeholder	Static/fixed	Dynamic
4G Americas	X	
AT&T	X	
CTIA	X	
Ericsson	X	
ENTELEC	X	
Echostar Satellite	X	
HKT Limited	X	
Mobile Future	X	
NSN	X	
PCIA	X	
Qualcomm	X	
SIA	X	
TIA	X	
T-Mobile	X	
Verizon	X	
Federated Wireless		X
Google		X
Microsoft		X
PISC		X
Sacred Wind		X
Sony Electronics		X
Spectrum Bridge		X
WSA		X
WISPA		X
DSA		X
InterDigital		X
Shared Spectrum		X

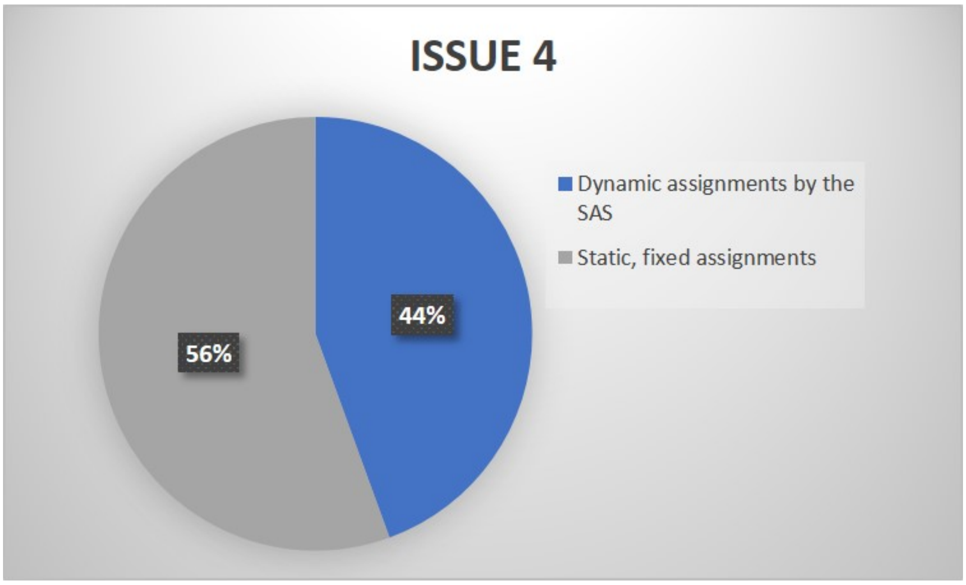

Figure A.19: Proposed GAA floor of 50 percent of frequencies available for GAA always in entire band?

Table A.20: ISSUE 5 - Proposed GAA 'floor' of 50%?

Stakeholder	Oppose	Favoring PAs/ too high	Support for $\geq$ 50%
Exelon	X		
Alcatel-Lucent		X	
T-Mobile[6]		X	
TIA		X	
NSN*		X	
PCIA*		X	
Qualcomm		X	
Verizon		X	
CTIA		X	
ENTELEC			X
API			X
Google			X
Federated Wireless			X
InterDigital			X
Microsoft[7]			X
PISC[8]			X
Motorola Solutions[9]			X
Motorola Mobility			X
WSA			X
WISPA			X
Wi-Fi Alliance			X
UTC			X
Shared Spectrum			X
Shure Inc.			X
NCTA			X

[6] 40MHz+50% for PA
[7] 50MHz for GAA always
[8] 50MHz for GAA always
[9] 60% for GAA

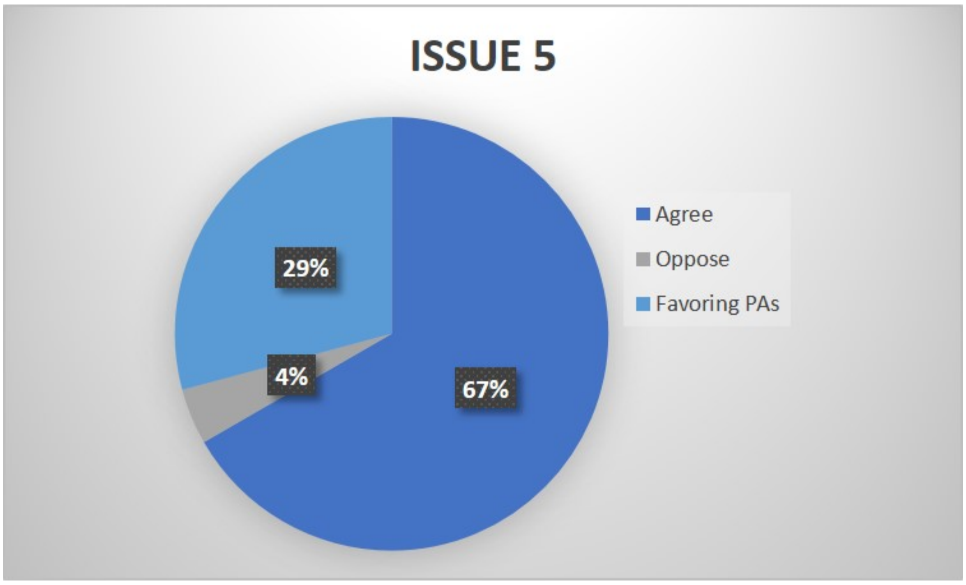

Figure A.20: Proposed GAA floor of 50 percent of frequencies available for GAA always in entire band?

Table A.21: ISSUE 6 - Setting aside frequencies fror CAF users?

Stakeholder	Agree	No	Yes, with changes/broader CAF
Interdigital	X		
Exelon	X		
Verizon		X	
Mobile Future		X	
PISC		X	
Wi-Fi Alliance		X	
Sony		X	
KEEP Enterprise		X	
Ercisson		X	
Microsoft		X	
WISPA		X	
TIA		X	
SIEMENS Ind.			X
Motorola Solutions			X
API			X
UTC			X
Federated Wireless			X
Oncor			X
Lockard&White			X
EWA			X
Southern Company			X
Shared Spectrum			X
XCEL Energy			X
WiMAX Forum			X
Shure Inc.			X
FWCC			X
ENTELEC			X

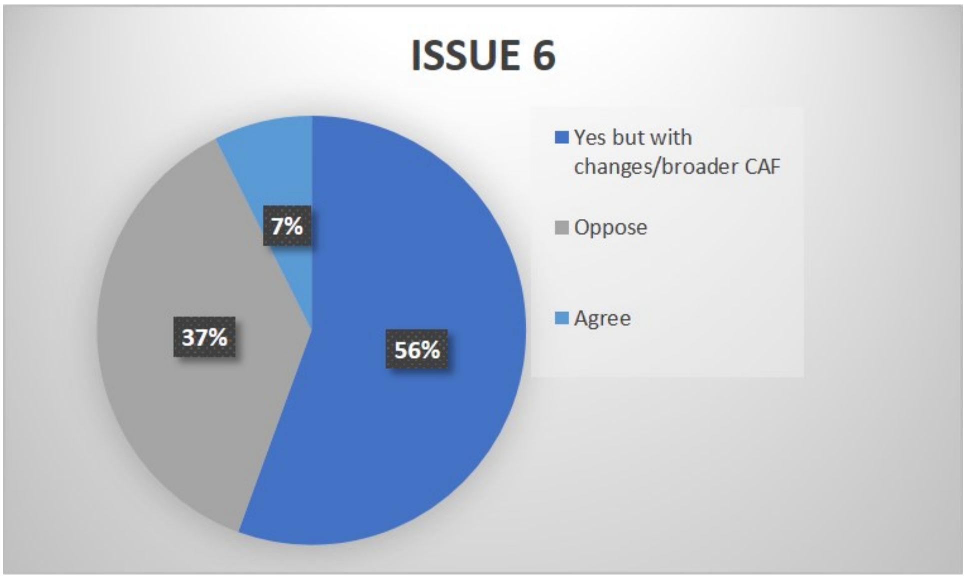

Figure A.21: Setting aside frequencies fror CAF users?

Table A.22: ISSUE 7 - Competitive bidding (if mutual exclusivity) for PAL assignment?

Stakeholder	Agree	Avoid mutual excl.	Oppose auctions
AT&T	X		
PISC	X		
WinnForum	X		
WISPA	X		
Google		X	
API			X
SIEMENS Ind.			X
Exelon			X
WiMAX Forum			X
UTC			X
Neptuno Networks			X
Iberdola			X
XCEL Energy			X
FWCC			X
Southern Company			X
ENTELEC			X
AMEREN Services			X
Oncor			X

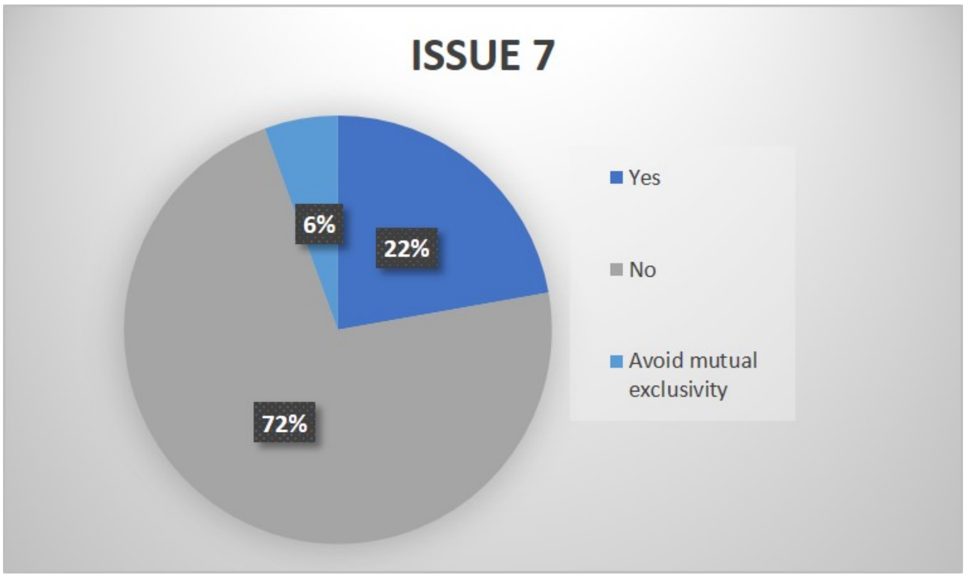

Figure A.22: Mutual Exclusivity triggering competitive bidding

Table A.23: ISSUE 8 - Proposal of PALs for 1 year term, non renewable, with five 1-y term aggregation?

Stakeholder	1y+multiple cap	$\leq$ 1year	longer terms, 1-10+ years
WISPA	X		
PISC	X		
Federated Wireless	X		
Motorola Mobility	X		
Cantor Telecom	X		
WinnForum		X	
API (CAF)			X
AT&T			X
NSN			X
Qualcomm			X
Ericsson			X
WiMAX Forum (CAF)			X
SIEMENS Ind. (CAF)			X
BLOOSTON Coalition (CAF)			X
CTIA			X
Cloud Alliance (CAF)			X
ENTELEC (CAF)			X
HKT Limited			X
Neptuno Networks (CAF)			X
Mobile Future			X
Sacred Wind Comm. (CAF)			X
T-Mobile			X
UTC (CAF)			X
Verizon			X
XCEL Energy (CAF)			X
PCIA			X
Great River Energy (CAF)			X

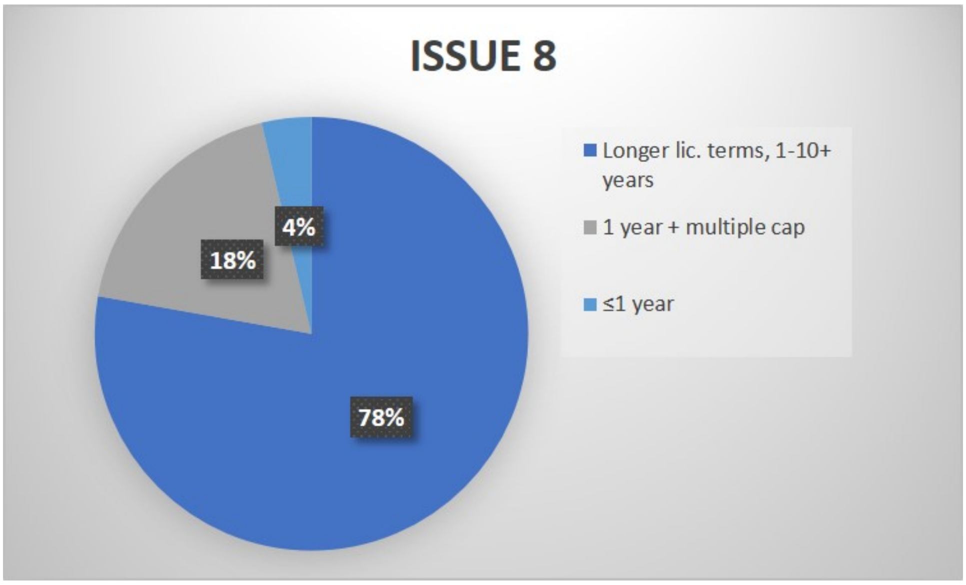

Figure A.23: What is the appropriate license term and temporal aggregation cap?

Table A.24: ISSUE 9 - Proposal for a robust, dynamic and responsive SAS?

Stakeholder	Dynamic SAS	Restrict SAS
WISPA	X	
PISC	X	
Federated Wireless	X	
Motorola Mobility	X	
DSA	X	
WinnForum	X	
WSA	X	
Google	X	
Spectrum Bridge	X	
InterDigital	X	
Sony Electronics	X	
Microsoft	X	
ENTELEC		X
API		X
CTIA		X
HKT Limited		X
NSN		X
Qualcomm		X
SIA		X
Mobile Future		X
Verizon		X
T-Mobile		X
4G Americas		X
Alcatel-Lucent		X
Ericsson		X
AT&T		X
PCIA		X

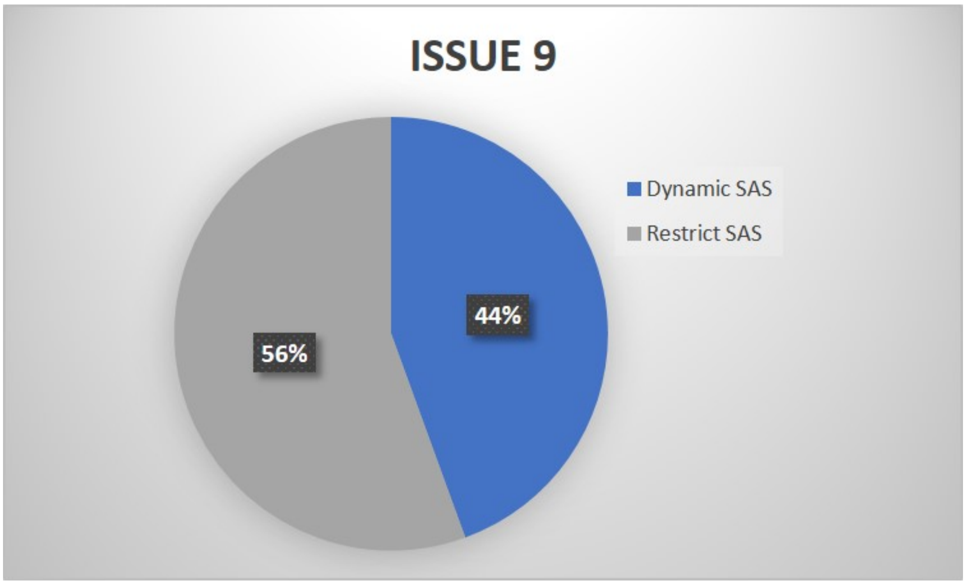

Figure A.24: What is the appropriate license term and temporal aggregation cap?

Table A.25: ISSUE 10 - Approach to CBRS operations within Exclusion Zones?

Stakeholder	Reduce excl zones	No	Dynamic/sensing	Coordination zones
WISPA			X	
Shared Spectrum			X	
Federated Wireless			X	
Google			X	
WinnForum			X	
PISC	X			
4G Americas	X			
Motorola Mobility	X			
WSA	X			
NSN	X			
WiFi Alliance	X			
TIA	X			
Shure Inc.	X			
InterDigital	X			
Qualcomm	X			
Microsoft	X			
ENTELEC	X			
API	X			
CTIA	X			
NCTA	X			
AT&T	X			
Alcatel-Lucent	X			
SIA		X		
NPR		X		
Mobile Future				X
Verizon				X
T-Mobile				X
Ericsson				X

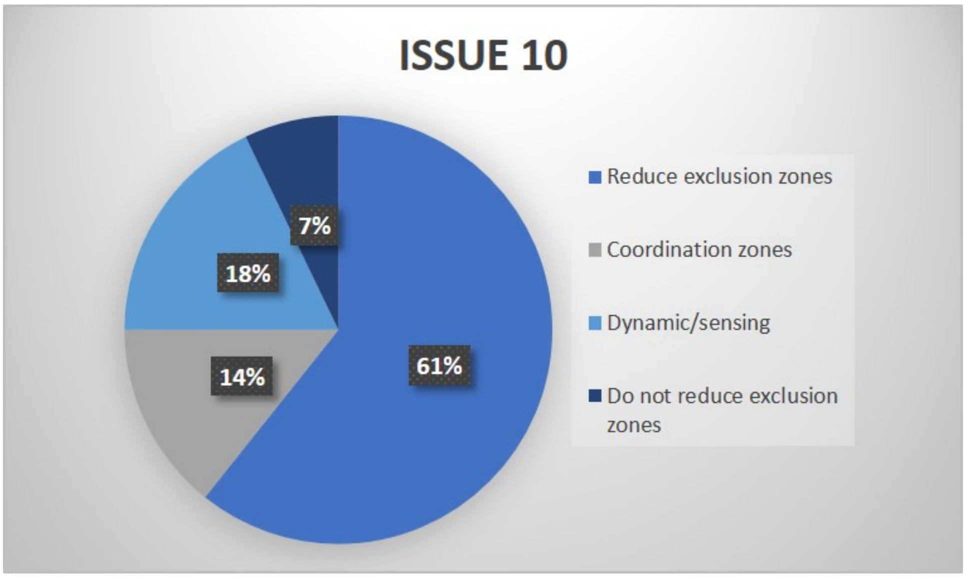

Figure A.25: What is the appropriate license term and temporal aggregation cap?

Table A.26: ISSUE 11 - Allow GAA access to unassigned/not in actual use PAL channels?

Stakeholder	Support	Oppose	Yes, but with concerns
WISPA	X		
Shared Spectrum	X		
Federated Wireless	X		
Google	X		
WinnForum	X		
PISC	X		
DSA	X		
WSA	X		
WiFi Alliance	X		
Microsoft	X		
InterDigital	X		
TIA		X	
Ericsson		X	
AT&T			X
CTIA			X
T-Mobile			X
Verizon			X

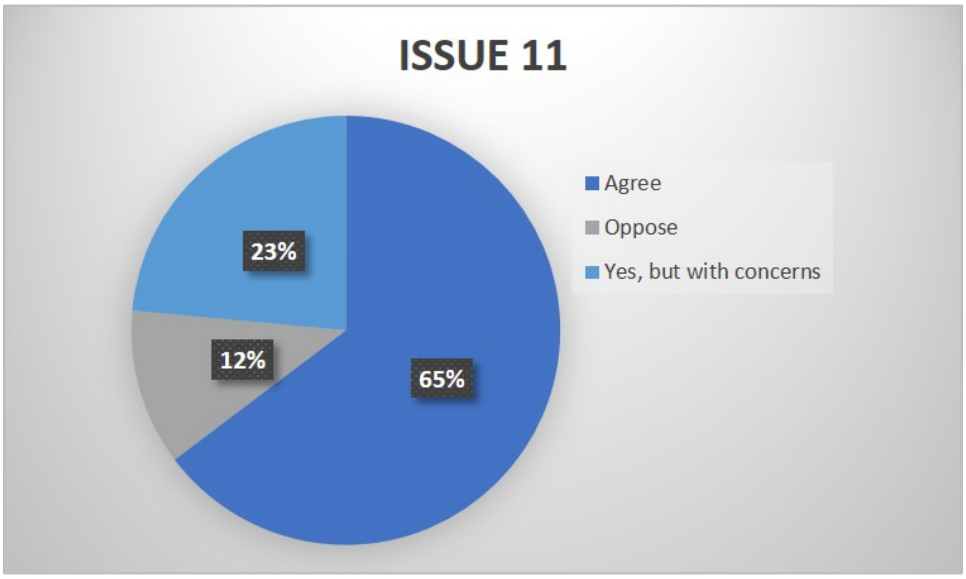

Figure A.26: What is the appropriate license term and temporal aggregation cap?

Table A.27: ISSUE 12 - Proposed spectrum aggregation limit for PAL spectrum of 30 MHz?

Stakeholder	$\leq$ 30MHz	$\geq$ 40MHz	20 MHz	no cap
WISPA	X			
Cantor Telecom	X			
Motorola Mobility		X		
T-Mobile		X		
Motorola Solutions			X	
PISC			X	
Sony Electronics			X	
AT&T				X
Verizon				X

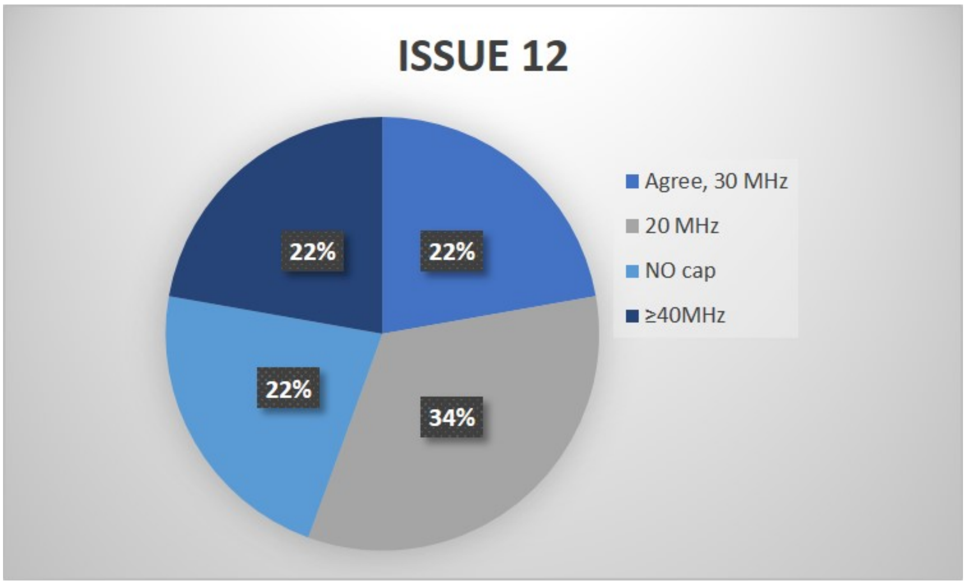

Figure A.27: Spectrum aggregation limit for PA spectrum?

Table A.28: ISSUE 13 - Authorising multiple SAS operators nationwide?

Stakeholder	Agree	Oppose/Challenges	Regional, not nationwide
WISPA	X		
Verizon	X		
Motorola Solutions	X		
AT&T	X		
Microsoft	X		
PISC	X		
Ericsson	X		
Google	X		
WinnForum			X
Federated Wireless			X
Alcatel-Lucent		X	
SIA		X	

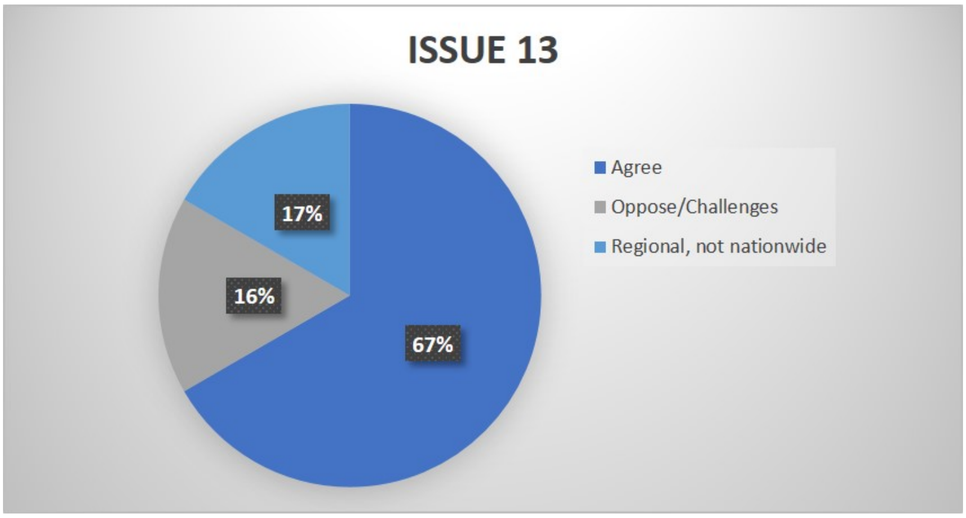

Figure A.28: Authorising multiple SAS operators nationwide?

Table A.29: ISSUE 14 - SAS to collect fees from CBRS tiers?

Stakeholder	Agree	No, collect from GAA
WISPA	X	
AT&T	X	
Ericsson	X	
Federated Wireless	X	
Google	X	
InterDigital	X	
Motorola Solutions	X	
PISC	X	
Spectrum Bridge	X	
T-Mobile		X

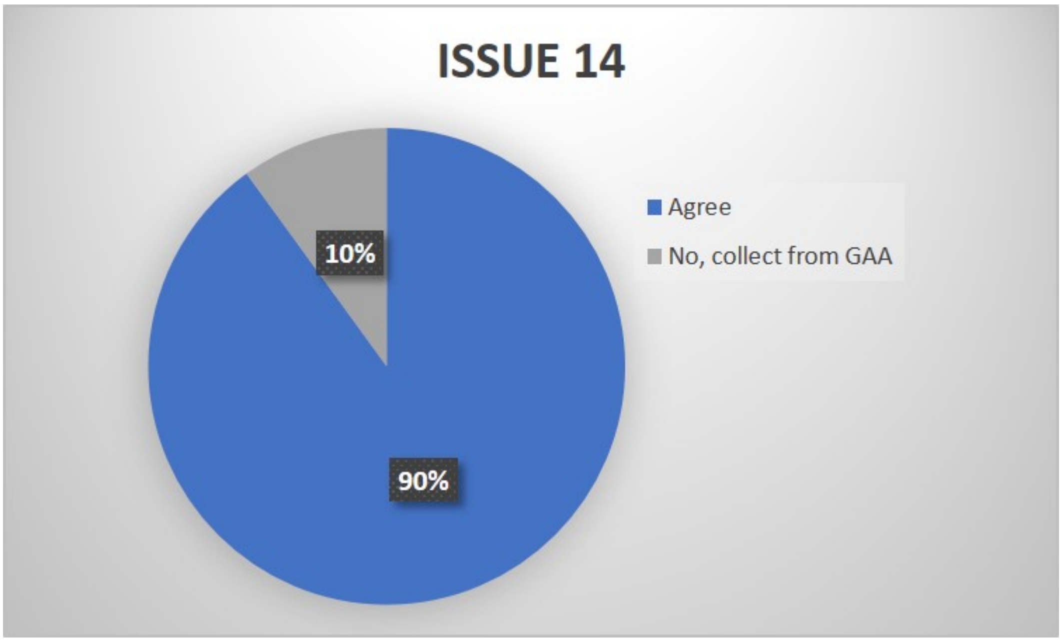

Figure A.29: SAS to collect fees from CBRS tiers?