



Terms and Conditions of Use of Digitised Theses from Trinity College Library Dublin

Copyright statement

All material supplied by Trinity College Library is protected by copyright (under the Copyright and Related Rights Act, 2000 as amended) and other relevant Intellectual Property Rights. By accessing and using a Digitised Thesis from Trinity College Library you acknowledge that all Intellectual Property Rights in any Works supplied are the sole and exclusive property of the copyright and/or other IPR holder. Specific copyright holders may not be explicitly identified. Use of materials from other sources within a thesis should not be construed as a claim over them.

A non-exclusive, non-transferable licence is hereby granted to those using or reproducing, in whole or in part, the material for valid purposes, providing the copyright owners are acknowledged using the normal conventions. Where specific permission to use material is required, this is identified and such permission must be sought from the copyright holder or agency cited.

Liability statement

By using a Digitised Thesis, I accept that Trinity College Dublin bears no legal responsibility for the accuracy, legality or comprehensiveness of materials contained within the thesis, and that Trinity College Dublin accepts no liability for indirect, consequential, or incidental, damages or losses arising from use of the thesis for whatever reason. Information located in a thesis may be subject to specific use constraints, details of which may not be explicitly described. It is the responsibility of potential and actual users to be aware of such constraints and to abide by them. By making use of material from a digitised thesis, you accept these copyright and disclaimer provisions. Where it is brought to the attention of Trinity College Library that there may be a breach of copyright or other restraint, it is the policy to withdraw or take down access to a thesis while the issue is being resolved.

Access Agreement

By using a Digitised Thesis from Trinity College Library you are bound by the following Terms & Conditions. Please read them carefully.

I have read and I understand the following statement: All material supplied via a Digitised Thesis from Trinity College Library is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of a thesis is not permitted, except that material may be duplicated by you for your research use or for educational purposes in electronic or print form providing the copyright owners are acknowledged using the normal conventions. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone. This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

Embedding Spectrum Sharing into LTE-Advanced



Jasmina McMenamy

Electrical Engineering Department

The University of Dublin

Trinity College

This dissertation is submitted for the degree of

Doctor of Philosophy



Trinity College Dublin

PhD
Engineering.

April 2016

TRINITY LIBRARY

27 JUL 2016

DUBLIN

Thesis 10997

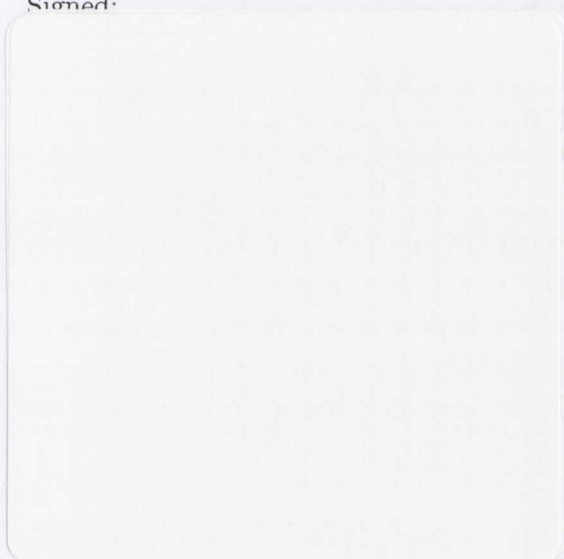
To my family...

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.

I agree to deposit this thesis in the University's open access institutional repository or allow the Library to do so on my behalf, subject to Irish Copyright Legislation and Trinity College Library conditions of use and acknowledgement.

Signed:



1

Jasmina McMenamy
April 2016

Acknowledgements

Firstly, I would like to express gratitude to my supervisor Prof. Linda Doyle for the opportunity to undertake a Ph.D. I would like to thank her for the support, expertise, encouragement and guidance she provided throughout this process.

I would also like to thank external and internal examiners - Assistant Professor Dr. Paulo Marques and Assistant Professor Dr. Nicola Marchetti for their interest in my work, engaging discussions and constructive feedback.

Furthermore, I would like to put on record my appreciation and special thanks to Dr. Irene Macaluso for her ongoing support, professional advice and suggestions, and an inspiring collaboration.

I would also like to thank all of my lab colleagues for the enjoyable time spent in the lab, interesting discussions, and great table-tennis tournaments.

Finally, special thanks goes to my family members.

Summary

Society needs more spectrum. It is required to support continuous data growth, a greater number of mobile connections, smarter devices with more powerful computing capabilities and the emergence of new applications/technologies. Despite these facts, the evidence points to a low spectrum utilisation, both in Europe and in the US, even in dense urban areas. Tackling these trends and associated challenges means finding new, better ways to meet the demands for more spectrum by enabling dynamic & flexible spectrum use, and by encouraging cellular operators to share spectrum. This thesis aimed to address some of these challenges. It proposed to avail of the dominant communication system LTE/LTE-Advanced and to enable a systematic approach to spectrum sharing. Its main contributions are as follows:

- The thesis proposed a well-defined spectrum sharing framework that embedded spectrum sharing deep in the LTE-Advanced system by relying on its inherent mechanisms of Carrier Aggregation and Dual Connectivity.
- It defined a three-tier spectrum-sharing approach, incorporating different spectrum classes - statically assigned, exclusively owned spectrum and two different shared spectrum classes. One spectrum class was based on the *exclusive operation*, providing guarantees on spectrum quality, but at a cost. The other was free, based on *common/open use*, but without guarantees on the quality. The aim was to enable future spectrum sharing bands to avail of the framework through these broad, but distinct spectrum classes.
- The thesis addressed relevant cellular network topologies and architectures, focusing on heterogeneous networks with macro and low-power nodes. It considered the low, medium & high density of low-power nodes, and the underlining centralised and distributed baseband architectures, with remote radio heads and small cells.
- The framework incorporated a spectrum selection mechanism, taking into account QoS and cost of the shared spectrum - the aspects of particular importance for a cellular operator. The QoS was defined in terms of end-user performance and a range of target values that the network should deliver. In this way, the issue typically regarded as a barrier to spectrum sharing by cellular operators - the lack of control over QoS - was

addressed. The spectrum selection mechanism reflected these two spectrum sharing models and also incorporated the cost related to acquiring spectrum resources from the exclusively shared class.

The thesis addressed a number of challenges for the framework, including shared spectrum characterisation, QoS criteria, the framework modelling using simulation-based approach, and analysis and performance of specific architectures. The shared spectrum characterisation was addressed by identifying the key spectrum attributes and drawing on the relevant spectrum sharing initiatives - TV White Spaces, Licensed Shared Access and Citizens Broadband Radio Service. Chapters 4, 6 and 7 dealt with the spectrum characterisation aspects as well as with the selection criteria. Chapter 6 presented an extensive system-level performance and QoS versus Cost analysis for the centralised baseband architecture with Carrier Aggregation with a low/medium density of LPNs. The shared spectrum classes and key attributes were derived from the most relevant spectrum sharing initiatives - TV White Spaces and Licensed Shared Access. Chapter 7 provided a comprehensive system-level analysis of the centralised and distributed baseband architectures with Carrier Aggregation and Dual Connectivity, using Citizens Broadband Radio Service model at 3.5 GHz as a basis. The study considered the low, medium and high density of low-power nodes, with the three-fold contributions. Firstly, the study provided the performance and QoS versus Cost analysis, taking into consideration a range of parameters that included: different density of low-power nodes, network load, commonly shared band availability and its interference levels, and target QoS. The results proved a significant benefit from spectrum sharing using low-power nodes. This was particularly pronounced in the network with the medium and high density of low-power nodes, due to the spatial spectrum reuse, and when free, commonly shared band was available. Secondly, the analysis identified the difference the baseband architecture made on the sharing framework. The results showed that it mattered whether low-power nodes used centralised or distributed baseband architecture. Hence, with low-power nodes, spectrum sharing should not be abstracted from the underlying fronthaul/backhaul infrastructure. With a range of considered values for different parameters, the results showed that in 17% percent of all cases, the baseband architecture played a differentiating role regarding the cost for the cellular operator. The effects were most pronounced for the medium density of low-power nodes. Thirdly, Sensitivity Analysis was presented for a given density of low-power nodes. It evaluated the impact of each of the parameters and their interaction. Due to a multitude of parameters that needed to be taken into account in the spectrum decision process, sensitivity analysis was found to be a valuable tool, determining the relevance of a particular parameter. The results showed that for the low & medium number of low-power nodes and high target QoS requirements, the cost was not sensitive to the change in the network load. With the high density of low-power nodes, the changes in the target QoS affected the cost in all instances, regardless of the network load, the availability of the commonly shared band, its power and congestion levels.

Table of contents

List of figures	xvii
List of tables	xxi
List of abbreviations	xxvi
1 Spectrum Sharing - Advances & Challenges	1
1.1 Relevance of spectrum sharing	1
1.2 Key initiatives in spectrum sharing	3
1.2.1 WLAN networks	4
1.2.2 Relieving cellular networks of data traffic load	7
1.2.2.1 Activities on inter-radio access technologies	8
1.3 Advent of Dynamic Spectrum Access & Cognitive Radio	9
1.3.1 Dynamic Spectrum Access & Cognitive Radio - Definitions	9
1.3.2 Brief discussion on spectrum sharing models	10
1.4 Main aspects of specific spectrum sharing models	12
1.4.1 TV White Spaces	12
1.4.2 PCAST Report & 3.5 GHz - Citizens Broadband Service	14
1.4.3 Licensed Shared Access	16
1.5 Why is there no real progress?	17
1.6 Proposed way forward	18
1.7 Summary of contributions	20
1.8 Thesis map	21
1.9 Publications record	22
2 Spectrum Meets Architectures	25
2.1 Heterogeneous topologies	25
2.2 Heterogeneity of baseband architectures	27
2.2.1 CBB architecture	27
2.2.2 DBB architecture	28
2.3 Main challenges and differences between the architectures	29

2.4	Aggregating spectral resources in heterogeneous baseband architectures . .	30
2.4.1	Carrier Aggregation	31
2.4.1.1	Deployment scenarios	32
2.4.1.2	Protocol impacts	33
2.4.1.3	Primary/Secondary cells	34
2.4.1.4	Tx/Rx architectures	35
2.4.1.5	PHY layer procedures	36
2.4.1.6	Network modes	37
2.4.1.7	Radio resource management & scheduling techniques . . .	37
2.4.1.8	State-of-the-Art	40
2.4.2	Dual Connectivity	41
2.4.2.1	Deployment scenarios	41
2.4.2.2	Protocol impact	41
2.4.2.3	Master/Secondary eNodeB	43
2.4.2.4	Support for Carrier Aggregation within Master/Secondary eNodeB	43
2.4.2.5	Network modes	44
2.4.2.6	State-of-the-Art	44
2.5	Summary	45
3	The Sharing Framework	47
3.1	The main propositions of the framework	47
3.1.1	Spectrum classes	48
3.1.2	Topology & spectrum employment	49
3.1.2.1	Employment of EO spectrum	49
3.1.2.2	Shared spectrum employment	50
3.1.2.3	Network mode	51
3.1.3	Spectrum selection mechanism	52
3.2	Challenges in developing the framework	52
3.3	Summary	54
4	Spectrum Characterisation	57
4.1	Attributes & characterisation of spectrum classes	57
4.1.1	Frequency bands	57
4.1.2	Availability of shared spectrum	58
4.1.3	Interference	59
4.1.4	Cost of shared bands	60
4.1.5	SNR/SINR distributions	60
4.2	Spectrum selection process	60
4.2.1	Stage 1	61

4.2.2	Stage 2	61
4.2.2.1	Achievable capacity & spectral efficiency equivalent	61
4.3	System model	62
4.3.1	Spectrum bands - the characterisation	63
4.3.2	Selection process	64
4.3.2.1	Stage 1	64
4.3.2.2	Stage 2	64
4.3.3	Input parameters	65
4.3.3.1	Spectrum bands - the characterisation	65
4.3.3.2	Selection process	66
4.4	Results & discussion	66
4.4.1	Stage 1	66
4.4.2	Stage 2	67
4.5	Summary	69
5	Simulation Tool for the CBB Architecture - HetNet+	71
5.1	Overview of HetNet simulator	71
5.1.1	Supported scenarios	71
5.1.2	Antenna models	73
5.1.3	The channel model	73
5.1.4	Traffic model	74
5.1.5	Radio resource management	74
5.1.5.1	RR algorithm	75
5.1.5.2	PF algorithm	75
5.1.6	Link-level model	76
5.2	HetNet+	77
5.2.1	Supported scenarios	77
5.2.2	Main simulation flow	78
5.2.3	Initialisation of ancillary cells	78
5.2.4	Initialisation of users	79
5.2.5	Extended Hata channel model	79
5.2.6	Radio Resource Management	81
5.2.6.1	Scheduling algorithms	81
5.3	Summary	81
6	CBB Architecture Analysis	83
6.1	A brief reminder of the CBB architecture	83
6.2	The framework	84
6.2.1	Topology	84
6.2.2	Spectrum characterisation	84

6.2.2.1	Availability & cost of shared bands	85
6.2.2.2	Power levels	85
6.2.2.3	Path loss	88
6.2.2.4	Interference	89
6.2.2.5	Bandwidth	89
6.2.3	Selection criteria for spectrum requirement decision	90
6.2.3.1	Link rate computation	91
6.2.4	Outline of the model	92
6.2.5	Input parameters	93
6.2.5.1	Parameters applicable to all bands	93
6.2.5.2	EO and ES band parameters	93
6.2.5.3	CS band parameters	93
6.3	Results	95
6.3.1	CS band effects	95
6.3.2	Spectrum requirements from the ES band	99
6.3.3	Analysis	100
6.4	Related work & state-of-the-art	102
6.4.1	TV White Space	103
6.4.2	LSA	104
6.5	Summary	105
7	Analysis of the Complete Sharing Framework	107
7.1	A brief reminder of the two architectures	107
7.2	The framework	108
7.2.1	Overall scenario	108
7.2.2	Control plane & signalling aspects	109
7.2.2.1	EO spectrum	110
7.2.2.2	Shared spectrum	110
7.2.3	Spectrum characterisation	111
7.2.4	Selection criteria for spectrum requirement decision	112
7.2.5	Mathematical formulation of the selection criteria	114
7.2.5.1	$SINR$ computation	115
7.2.5.2	Computation of a normalised throughput	116
7.2.5.3	Average bandwidth per a user	118
7.2.5.4	Constraints computation finalised	118
7.2.6	Modelling the framework	121
7.3	System parameters	121
7.4	Results	123
7.4.1	Access probability & mean normalised throughput	123

7.4.2	Spectrum requirement - both baseband architectures	127
7.4.2.1	Impact of CS spectrum availability	127
7.4.2.2	Impact of power scaling and "foreign" interferers in the CS band	131
7.5	Sensitivity Analysis	136
7.5.1	CS band not available	137
7.5.2	CS band available	139
7.5.2.1	2 LPNs	139
7.5.2.2	4 LPNs	139
7.5.2.3	10 LPNs	140
7.5.2.4	20 LPNs	141
7.5.3	Synopsis of the sensitivity analysis	142
7.6	Key findings - Discussion & Summary	143
8	Conclusion	147
8.1	What this thesis addresses	147
8.1.1	The main findings	148
8.2	Developments with LTE in unlicensed 5 GHz spectrum	152
8.3	Future Work	154
	References	157
	Appendix A Sensitivity analysis tables	171
A.1	2 LPNs	171
A.1.1	SI_K	171
A.1.1.1	CBB architecture	171
A.1.1.2	DBB architecture	172
A.1.2	SI_T	174
A.1.2.1	CBB architecture	174
A.1.2.2	DBB architecture	174
A.1.3	SI_I	175
A.1.3.1	CBB & DBB architecture	175
A.1.4	SI_p	176
A.1.4.1	CBB architecture	176
A.1.4.2	DBB architecture	177
A.2	4 LPNs	178
A.2.1	SI_K	178
A.2.1.1	CBB architecture	178
A.2.1.2	DBB architecture	178
A.2.2	SI_T	179

A.2.2.1	CBB architecture	179
A.2.2.2	DBB architecture	181
A.2.3	SI_I	181
A.2.3.1	CBB & DBB architecture	181
A.2.4	SI_p	183
A.2.4.1	CBB architecture	183
A.2.4.2	DBB architecture	184
A.3	10 LPNs	185
A.3.1	SI_K	185
A.3.1.1	CBB architecture	185
A.3.1.2	DBB architecture	187
A.3.2	SI_T	189
A.3.2.1	CBB architecture	189
A.3.2.2	DBB architecture	191
A.3.3	SI_I	193
A.3.3.1	CBB architecture	193
A.3.3.2	DBB architecture	194
A.3.4	SI_p	197
A.3.4.1	CBB architecture	197
A.3.4.2	DBB architecture	198
A.4	20 LPNs	199
A.4.1	SI_K	199
A.4.1.1	CBB architecture	199
A.4.1.2	DBB architecture	200
A.4.2	SI_T	201
A.4.2.1	CBB architecture	201
A.4.2.2	DBB architecture	202
A.4.3	SI_I	203
A.4.3.1	CBB architecture	203
A.4.3.2	DBB architecture	205
A.4.4	SI_p	207
A.4.4.1	CBB Architecture	207
A.4.4.2	DBB Architecture	209

List of figures

1.1	Monthly traffic increase year on year according to Cisco forecast 2014-2019.	2
1.2	Current allocations for 5 GHz band in the US and Europe. Spectrum sharing between Wireless Access Systems/Radio Local Area Networks with the incumbent services in 5.35-5.47 and 5.725-5.85 GHz in Europe are still under study.	6
1.3	Different planes of classification. Licensing mode is on the top and spectrum access techniques are at the bottom.	13
2.1	The classification and types of LPNs considered in the thesis.	27
2.2	Mix of small cells and RRHs. Small cells use a range of technologies to connect to the rest of the radio network, and the core network. RRHs use fibre connectivity with very high throughput, low latency and low jitter to connect to the BBU. Only BBU provides the interface to the core network.	28
2.3	Intra- and inter-band Carrier Aggregation. CCs can be of different widths. Primary component carrier and secondary component carriers are defined per a user.	32
2.4	Deployment scenarios as envisaged by 3GPP. In scenarios a), b) and c), both component carriers - f_1 and f_2 - operate on macro nodes. In scenario d), f_1 is employed by macro tier, whereas f_2 is deployed on the tier of RRHs. . . .	33
2.5	Carrier Aggregation protocol stack - DL. The scheduler, situated in MAC, controls data rate.	34
2.6	Overview of a signalling flow for the addition of SCell.	35
2.7	Cross-carrier scheduling. Control region on CC2 on the right does not carry scheduling assignments for its users.	36
2.8	Carrier Aggregation introduces L3 CC assignment component. Link adaptation and fast retransmissions are handled per a CC.	37
2.9	Dual Connectivity scenarios in 3GPP. Macro and small cells may operate on the same, or different frequencies. Small-cells only scenario is also considered.	42
2.10	Control plane for Dual Connectivity. RRC messages are only exchanged between the Master eNodeB and UE.	43

2.11	User plane for Dual Connectivity. Separate bearers (left) and split bearer (right) options. With separate bearers considered in this thesis, both nodes have the complete protocol stack below Packet Data Convergence Protocol (PDCP).	44
3.1	The main concept of the proposed framework. Spectrum resources considered in the selection criteria depend on the baseband architecture. The objective and selection criteria determine how the shared carriers are used.	48
4.1	The proposed process for the selection of CS resource blocks. Depending on their availability and quality, a cellular operator can decide should the additional resources from the ES band be resorted to.	62
4.2	CDFs of SNR/SINR in the ES and CS bands	66
4.3	The ES spectral efficiency equivalent for different values of probability thresholds	67
4.4	Minimum SINR required to use the CS band	68
5.1	Outline of the scenarios supported by HetNet simulator	72
5.2	Additional scenarios in HetNet+	77
5.3	High-level overview of the main HetNet+ flow	78
5.4	HetNet+ uses existing link models and scheduling algorithms	79
5.5	The introduction of ancillary carriers is analogous to the activation of secondary carriers as defined in LTE-Advanced. All major attributes are set separately per a carrier.	79
6.1	Deployment scenario considered in this chapter, with different RRH densities. RRHs employ shared carriers. Users are distributed throughout the macro cell area.	84
6.2	Path loss in urban environment with Extended Hata model (transmitter height of 5 meters).	89
6.3	Median and cell-edge user throughput across all spectrum bands determine the requirement from the ES spectrum.	91
6.4	Combined median user rate for the maximum and minimum considered power levels. There is no power sharing with other spectrum users/entities. X-axis represents the number of users per macro cell. Y-axis represents 50%-ile user throughput.	96
6.5	Combined cell-edge user rate with RRH power set to the maximum and the minimum considered levels. There is no power sharing with other spectrum users/entities. X-axis represents the number of users per macro cell. Y-axis represents 5%-ile user throughput.	97

6.6 Combined median user rate for the case when the operator has to share spectrum with other, "foreign" entities. Power levels are scaled when RRHs are in a good (18 dBm) and a poor DTT service area (5.5 dBm). 98

6.7 Spectrum requirement for the median user target throughput of 5 Mb/s in a good DTT service area - cell density 2 99

6.8 Spectrum requirement for the cell-edge case with target throughput of 1.5 Mb/s in a good DTT service area. The case with 2 RRHs is shown. 101

6.9 Spectrum requirement for median user target throughput of 5 Mb/s in a poor DTT service area. The case with 2 RRHs is shown. 102

6.10 Flexibility is characterised in terms of QoS reduction. The impact on the spectrum requirement is shown (9 dBm). 103

7.1 Deployment scenario with different RRH/small cell densities, featuring operator's and "foreign" LPNs. LPNs employ shared carriers. A fixed number of users is clustered around LPNs, whereas the remainder of users is distributed across the whole macro cell area. 109

7.2 Computation of spectrum requirement for CBB (left) and DBB architecture (right). 114

7.3 Flowchart of the decision-making process to compute the spectrum requirement from the ES spectrum. 120

7.4 Access probability for the CS band for all cases with different cell densities and a different number of "foreign" interferers. The power level is set to 30 dBm. For the case of 2 LPNs, the difference in coverage between 0 and 30 "foreign" interferers is pronounced and ranges from 98% to 12%. With 20 LPNs, the difference in coverage probability with a different number of "foreign" interferers subsides significantly. It falls from 100% with 0 to 73% with 30 "foreign" interferers. 125

7.5 Access probability for the CS band for all power levels, and no "foreign" interferers. The impact of power levels for the low and medium LPN density is pronounced. 126

7.6 Mean spectral efficiency in the CS band for the case of 0 "foreign" interferers. The highest mean spectral efficiency is achieved in the case of 10 LPNs (except for the power of 1 dBm). The effects of different transmit power are noticeable for power levels up to 21 dBm, and 4 LPNs. 127

7.7 Mean spectral efficiency in the CS band for the power of 26 dBm. 128

7.8 Spectrum requirement for the CBB architecture for the case of 10 LPNs per macro cell. Power in the CS band, when available, is 1 dBm, and there are 3 "foreign" interferers. The x-axis represents the availability of the CS band, and the y-axis depicts the number of users in a macro cell. 129

7.9	Spectrum requirement for the CBB and DBB architectures for the case of 2 LPNs per macro cell. Power in the CS band, when available, is 30 dBm, and there are no "foreign" interferers. The x-axis represents the availability of the CS band and y-axis depicts the number of users in a macro cell. Each row represents spectrum requirement for the indicated target throughput gain. .	130
7.10	Spectrum requirement for the case of 10 LPNs per macro cell. Power in the CS band, when available, is 30 dBm, and there are 3 "foreign" interferers. .	131
7.11	Spectrum requirement for the case of 20 LPNs per macro cell. Power in the CS band, when available, is 30 dBm, and there no "foreign" interferers. . .	132
7.12	Spectrum requirement for medium-loaded macro cell ($K = 20$), when the CS band is available. Power levels are 1 and 30 dBm.	133
7.13	Spectrum requirement for highly-loaded macro cell ($K = 50$), when the CS band is available. Power levels are 1 and 30 dBm.	134
7.14	Figure depicts bandwidth requirement when CS band is available, with power levels of 1 and 21 dBm, with 0 "foreign" interferers.	135

List of tables

1.1	Key aspects of the main technologies used in the ISM bands. Older 802.11 standard (802.11b) uses spread spectrum (SS) techniques - Frequency Hopping (FH-SS), and Direct Sequence (DSSS) together with Complementary Code Keying (CCK). Newer 802.11 standard (802.11a/g/n/ad/ac use Orthogonal Frequency Division Multiplex (OFDM)).	4
2.1	Summary of latency and throughput requirements according to 3GPP. . . .	29
4.1	Summary of the parameters used in the simulation.	65
5.1	Minimum distance between the nodes and UEs in homogeneous (macro-only) and heterogeneous network scenarios according to 3GPP	73
5.2	Relevant channel models	73
5.3	Probability of LoS for macro nodes and LPNs (urban environment)	74
5.4	Extended Hata path loss formulae	80
6.1	All power options are considered in the CS band.	88
6.2	Input parameters used in all bands	94
6.3	Input parameters used in the EO band	94
6.4	Input parameters specific to the ES band	94
6.5	Permitted EIRP levels in the CS band for different cases	95
6.6	Other input parameters specific to the CS band	95
7.1	Distance between the nodes and UEs in this chapter	122
7.2	Density of the LPN nodes	122
7.3	Input parameters for the EO, ES and CS bands	122
7.4	System efficiency calculations for both architectures	124
7.5	SI_K when the CS band is not available. The value is computed, based on the spectrum requirement for $K = 10$ and $K = 50$	138
7.6	SI_T when the CS band is not available. The value is computed, based on spectrum requirement for target TH gain $\times 2$ and $\times 20$	138

A.1	Sensitivity Index (SI_K) for the case of 2 LPNs in the CBB architecture . .	171
A.2	Sensitivity Index (SI_K) for the case of 2 LPNs in the DBB architecture . .	172
A.3	Sensitivity Index (SI_T) for the case of 2 LPNs in the CBB architecture . .	174
A.4	Sensitivity Index (SI_T) for the case of 2 LPNs in the DBB architecture . .	174
A.5	Sensitivity Index (SI_I) for the case of 2 LPNs in both architectures	175
A.6	(SI_p) for the case of 2 LPNs in the CBB architecture	176
A.7	(SI_p) for the case of 2 LPNs in the DBB architecture	177
A.8	Sensitivity Index (SI_K) for the case of 4 LPNs in the CBB architecture . .	178
A.9	Sensitivity Index (SI_K) for the case of 4 LPNs in the DBB architecture . .	178
A.10	Sensitivity Index (SI_T) for the case of 4 LPNs in the CBB architecture . .	179
A.11	Sensitivity Index (SI_T) for the case of 4 LPNs in the DBB architecture . .	181
A.12	Sensitivity Index (SI_I) for the case of 4 LPNs in both architectures	181
A.13	(SI_p) for the case of 4 LPNs in the CBB architecture	183
A.14	(SI_p) for the case of 4 LPNs in the DBB architecture	184
A.15	Sensitivity Index (SI_K) for the case of 10 LPNs in the CBB architecture . .	185
A.16	(SI_K) for the case of 10 LPNs in the DBB architecture	187
A.17	Sensitivity Index (SI_T) for the case of 10 LPNs in the CBB architecture . .	189
A.18	Sensitivity Index (SI_T) for the case of 10 LPNs in the DBB architecture . .	191
A.19	Sensitivity Index (SI_I) for the case of 10 LPNs in the CBB architecture . .	193
A.20	Sensitivity Index (SI_I) for the case of 10 LPNs in the DBB architecture . .	194
A.21	(SI_p) for the case of 10 LPNs in the CBB architecture	197
A.22	(SI_p) for the case of 10 LPNs in the DBB architecture	198
A.23	(SI_K) for the case of 20 LPNs in the CBB architecture	199
A.24	(SI_K) for the case of 20 LPNs in the DBB architecture	200
A.25	Sensitivity Index (SI_T) for the case of 20 LPNs in the CBB architecture . .	201
A.26	Sensitivity Index (SI_T) for the case of 20 LPNs in the DBB architecture . .	202
A.27	Sensitivity Index (SI_I) for the case of 20 LPNs in the CBB architecture . .	203
A.28	Sensitivity Index (SI_I) for the case of 20 LPNs in the DBB architecture . .	205
A.29	(SI_p) for the case of 20 LPNs in the CBB architecture	208
A.30	(SI_p) for the case of 20 LPNs in the DBB architecture	209

List of abbreviations

Acronyms / Abbreviations

3GPP	3rd Generation Partnership Project
4G	Fourth generation of wireless communication systems
5G	Fifth generation of wireless communication systems
ACI	Adjacent Channel Interference
AP	Access Point
AWGN	Additive White Gaussian Noise
BLER	Block Error Rate
CBB	Centralised Baseband
CBS	Citizens Broadband Radio Service
CC-PF	Cross-Carrier Proportional Fair
CC	Component Carrier
CDMA	Code Division Multiple Access
CEPT	European Conference of Postal and Telecommunications Administrations
CIF	Carrier Indicator Field
CoMP	Coordinated MultiPoint
CP	Cyclic Prefix
CPRI	Common Public Radio Interface
CR	Cognitive Radio
CRS	Cell Reference Signal

CS	Commonly Shared
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
DBB	Distributed Baseband
DCF	Distributed Coordination Function
PCF	Point Coordination Function
DCI	Downlink Control Information
DFS	Dynamic Frequency Selection
DL	Downlink
DMRS	Demodulation Reference Signal
DSA	Dynamic Spectrum Access
DTT	Digital Terrestrial TV
DVBT	Digital Video Broadcasting — Terrestrial
DySPAN	Dynamic Spectrum Access Networks
E-UTRA	Enhanced UMTS Terrestrial Radio Access
ECC	Electronic Communications Committee
eICIC	enhanced Inter Cell Interference Coordination
EIRP	Effective Isotropic Radiated Power
EO	Exclusively Owned
EPS	Enhanced Packet Service
ESC	Environment Sensing Capability
ES	Exclusively Shared
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access

GAA	General Authorized Access
GPF	Generalised Proportional Fair
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat reQuest
HCF	Hybrid Coordination Function
ICIC	Inter Cell Interference Coordination
IFOM	IP Flow Mobility
ISM	Industrial, Scientific and Medical bands
LAA	License Assisted Access
LBT	Listen Before Talk
LPN	Low Power Node
LSA	Licensed Shared Access
LTE-U	LTE Unlicensed
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
M2M	Machine to Machine
MAPCON	Multi Access Packet Data Network Connectivity
MIMO	Multiple Input Multiple Output
NTIA	National Telecommunications and Information Administration
OBSAI	Open Base Station Architecture Initiative
OFDMA	Orthogonal Frequency Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
ORI	Open Radio equipment Interface
PAL	Priority Access License
PCAST	President's Council of Advisors on Science and Technology
PCell	Primary Cell

PF	Proportional Fair
PGW	Packet Gateway
PMSE	Programme Making and Special Events
QoS	Quality of Service
RRC	Radio Resource Control
RRH	Remote Radio Head
RR	Round Robin
RSPG	Radio Spectrum Policy Group
RTS	Request to Send
SAS	Spectrum Access System
SCell	Secondary Cell
SGW	Serving Gateway
SINR	Signal to Interference and Noise Ratio
SIPTO	Selected IP Traffic Offload
SNR	Signal to Noise Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TV WS	TV White Spaces
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
UWB	Ultra-wide Band
VHF	Very High Frequency
WLAN	Wireless Local Area Network
WRC	World Radiocommunication Conference

Chapter 1

Spectrum Sharing - Advances & Challenges

1.1 Relevance of spectrum sharing

The global demand for spectrum is growing and is set to continue to increase due to a variety of reasons. These include factors such as a massive increase in mobile connections and the proliferation of smarter mobile devices, with greater computing resources and advanced connection capabilities [1]; the fast rise in the number of machine-to-machine (M2M) applications and devices; the emerging of wearable devices; and a tremendous increase in mobile video traffic [1]. According to the Cisco forecast for 2014-2019 [1], cellular data traffic alone will globally increase nearly ten-fold by 2019, compared to 2014, see Fig.1.1. A number of national regulatory agencies also forecast high spectrum demands in the medium to long-term. In a recent analysis for Ofcom¹ for the UK [3], it is found that in the case of medium-to-high estimates of mobile broadband traffic, current mobile broadband spectrum allocations may not be sufficient by 2020. Furthermore, all projects and research activities focused on defining the *fifth generation* (5G) cellular networks put a requirement for more spectrum on a top of the list of priorities, see examples in [4], [5].

Despite these extraordinary requirements for spectrum, portions of this unique resource lay underutilised. In Europe, the overall utilisation is shown to be below 10%, [6]. In the US, less than 20 % of spectrum below 3.7 GHz is utilised [7], even in densely populated areas. The cause of such a state of affairs cannot be reduced to a single issue, as spectrum usage is a complex subject due to its inherent physical and technical limitations. Nevertheless, it is recognised, notably in [6] and [7], that one of the contributing factors to this situation is the traditional approach to spectrum management. Furthermore, current spectrum management practices are designed for the technology that is now decades old [8]. This approach entails

¹Ofcom is the UK's communications regulator [2].

allocation of spectrum bands to a particular service or services, with a block of spectrum assigned to a particular entity within each band. Spectrum assignment is typically done on a long-term basis, regardless of the spectrum utilisation.

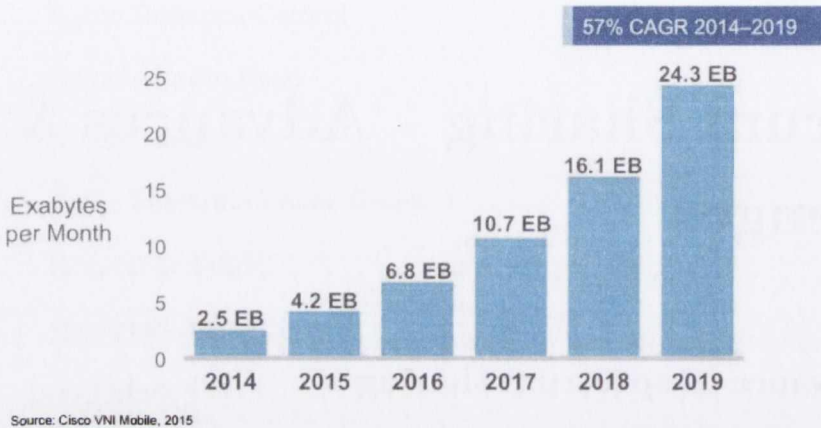


Fig. 1.1 Monthly traffic increase year on year according to Cisco forecast 2014-2019.

It is clear that meeting future spectrum demands by clearing current spectrum allocations and assignments to give way to the services and entities that may, or may not, increase the spectrum efficiency and utilisation could be a long and costly process. In [7], it was estimated that clearing 95 MHz of Federal spectrum could cost around 18 billion US dollars, and it could take around ten years. Furthermore, these are the traditional methods of spectrum management, which have significantly contributed to the issue. Therefore, it has been recognised that one way to address this problem is to enable spectrum sharing and increase spectrum efficiency through a better spectrum management. Both [6] and [7] propose spectrum sharing as a new norm and integral part of spectrum management. Steps are being taken to approve spectrum sharing in certain bands. For example, in the US, following the President’s Council of Advisors on Science and Technology (PCAST) report [7] and a series of consultations, the Federal Communication Commission (FCC)² adopted the final rules for spectrum sharing in the 3.5 GHz band in April 2015. In the UK, Ofcom has recently approved of spectrum sharing in the TV Ultra High Frequency (UHF) band, following a series of trials [9].

In addition to the above motivation for spectrum sharing, there is also a general acknowledgement of significant potential for new technologies and associated socio-economic

²FCC in the US manages all spectrum but Federal. The Federal spectrum is managed by the National Telecommunications and Information Administration (NTIA).

benefits. Socio-economic benefits of opening spectrum for sharing are recognised in [7] as the means to foster innovation, contribute to economic growth and revenue generation, and improve the quality of service. In [6], a detailed study on the socio-economic impacts of shared spectrum is provided. It considers a modest sharing scenario, which allocates 200 MHz of spectrum for sharing through complementary sharing options in certain frequency bands, such as terrestrial broadcast bands, as well as light licencing that enables the shared use of military and other public services bands. It is estimated that such scenarios in the EU could result in a net stimulus of 270 billion Euros in the period 2012-2020. The radical approach that allocates 400 MHz of spectrum for sharing would amount to some 776 billion net benefit to the EU economy [6]³. These are significant returns for the EU economy, even with a considerable margin of error.

In [10], a probability-weighted analysis is conducted to evaluate the economic impact of vertical spectrum sharing between a mobile network operator and the incumbent in the period 2018-2030. The economic impact (value) is scaled down with the geographic and timing restrictions on spectrum use. The analysis is conducted for two popular bands - 2.3 GHz in Europe and 3.5 GHz in the US. It is estimated that the effect of spectrum sharing in the US may range from 7 to 260 billion US dollars, depending on the contract length and the size of the areas where sharing is not possible. In the EU, between 5-86 billion Euros could be the value of spectrum sharing in 2.3 GHz, across the EU countries, again dependent on the time and geographic restriction, and the adoption levels across the EU states. While different sources may have a different methodology in how they derive the estimated economic value⁴, it is evident that all reports thus far, recognise a significant economic and social value of spectrum sharing for the society.

1.2 Key initiatives in spectrum sharing

The Industrial, Scientific and Medical (ISM) radio bands⁵ are the original spectrum sharing bands. They have been a huge success, and today are the most prevalent examples of spectrum sharing. The operation in the ISM bands allows heterogeneous systems to co-exist. For example, in the 2.4 GHz ISM band, which spans from 2.4-2.5 GHz, several technologies coexist. They include Wireless LAN (WLAN)⁶ and other wireless technologies such as Bluetooth (based on IEEE 802.15.1) and ZigBee (based on IEEE 802.15.4) [12]. Also, microwave

³These are rough estimates, and according to [6], take into account $\pm 50\%$ margin of error.

⁴For example, [10], considers solely vertical sharing between a mobile network operator and the incumbent. It also argues that the level of investment and, therefore, the associated economic value is reduced with more dynamic sharing arrangements, and uncertainty.

⁵There are a number of internationally defined bands for the ISM operation. They are 6.78, 13.56, 27.12 and 40.68 MHz, as well as 2.45 GHz, 5.8 and 24.125, 61.25 and 245 GHz. There are also some ISM bands that are defined only in certain regions, such as 900 MHz in the ITU Region 2 (Americas), [11].

⁶WLAN networks are based on the standard developed by the International Institute of Electrical and Electronics Engineers (IEEE) and include 802.11 b/g/n standard.

ovens, baby monitors, and many other systems transmit in this band. The transmission is limited to a low-power regime, and the operation in the band does not provide interference protection. All systems have access to the band on an equal basis, provided they abide by the rules of the band. Each system uses different coexistence mechanisms - for example, the IEEE 802.15.1 family uses frequency hopping - spread spectrum (FH-SS), and adaptive frequency hopping to avoid collisions with Wireless LAN [12]. Table 1.1 depicts different

Table 1.1 Key aspects of the main technologies used in the ISM bands. Older 802.11 standard (802.11b) uses spread spectrum (SS) techniques - Frequency Hopping (FH-SS), and Direct Sequence (DSSS) together with Complementary Code Keying (CCK). Newer 802.11 standard (802.11a/g/n/ad/ac use Orthogonal Frequency Division Multiplex (OFDM)).

	WiFi (IEEE 802.11)	Bluetooth (802.15.1)	UWB (802.15.3)	ZigBee (802.15.4)
Frequency	2.4 & 5 GHz	2.4 GHz	3.1-10.6 GHz	2.4 GHz
Physical Layer	FH-SS, DS-SS/CCK, OFDM	FH-SS	MultiBand OFDM	DS-SS
Nominal Transmit Power (dBm)	15-20	0-10	-41.3 dBm/MHz	-25-0
Channel Bandwidth (MHz)	22 (20, 40, 80, 160 for 802.11g/n/ac)	1 (up to 5MHz with 15 hopping channels)	500 MHz - 7.5 GHz	0.3/0.6; 2
Nominal Range (m)	100 (50 for 802.11a)	10	10	10-100
Coexistence Mechanism	DFS/TPC in 5 GHz bands	Adaptive frequency hopping	DFS	Adaptive frequency hopping

technologies, typical powers and co-existence mechanisms used in the ISM bands, according to [12],[13].

As WLAN networks have a pivotal role in pioneering and promoting spectrum sharing, in the next subsection the thesis specifically turns to these networks.

1.2.1 WLAN networks

WLAN networks, popularly also known as Wireless Fidelity (WiFi) networks, include the family of IEEE 802.11 a/b/g/n/ac/ad protocols for wireless local area networks and include PHY and MAC layer specifications [14]. The majority of 802.11 standards use OFDM as a waveform while only the early versions (802.11b) used spread spectrum techniques [15]. From the architecture point of view, the WiFi standards support infrastructure mode, where the network consists of an access point (AP) and connecting stations. In ad-hoc mode,

the stations can communicate directly [14]. For controlling the access to the medium, the 802.11 family of protocols uses either mandatory, contention-based Distributed Coordination Function (DCF), or optional contention-free Point Control Function (PCF). DCF is a distributed mechanism, which does not require a centralised control. It is based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) and enables asynchronous data transport⁷. DCF also includes Request to Send/Clear to Send (RTS/CTS) handshakes to avoid transmission collisions with a node not seen by the transmitting station (i.e. the hidden node) [13]. Although DCF provides a simple, distributed operation, it is recognised that it suffers from serious throughput limitations [16]. They are caused by the collisions, idle periods in between the transmissions and transmission times for PHY and MAC headers [16]. In addition, poor requirements on out-of-band emissions (particularly for 802.11 a/g) cause Adjacent Channel Interference (ACI), which coupled with DCF reduces spectrum utilization [17],[18]. PCF is optional, typically implemented in the AP. It uses a poll-and-response protocol to ensure a contention-free access to the medium but is not widely implemented due to its poor robustness to the hidden node problem [15].

The 802.11 is a large family of protocols, which has seen a continuous updates and developments to the basic standard, published in 1997 [15]. The latest developments are 802.11n and 802.11ac versions that introduce spatial multiplexing with multiple antennas at the transmitter and receiver, adaptive beamforming, and greater channel widths, supporting channels of up to 160 MHz width [15]. The aim is to reach Gigabit throughputs in the 5 GHz band. This band is of particular interest, as it has the potential to provide high throughputs while operating in the attractive sub-6 GHz band. The operation in the 5.8 GHz ISM bands (5.725-5.875 GHz) is different in the US and Europe [13]. In the US, the ISM band at 5.8 GHz is used by IEEE 802.11 and can be used indoor, or outdoor. In Europe, it can be used by non-specific short-range devices, provided that the emission⁸ levels are below 25 mW [19].

⁷DCF uses physical layer and virtual carrier functions to determine if another node is transmitting. It allows a station to transmit, following a specified period during which the channel is free. Otherwise, if a transmission by another node is detected, the station will defer until the transmission has ceased. Following this, a random back-off timer (ranging from 0 to Contention Window - CW) is activated to determine the slot for its transmission. The transmission can start at the expiry of a back-off timer. If the transmission is not successful, the size of CW is doubled. This process is repeated until the transmission is successful, or packet is discarded.

⁸The term emission in this thesis, unless otherwise stated, refers to the Effective Isotropic Radiated Power (EIRP).

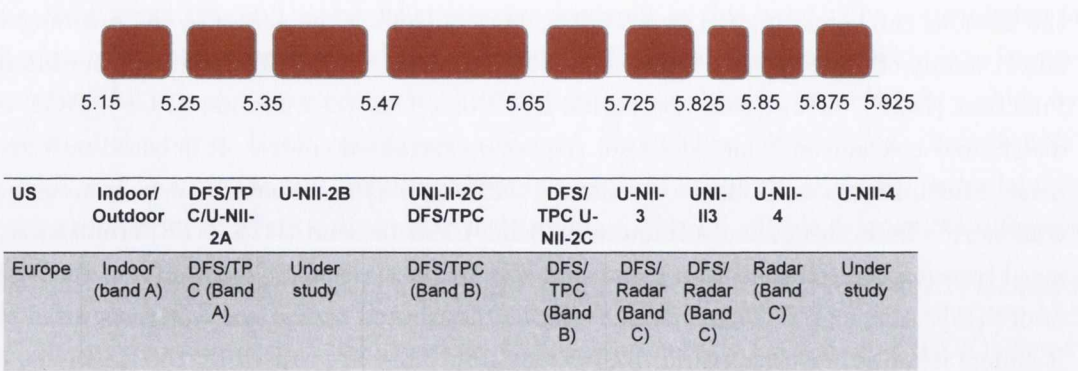


Fig. 1.2 Current allocations for 5 GHz band in the US and Europe. Spectrum sharing between Wireless Access Systems/Radio Local Area Networks with the incumbent services in 5.35-5.47 and 5.725-5.85 GHz in Europe are still under study.

Besides, the Dynamic Frequency Selection (DFS), a mechanism which ensures coexistence with radar systems is also stipulated. In addition to the ISM band, in 5 GHz band, WLANs may operate between 5.15-5.25 GHz (indoor only Europe), as well as in 5.25-5.35 GHz and 5.470-5.725 GHz on a co-primary basis with various radar systems, see Fig.1.2 [13], [20]. The co-existence is ensured through the use of DFS, as well as Transmit Power Control (TPC), introduced in 802.11h [15]. Namely, to protect the operation of radars, the DFS functionality is responsible for the detection of radar signals, and when the signal is detected, for clearing the channel of a WLAN transmission. Radar systems are used in different applications - typically weather analysis, maritime and air navigation, and in the military [13]. Two key features of radars - high antenna gains and sensitive receivers make them very susceptible to interference. Detection of radar is determined by a WLAN AP through the measurements of interference, using a detection threshold, which is well above the noise floor. When a radar signal is detected, the WLAN must cease transmission within a so-called *channel closing time* (10s), although it is allowed to send the control information for a certain period, which must be within the channel closing time. In this way, it can coordinate the changes when moving from one channel to another. After the channel is cleared, there is a so-called *non-occupancy period* when the original channel cannot be used (30 minutes). Although the principle appears simple, the implementation of DFS is complex, as radar signals vary in spatial, frequency and time domains. As per TPC, it is responsible for a reduction in transmission power between WLAN devices. There are two aspects to this mechanism: one aspect is that the AP advertises the maximum power permitted on a particular channel; the second aspect is that the optimum power level is determined based on the quality of the link between the AP and the station. These features ensure that minimum power, necessary for communication between the devices, is used to reduce the overall RF transmissions, and ultimately interference to other systems.

The 802.11 standard now also supports the operation in millimetre wave band in 60 GHz band, using 802.11ad standard. In this way, the operation using much wider channels, available in 60 GHz band, is included in the unlicensed 60 GHz spectrum⁹.

Finally, it should be noted that in 802.11e, support for Quality of Service (QoS) is proposed. This standard uses Hybrid Coordination Function (HCF) [15], which divides the transmission time between the devices. During the transmission time, a device may send multiple frames, after an initial contention; hence, the users with good network conditions can achieve better throughput than with typically used DCF mechanism.

1.2.2 Relieving cellular networks of data traffic load

WiFi networks have played an essential role in enabling a mass market for wireless data services. They are extensively used for offloading traffic from the cellular networks¹⁰ and carry a huge portion of the world's data traffic. Namely, according to Cisco data, in 2014 45% of cellular traffic (1.2 exabytes/month) is offloaded. The 2014-2019 forecast states that this will rise to over 54 % (28.9 exabytes/month) by 2019.

Offloading takes place in a way that a user equipment within a range of a WiFi access point switches to the access point for data connectivity. The switch from cellular network to WiFi occurs as soon as the availability of an AP is detected. Different performance aspects of offloading cellular data traffic to WiFi networks are considered in some early works, see for example [22], [23].

While offloading cellular data traffic is one of the key methods of carrying the data traffic, there are a number of challenges associated with the way WiFi offload currently works [24]. Some of them include:

- A variety of implementations of network selection and traffic steering in the user equipment, which makes it difficult to provide consistent user's experience.
- The decision to switch to WiFi is based on a single WiFi AP, regardless of the conditions in that access point, which may be under a heavy load.
- In some cases, the switch to WiFi may result in a reduced performance due to e.g. differences in backhaul capability.
- The users may experience ping-pong effect, in a mobile environment where the signal strength of cellular and WiFi may be similar.

⁹There are four channels - 2.16 GHz wide, [21].

¹⁰There are also solutions that perform the offloading from WiFi to cellular, provided by the companies such as *Republic Wireless*, *Scratch Wireless*. The recently announced Google's *Project FI* also aims at offloading traffic from WiFi to cellular. These solutions are, however, not considered here.

From a cellular operator's perspective, there are a number of other, system-level challenges. Firstly, and most importantly, WiFi offload does not provide QoS or congestion management, as there is no control over radio resources or the quality of backhaul. There are also other issues. They include a lack of solutions that integrate security, authentication and billing across the two technologies and that provide unified deep-packet inspection solutions [25]. Both cellular and WiFi communities recognise these challenges. As a result, in recent years, a number of solutions have emerged aiming to provide a level of integration between the two technologies. Some of them are described below.

1.2.2.1 Activities on inter-radio access technologies

In the last few years, 3GPP on one, and WiFi Alliance, IEEE and Wireless Broadband Alliance (WBA) on the other side, have proposed a number of standards towards better interworking between WiFi and cellular technologies, [24]. To give the reader a flavour, below are some of them (mainly 3GPP-based) defined for different releases¹¹ [24], [26], [27]:

- Dual-Stack Mobile IP (DSMIP) introduced in Release 8 to enable IP address preservation across the networks, but requires a dual-stack (IPv4 and IPv6) server in the core network, and dual-stack capable user terminal [28].
- In Release 9, a Local IP Access (LIPA) solution is proposed for home base stations (femto cells), allowing cellular traffic to bypass the cellular network. This solution requires the additional functionality in the home base stations.
- In Release 10, there are several solutions proposed. They are Selected IP Traffic Offload (SIPTO), Multi-Access PDN Connectivity (MAPCON), and IP Flow Mobility (IFOM). SIPTO provides a mechanism for offload of traffic from the core network and applies to femto and macro cells. In MAPCON, multiple IP addresses are associated with different packet networks via a different access network. The core network performs steering of traffic connected to various access networks. In the case of IFOM, the user equipment has the same connection, but different flows can be routed through two access networks. IFOM also requires dual stack in the user equipment and support in WiFi.
- Security and authentication are one of the key challenges in a greater integration of the two access networks. Release 2 of Hotspot 2.0 standard, which is a WiFi industry initiative, aims to bring some of the cellular network functionality regarding security, automatic login, network selection and policy provisioning to WiFi. Hotspot 2.0 Release 2 came out in 2015. 3GPP Release 12 aligns with some of the Hotspot 2.0 functionality.

¹¹Note that 3GPP specifies functionality in Releases. A particular release refers to functionality and set of features available in the release, and at the same time provides a stable baseline for developers.

- Intelligent Network Selection with Access Network Discovery and Selection Function (ANDSF) is an optional network element in cellular networks and has been evolving since Release 8. It is designed to guide the user equipment in relation to network selection (non-3GPP), based on a local environment - 3GPP and WiFi, and set of network and specific user policies.

Finally, it should be noted that the recent focus of 3GPP has turned towards studying the solutions that would extend the operation of cellular systems into WiFi bands at 5 GHz. Related work and discussion on this topic are left for Conclusion in Chapter 8.

1.3 Advent of Dynamic Spectrum Access & Cognitive Radio

This section looks at the advent of dynamic spectrum access (DSA) schemes and cognitive radio (CR), as these topics have ignited a huge amount of research on different aspects of spectrum sharing. Particularly, the discussion here is centred around the spectrum sharing models proposed in the literature, relevant for the future cellular communications systems. Few spectrum sharing models that have emerged from this research are described, namely TV White Spaces, LSA - the spectrum sharing model in 2.3 GHz being standardised in Europe, and in the US, spectrum sharing in 3.5 GHz.

1.3.1 Dynamic Spectrum Access & Cognitive Radio - Definitions

The term Dynamic Spectrum Access (DSA) is an umbrella term found in literature, encompassing a broad range of spectrum access models that enable a more efficient spectrum use through different forms of spectrum sharing. As such, DSA can be seen as the antithesis to the static spectrum allocation that dominated radio communications for more than a century. An enabling technology for DSA is Cognitive Radio. Cognitive Radio (CR) has been proposed in [29] as a radio aware of its environment, with the ability to learn from it, to identify the best spectrum opportunity for the efficient and reliable communication, and to adjust its operating parameters accordingly, [30], [29]. CR does this by:

- detecting spectrum opportunities using a variety of techniques, such as spectrum sensing, cooperative spectrum sensing, geo-location database or beacon signalling [31]
- deciding on the best spectral resource to use, based on the user requirements
- coexisting with other spectrum users or coordinating spectrum use with them
- maintaining smooth communication during the transition to other channels [32].

Regarding the standardisation efforts for DSA and CR, it is worth noting the IEEE Standards Committee on Dynamic Spectrum Access Networks (IEEE DySPAN-SC)¹², which operates

¹²<http://grouper.ieee.org/groups/dyspan/index.html>

under the IEEE Communications Society, and aims to develop standards related to a more efficient use of spectrum. IEEE DySPAN-SC has a number of Working Groups (WGs). Particularly, the IEEE 1900.1 WG has been developing standard definitions and concepts for dynamic spectrum access. In Europe, the European Telecommunications Standards Institute (ETSI)¹³ and its Radio Reconfigurable Systems (RRS) Technical Committee (TC) are defining standards with a focus on software defined radio (SDR) and standards beyond what is within the IEEE scope. There are four ETSI RRS WGs, which deal with system aspects (WG1), reconfigurable radio equipment architecture (WG2), cognitive management and control (WG3), and public safety (WG4) [33].

This chapter will not further discuss the CR and DSA capabilities. The reader is referred to a plethora of research and standardisation in this domain. For example, [34] provides an overview of some of the recent techniques, potential challenges, and future applications of CR. [35] reviews the state-of-the-art and the advances in spectrum sensing. A survey of the main standardisation efforts in cognitive radio networks up to 2011 is given in [36]. In [37], survey of cognitive radio MAC approaches is presented.

1.3.2 Brief discussion on spectrum sharing models

Spectrum sharing is intrinsically linked with spectrum dimensions, as they facilitate spectrum sharing between different entities. The major spectrum dimensions are frequency, time and space, although power can also be considered closely linked with space. In [38], frequency, time, space, power and polarisation are referred to as the main spectrum dimensions. Others, such as [13], refer to frequency, time, space and information (code) domains. In [39], spectrum is defined as N-dimensional 'electrospace', where the N depends on the number of characteristics of radio signals that receiver technologies can separate from one another. Regardless of a dimension, or a combination of dimensions that facilitate spectrum sharing, they are also intertwined with other aspects. They include the hierarchy of the entities sharing spectrum, the level of cooperation between them, and spectrum sharing scenarios that are considered.

It is evident from the discussion in this chapter that spectrum sharing is a complex subject, and that the models relevant to the future cellular systems will, therefore, need to incorporate a number of aspects. These include regulatory and licencing aspects, architecture choice - i.e. centralised or distributed architecture, spectrum access behaviour and others. Different works address the classification differently - see for example older works [32], [38], [40], and more recent ones such as [41]. From the perspective of this work, the following planes of classification are identified:

¹³ETSI is a European standardisation organisation, which defines global standards for information and communication technologies.

- Spectrum management (licencing) mode, which defines whether a spectrum band is reserved for the *exclusive use*, if it is *open access*, or whether it can be used in a *hybrid mode*, with a hierarchy of defined primary and secondary spectrum entities. The spectrum management mode is, hence, specified by the regulator. *Exclusive use* means that a single entity has the exclusive right to transmit. In [38], it is pointed out that the identity of the owner and the type of use can change - either through a transfer of a licence (secondary market) or through spectrum allocation by a central entity that manages spectrum. Exclusive use is defined similarly in [42], [43]. *Open access* allows a number of systems to use the same band. In most works, this management mode is termed *commons*. There may be many flavours of the *open access/commons* model. In [38], *commons* are divided into uncontrolled commons, private commons and managed commons. In the uncontrolled commons, spectrum is unlicensed and shared between an unlimited number of users/entities, as is today's ISM band. In the managed commons model, [38] envisages a distributed management protocol, supporting heterogeneous systems and users. The challenge, according to the authors, is scalability and rule enforcement. In [40], the distinction is made between coexistence and cooperation between spectrum users. In [44], the authors refer to the *unlicensed mode* as the mode where spectrum is shared with other unlicensed systems, although in some special cases, there may also be a primary user of the band. The hybrid model is a cross between the two modes, and in [38], [42] and [43], it is divided between *spectrum overlay*, and *spectrum underlay*. Spectrum underlay allows transmission even while a primary user is present, as long as the transmission is at a very low-power level. An example of spectrum underlay is Ultra-Wideband (UWB). In spectrum overlay, the transmission by a sharing entity is managed in a way that the secondary user opportunistically uses spectrum. In this mode, when and where an entity may transmit is decided based on the presence of a primary system.
- Hierarchy, which determines whether the systems have equal rights to transmit, or there is a hierarchy of the access/transmission rights. In the case of vertical sharing, a primary user enjoys interference protection from the secondary users. A typical example of a hierarchical system is TV White Spaces. Here, TV receivers enjoy protection from co-channel and adjacent channel interference caused by other (secondary) transmitters. Secondary transmission occurs in TV channels that are not used by the TV transmitters in a specific geographical area - these channels are referred to as TV White Spaces, see subsection 1.4.1, p.12. Regarding horizontal sharing where entities have equal rights, it is also important whether the sharing systems are heterogeneous or homogeneous. Sharing between heterogeneous systems is more complex and requires, amongst others, spatial coordination - for example, in [45] the difference in coverage between different systems (DVB-T and GSM/UMTS) is pointed out. The authors in [44] argue that the highest sharing efficiency is obtained when systems use the same or very similar radio

access technology. In this case, the spectrum sharing entities can coordinate the usage of spectrum with high granularity built into transmission systems (and standards), and in this way, they can minimise the interference.

- Spectrum access behaviour, which characterises whether the sharing systems cooperate, or only coexist. Cooperation typically requires a degree of commonality between the systems, and implementation of explicit signalling, [40], [44]. In the case of cooperative spectrum sharing, the systems must communicate to avoid interference while in the coexistence model, the systems avoid interference without explicit signalling [40]. The author points out the drawbacks of e.g. coexistence approach in a commons model that has no limit on the number of devices that can access the band, posing a risk of significant mutual interference. In the case of cooperative commons, the author points to the potential gains of such an approach (i.e. increase in the capacity of the system). However, this approach also poses challenges, particularly concerning security and definition of a protocol to enable the cooperation.
- Spectrum access techniques refer to the techniques used to implement spectrum sharing. A number of techniques have been developed for different sharing models. They range from geo-location database-based techniques to the ones using spectrum broker, to spectrum sensing and DFS-based techniques [31], [44]. It is clear that some of them are centralised (e.g. techniques using spectrum-broker), whereas others are distributed (e.g. DFS and sensing techniques).

Fig. 1.3 depicts the above-discussed planes, similar to [44]. The spectrum management mode, or the licencing plane, is at the top. From there, there is a range of interconnections regarding hierarchy and heterogeneity of the systems. At the bottom plane are spectrum access techniques, determined by the top plane, and the interconnections between different planes in the middle.

1.4 Main aspects of specific spectrum sharing models

This section outlines the major aspects of a few, well-defined models, stemmed from the research in the domain of CR and DSA: TV White Spaces, 3.5 GHz Citizens Broadband Service and Licensed Shared Access (LSA). As the thesis draws on certain aspects of these models, in the following chapters, the relevant descriptions are provided.

1.4.1 TV White Spaces

TV White Spaces provide spectrum opportunities in Very High Frequency (VHF) and UHF TV Bands in the US (54-216 MHz and 470-698 MHz) [46], and the TV UHF band in Europe

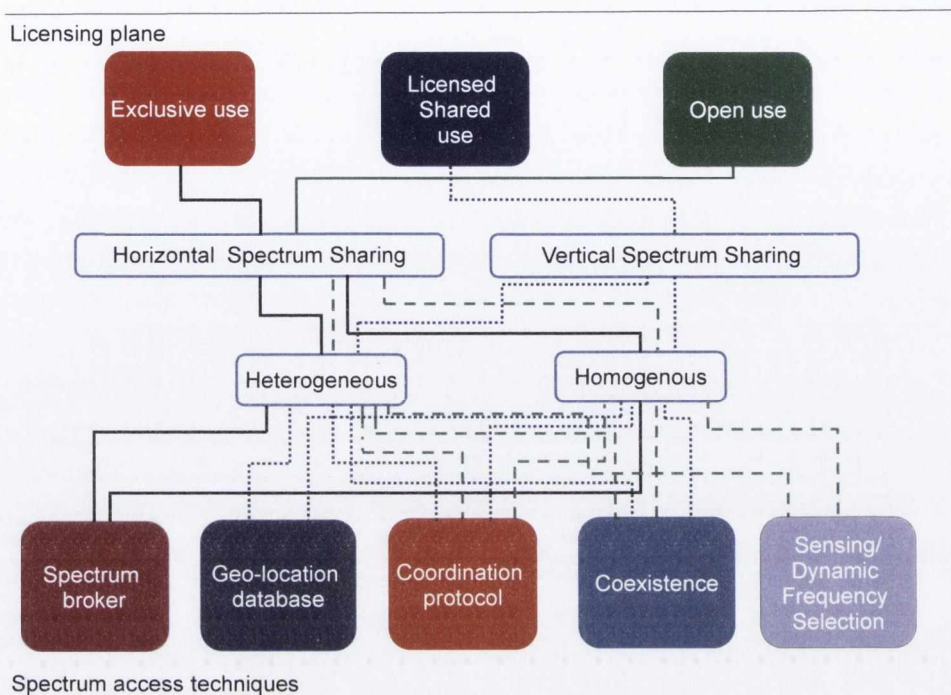


Fig. 1.3 Different planes of classification. Licensing mode is on the top and spectrum access techniques are at the bottom.

(470-790 MHz) [47], [48]¹⁴. TV White Spaces are channels not used by the Digital Terrestrial Transmitters (DTT) and other incumbent users (mainly wireless microphones) and have become available as a result of a switch-over from analogue to digital TV transmission¹⁵. Hence, TV White Spaces represent spectral opportunities in space, but also in time, as certain channels are not used all the time [50]. In TV White Space model, both in Europe and the US, a geo-location database plays a central role in protecting the incumbents (DTT receivers, and wireless microphone users) from co-channel and adjacent channel interference by the entities using the TV White Spaces. The database provides TV White Spaces users with the information on the available channels, permitted power levels, and other transmission parameters [47], [46]. Both models distinguish between different types of devices, according to whether devices have the capability to access the database, but also other aspects. The approach to determining transmission parameters for TV White Spaces, however, differ between the two regions. In the US, there are so-called exclusion zones, where no TV White Space device (TV WSD) can emit - the exclusion zones refer to the

¹⁴The switch from analogue to digital TV also cleared some channels - e.g. 790-862 MHz in the EU [49], referred to as digital dividend, which are subsequently allocated to cellular services.

¹⁵Every digital channel through compression of digital (visual and audio) signal allows the transmission of a number of digital programmes, making much more efficient use of spectrum

co-channel and the adjacent channel, and depend on the antenna height of the device. The power limits are fixed, based on the device type. Outside the exclusion zones, TV WSDs are allowed to transmit at maximum power, again, according to the device type. In the European method, permitted transmit power varies, and is calculated depending on the spatial and the frequency distance of a TV WSD to the closest incumbent user, and taking into account permitted transmission leakage [47], [51], [52]. The calculations for permitted transmission parameters are calculated across the pixel-based grid (100mx100m), and for every considered channel, and also provide time validity [47], [52]. It should be noted that several standards organisations have been specifying different aspects of the operation in TV White Spaces. ECMA International¹⁶ developed ECMA-392 that specifies MAC sub-layer and a physical (PHY) layer for cognitive wireless networks operating in TV bands. IEEE 802.22 Working Group on Wireless Regional Area Networks (WRANs) is responsible for developing PHY/MAC standards for a cognitive radio [53]. which targets providing the connectivity in rural areas. Another standard, based on 802.11af has also emerged, focusing on urban environments [54]. WeightlessSIG [55] is the standard that targets connectivity for machine-to-machine (M2M) devices using TV White Spaces. Besides, in 2011, the IEEE DySPAN-SC created the White Space Radio Working Group to develop the IEEE 1900.7 standard, specifying use cases, PHY and MAC sublayer and coexistence requirements in TV White Spaces [56]. In Europe, ETSI RRS WG1 is active in producing technical specifications for system aspects, such as [57] and [58]. For example, in [57], the system architecture for operations in UHF TV Bands is specified, allowing the operation of both - coordinated and uncoordinated TV WSDs, while the architecture and procedures for exchanging information between different databases are specified in [58]. These specifications are taken as input into the European standards, such as [59] and [60].

Finally, it should be noted that there is a significant body of research work in the domain of TV White Spaces - Chapter 6 gives an overview of the research in TV White Spaces, which is pertinent to the thesis.

1.4.2 PCAST Report & 3.5 GHz - Citizens Broadband Service

PCAST report [7] was issued in 2012. It represents a milestone in setting out strong recommendations regarding the need for spectrum sharing, proposing a creation of spectrum "superhighways". The report envisages identifying 1000 MHz of the US Federal spectrum, which would be shared by different wireless services and recommends a number of measures. They include aspects such as dividing the spectrum into significant frequency blocks with 'common characteristics'; managing spectrum based on both - transmitter and receiver characteristics; and encouraging the unlicensed spectrum use. In the report, a three-tier

¹⁶Ecma International is an industry association working on the standardisation of Information and Communication Technology and Consumer Electronics - <http://www.ecma-international.org/default.htm>

spectrum access hierarchy is proposed, centred around a database. At the top of the hierarchy are Federal users, with the exclusive right to spectrum use, but who can exclude other spectrum users from availing of the spectrum. Second in the hierarchy are Priority Access (PA) users, who can be high-power or low-power users. PA users have to register with a database, and they may or may not pay for access to spectrum, depending on the policy. Finally, the third tier in the hierarchy is Generalized Authorized Access (GAA) i.e. the low-power users who do not have to pay for spectrum use, but have the lowest priority in spectrum access.

Following issuing of the PCAST report, the FCC conducted a number of consultations for the 3.5 GHz band, with the aim of opening this band otherwise used by defence radar systems and fixed satellite service. In April 2015, the FCC adopted the final rules for commercial use of 150 MHz in the 3550-3700 MHz band (3.5 GHz Band) [61]. The ruling follows the recommendations of the PCAST report, regarding hierarchy and tiers. The bottom, GAA tier occupies the whole band while users in PA tier may operate in the 3.55-3.65 GHz part of the band, in a license area that consists of a single census tract. Each PA licensee (PAL) is assigned a 10 MHz channel and the license of three years. Considering that a limited number of PALs are issued and that they are mutually exclusive, the FCC intends to perform competitive bidding to resolve conflicting applications. Also, aggregation of PALs is permitted, and up to four PALs can be aggregated in a licence area. Frequencies that are not designated to the PA tier may be used by the bottom GAA tier in the 3.55-3.65 GHz band. All devices must register with the database - the Spectrum Access System (SAS). Another entity in the system is the Environment Sensing Capability (ESC), which is a system of sensors aimed to detect the presence of the incumbent in the band, and/or adjacent to it [61]. There are two categories of devices - one operating with a maximum emission of 30 dBm (Type A), and the other operating outdoors only, with emission levels up to 47 dBm (Type B) in rural areas, and up to 40 dBm in all other areas. Type B device type can only emit if permitted by ESC. All devices must employ TPC. As per the exclusion zones, FCC adopted a phased approach. Initially, geographic exclusion zones are to encompass 80 km radius from the designated radar locations. The CBS devices with an EIRP up to 30 dBm (in a 10 MHz bandwidth) would be authorised to operate outside exclusion zones during this phase. However, higher power operations would not be permitted. In the second phase, the exclusion zones would be turned into protection zones i.e. the zones where CBS devices may emit with the permission of SAS and ESC [61]. PCAST report and subsequent FCC ruling have also sparked a significant amount of activities and research. Related work pertinent to the thesis is given in Chapter 7.

1.4.3 Licensed Shared Access

LSA is a spectrum sharing framework being defined by the Electronic Communications Committee (ECC)¹⁷. It represents a regulatory framework in Europe [62], targeting under-utilised spectrum bands below 6 GHz. LSA follows the industry initiative named Authorised Shared Access (ASA), first unveiled by Nokia-Siemens Networks (NSN) and Qualcomm in 2011, as a response to a Radio Spectrum Policy Group (RSPG) consultation on cognitive technologies [6]¹⁸. Following on from this initiative, EC instructed RRS WGs to take on the standardisation efforts for LSA [63]. LSA represents an "individual licensing regime", complementing the existing licensed and license-exempt regimes. It allows a limited number of entities to share spectrum with the incumbent. The general description of the LSA framework can be found in [62]. It should be noted that the LSA licensee and incumbent of the band cannot provide the same service. Under the framework, the exclusive use of spectrum is guaranteed as the aim is to ensure consistency in Quality of Service (QoS) for all authorised users of the band. The access to spectrum is determined based on an agreement between the incumbent and a potential LSA licensee, and also takes into account the requirement on vacating the band upon the incumbent's request. The role of the regulator is to grant the individual *right to use* to the LSA licensee. The main functional entities in the LSA architecture are the LSA Repository, which contains all the relevant information about the spectrum, and the LSA Controller, which manages the access to spectrum, based on the information provided by the LSA Repository. The current focus of LSA regulatory activities is on the 2.3-2.4 GHz band, which is the globally allocated band for mobile service and cellular network operators, as the additional users of the band. The harmonisation of the band was completed in 2014 [64]. The technical conditions in the band depend on the nature of the incumbent. Typical incumbents in Europe in this band include Programme Making and Special Events (PMSE) links, fixed links and military systems [65].

In relation to the standardisation of LSA, the reference design, architecture and interfaces are specified within ETSI - for example [66], [67] and [68], while CEPT ensures technical harmonisation between different national administration in relation to LSA [62]. For example, CEPT report [65] describes possible sharing options and considerations for several types of incumbents. An overview of regulation and standardisation activities can be found in [63]. Also, Chapter 6 presents state-of-the-art in the domain of LSA, related to the thesis.

¹⁷ECC, within CEPT, is responsible for radio communications and telecommunications matters.

¹⁸RSPG is an advisory group to the EC in the development of radio spectrum policy.

1.5 Why is there no real progress?

It is evident that spectrum sharing is a complex subject, which requires a synchronised approach and developments on many fronts - technical, standardisation and regulatory. The proposed solutions also need to have commercial viability. The sections outlined earlier are the evidence of huge developments in the domain of spectrum sharing. Despite these, the real progress to systematic spectrum sharing is lacking. The dominant sharing model in the ISM bands has been very successful, triggering a global availability of wireless technologies, particularly WiFi networks, which have seen a huge rise in popularity. However, the sharing model of the ISM bands, particularly the one at 2.4 GHz, cannot be the ultimate sharing model due to the reasons discussed in 1.2.1: the requirement for a better spectrum utilisation and efficiency; and simply as this is the model initially created decades ago, and as such does not fully leverage significant technical advances made in this period. Further, the WiFi networks within the ISM bands only represent one type of sharing model, i.e. the *commons model*. WiFi networks, as they are today, suffer from inconsistent behaviour in congested environments with a variety of backhaul solutions, which may or may not provide the required level of service. The CSMA/CA mechanism is spectrally inefficient, and there are a number of extensions to the standard that have not gained widespread support, making it somewhat disjoint. However, the role of WiFi networks in alleviating the burden from the cellular networks has been remarkable. This has been recognised, and, as a result, in the last few years, there has been a rise in the number of solutions by 3GPP and WiFi communities aimed at a tighter integration of the two technologies. The solutions offer a different level of integration/interworking, but most require additional entities and interfaces. The widespread deployment is lacking, although it is yet to be seen whether the solutions such as Hotspot 2.0 will be widely adopted. Nevertheless, regardless of the type of integration provided between the cellular and WiFi system, it represents merely a solution aimed at integrating one type of a band, or bands (WiFi), with the cellular systems and is not a holistic approach to the question of spectrum as it considers one band at a time.

There are also issues concerning other models described in this chapter. For example, the LSA model in Europe although proven to be technically feasible, and having harmonised conditions in the band (2.3 GHz) has not taken off. So far, only a single country (France) has shown an interest in the actual use of band for sharing, although, considering the restricted area in which the incumbent uses the spectrum, it could be argued that there is very little spectrum sharing involved [69]. As per TV White Spaces, despite becoming a well-defined model after thirteen years of regulatory activity, the path its widespread use does not seem to be straight forward. The biggest hurdle in the past was the fact that the use of sensing in detecting TV White Spaces had to be abandoned. The use of sensing techniques is however not precluded in the future, but currently, it is the database-controlled model that

prevailed¹⁹. More importantly, however, at WRC-15, the 694-790 MHz bands were allocated to mobile broadband in ITU Region 1, which makes it a globally harmonised band for mobile services [70]. In the US, the TV White Spaces spectrum is set for auction to cellular operators, with only a portion of the spectrum left for TV White Spaces. This rules out the use of this spectrum globally, despite the fact that it will be utilised in some countries - notably in the UK, where Ofcom has recently approved its use, and in some African countries.

Finally, it needs to be noted that significant steps in the right direction have been made. Namely, the need for systematic approaches to spectrum sharing has been identified and strongly advocated - notably in [6] and [7]. In 3.5 GHz band, the FCC has just passed the final ruling on the shared use of this spectrum. Also, at the time of writing of this thesis, Google has successfully demonstrated the SAS database. However, systematic spectrum sharing has to come at a faster pace.

1.6 Proposed way forward

Given the discussion in the chapter, the focus of the thesis is on enabling systematic spectrum sharing through the use of existing, globally available standard, which will allow different types of spectrum sharing. As the cellular communication systems are the most widely available radio access technology, the thesis turns to the cellular communication system based on Long Term Evolution (LTE) and LTE-Advanced.

LTE is a radio access technology based on orthogonal frequency-division multiplexing (OFDM) waveform and discrete Fourier transform spread OFDM (DFTS-OFDM) on the uplink, [71]. The first release of LTE - Release 8 was specified in 2008. Today, LTE is deployed in more than 140 countries. It defines downlink peak rates of up to 300 Mb/s on the downlink and 75 Mb/s on the uplink. The LTE Release 8 already provides a rich set of features, including [71]:

- flat, simplified and fully IP-based architecture
- Orthogonal Frequency Division Multiplex (OFDM) as a waveform
- multiple access combining frequency and time planes using Time Division Multiple Access (TDMA) and OFDM access (OFDMA)
- various forms of multi-antenna transmission
- spectrum flexibility that allows the use of LTE in a number of different frequency bands

¹⁹Sensing-only device are permitted to operate in the US with the FCC certification.

- support for both types of duplexing - TDD and FDD
- bandwidth flexibility through support of different channel widths
- beamforming.

LTE-Advanced is the same cellular technology like LTE, where "Advanced" relates to the fact that apart from the functionality supported by LTE, the additional functionality is introduced that meets the ITU-specified International Mobile Telecommunications (IMT)-Advanced requirements. The IMT-Advanced requirements include, for example, the transmission bandwidths of at least 40 MHz. Also, peak spectral efficiency of 15 b/s/Hz on the downlink and 6.75 b/s/Hz on the uplink, and control plane latency that does not exceed 100 ms and user plane latency up to 10 ms are specified [72]. Hence, LTE-Advanced relates to the functionality provided from Release 10 onwards. It supports the IMT-Advanced features, and for this reason, it is considered that LTE-Advanced is a true 4G system, [72]. Furthermore, LTE/LTE-Advanced is the first truly global cellular technology for the network operators, as it is the next step for CDMA2000 and UMTS operators alike [71]. Therefore, the central question the thesis addresses is:

How can spectrum sharing be systematised within LTE-Advanced?

In that regard, the thesis looks at the major features of LTE-Advanced that allow aggregation and joint use of spectrum resources from multiple bands, also supporting different channel widths [72]. Furthermore, the LTE-Advanced features address not only spectrum, but also architecture aspects targeting both - networks with centralised, and distributed baseband processing functions. These features are Carrier Aggregation and Dual Connectivity. Carrier Aggregation is introduced in LTE-Advanced Release 10 and enables aggregation of different blocks of spectrum to form larger transmission bandwidths of up to 100 MHz. It addresses spectrum aggregation in the architectures with a centralised processing of baseband functions. Dual Connectivity is the later addition to the feature set, introduced in Release 12, and enables a joint use of spectrum resources in networks with distributed baseband processing. Considering these inherent capabilities of LTE-Advanced, it is natural the thesis utilises Carrier Aggregation and Dual Connectivity in providing the proposed solution, hereinafter referred to as *the sharing framework*. The sharing framework was first introduced in [73]. The framework aims to combine different types (classes) of shared spectrum resources with the spectrum that is exclusively owned by the cellular operator. For this, Carrier Aggregation and Dual Connectivity provide a solid basis, as spectrum sharing can be deeply embedded in the wireless communications system. Furthermore, the framework proposes to address a variety of future deployment scenarios that will invariably include multi-layer networks utilising different baseband architectures with dense deployments of

low-power nodes [5]. Hence, more specifically, the thesis emphasis is on addressing the following questions:

- *How can sharing with the different spectrum classes best be incorporated into LTE-Advanced?*
- *In what way can the QoS requirements be maintained when using shared spectrum?*
- *What are the implications of using different baseband architectures for the sharing framework?*

1.7 Summary of contributions

The main contributions of the thesis are as follows:

1. The thesis proposes well-defined, LTE-Advanced based spectrum sharing framework:
 - The framework embeds spectrum sharing deep in the LTE-Advanced system by considering spectral resources, which may come from different frequency bands. In that, it relies on the existing LTE-Advanced mechanisms of Carrier Aggregation and Dual Connectivity.
 - It defines a three-tier spectrum-sharing approach that incorporates different classes of spectrum - statically assigned exclusively owned (EO) spectrum and two different shared spectrum classes. The spectrum sharing classes - the exclusively shared (ES) and commonly shared (CS) spectrum are two broadly defined models, characterised by the key identified attributes to reflect the intrinsically different spectrum resources. In this way, the framework addresses the heterogeneity of spectrum resources.
 - It addresses the relevant cellular network topologies and architectures, featuring different types of nodes - macro and low-power nodes (LPNs). The particular focus is on heterogeneous networks, where LPNs are overlaid on a layer of macro cells. The framework considers the low, medium and high density of LPNs; and the underlining centralised and distributed architectures from the baseband processing point of view. The baseband architectures correspond to heterogeneous networks featuring Remote Radio Heads (RRHs) and small cells.
2. The framework proposes a spectrum selection mechanism that, as selection criteria, considers the two typically conflicting objectives - QoS, and the cost of spectrum. The QoS is defined in terms of end-user performance and a range of target values that the network should deliver. The spectrum selection mechanism addresses the issue that

cellular operators often regard as a barrier to spectrum sharing - the lack of control over QoS. On the other hand, a reduction in cost is always an incentive for the cellular operators. The proposed spectrum selection mechanism reflects different spectrum sharing models and incorporates the cost of *exclusive transmission*, directly related to acquiring spectrum resources from the ES spectrum class.

3. The thesis presents an extensive system-level performance and QoS versus Cost analysis for the centralised baseband (CBB) architecture with Carrier Aggregation. It considers a low and a medium density of LPNs, with a range of parameters of significance for a heterogeneous network deployment. The shared spectrum classes and key attributes are derived from the most relevant spectrum sharing initiatives - TV White Spaces and LSA.
4. The thesis provides a comprehensive system-level analysis of the centralised and distributed baseband (CBB and DBB) architectures. The analysis relies on Carrier Aggregation and Dual Connectivity in 3.5 GHz band, with a low, medium and high density of LPNs. The contribution is three-fold:
 - (a) It provides performance and QoS versus Cost analysis, taking into consideration a range of parameters for a heterogeneous network deployment that include: different density of LPNs, network load, power levels, availability of the CS band, intra- and inter-system interference, and target QoS. The shared spectrum classes and key attributes are derived from the 3.5 GHz Citizens Broadband Service band.
 - (b) It identifies the difference the baseband architecture makes for the sharing framework.
 - (c) It puts forward the Sensitivity Analysis that, for a given density of LPNs, evaluates the impact of each of the parameters and their interaction with regard to the proposed spectrum selection mechanism.

There are also other contributions. They include:

5. extending the existing Matlab-based HetNet simulator to support the Carrier Aggregation-based scenarios
6. identifying the key required control plane and signalling aspects to support the proposed framework.

1.8 Thesis map

Before the map of the thesis is presented, it should be noted there is no separate chapter on the related work and state-of-the-art. Namely, certain chapters deal with distinct aspects

of the framework, while throughout the thesis, different sharing models are considered. Hence, for better readability, it was deemed more appropriate to discuss related work and state-of-the-art within each chapter.

The thesis is organised in the following way:

- Chapter 2 describes the main aspects of the three key components used as a basis for the thesis: the heterogeneous topology with the multi-layer network featuring macro and LPNs; two distinct baseband architectures - CBB and DBB; and two prominent features of LTE-Advanced - Carrier Aggregation and Dual Connectivity.
- Chapter 3 presents the main idea of the framework and associated challenges.
- Chapter 4 describes the initial analysis in building the spectrum sharing framework, with a focus on the characterisation of the shared spectrum.
- Chapter 5 explains the key aspects of HetNet simulator and its extension HetNet+, which is selected as one of the main tools for modelling the framework.
- Chapter 6 presents the analysis of the proposed framework, using CBB architecture, with shared spectrum derived from TV White Spaces model and LSA.
- Chapter 7 describes the analysis of the complete framework, using both baseband architectures, in 3.5 GHz band. This chapter also includes the sensitivity analysis for the two architectures.
- Chapter 8 gives the conclusion and future work.
- Appendix 1 contains the sensitivity analysis tables.

1.9 Publications record

The following publications relate directly to this thesis:

- L. Doyle, **J. McMenamy**, T.K.Forde, "Regulating for Carrier Aggregation & Getting Spectrum Management Right for The Longer Term," Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on, Year: 2012, Pages: 10 - 20, DOI: 10.1109/DYSPAN.2012.6478111
- **J. McMenamy**, I. Macaluso, N. Marchetti, L. Doyle, "A Framework for Enhanced Carrier Aggregation with Dynamic Carrier Selection," Wireless Days (WD), 2013 IFIP, Year: 2013 Pages: 1 - 6, DOI: 10.1109/WD.2013.6686455

- **J. McMenamy**, I. Macaluso, N. Marchetti, L. Doyle, "A Methodology to Help Operators Share the Spectrum Through an Enhanced Form of Carrier Aggregation," Dynamic Spectrum Access Networks (DYSPAN), 2014 IEEE International Symposium on, Year: 2014, Pages: 334 - 345, DOI: 10.1109/DySPAN.2014.6817810
- **J. McMenamy**, I. Macaluso, L. Doyle, "RRH and Small Cells - the Implications for Spectrum Sharing," Dynamic Spectrum Access Networks (DySPAN), 2015 IEEE International Symposium on Year: 2015, Pages: 176 - 187, DOI: 10.1109/DySPAN.2015.7343901
- Patent filed "Method and System for Computing Bandwidth Requirement in a Cellular Network", United Kingdom Patent Application No. 1517121.8.

Chapter 2

Spectrum Meets Architectures

The aim of this chapter is to provide the reader with the required background on all the main components used later in the development of the proposed spectrum sharing framework. The sharing framework proposes to avail of the dominant LTE-Advanced system and its inherent capabilities. This requires defining how fragmented, heterogeneous spectrum resources may be combined using specific LTE-Advanced features, taking into account the underlying topologies and architectures. The focus is on the topologies and architectures that are to dominate the future cellular systems. Hence, the chapter starts with the description of the topologies in Section 2.1. What follows in Section 2.2 is a brief discussion of the requirements, advantages and challenges of the two distinct baseband architectures - CBB and DBB. The discussion then returns to the subject of spectrum and the two LTE-Advanced features designed to provide the aggregation of spectrum resources - namely, Carrier Aggregation and Dual Connectivity, described in Section 2.4.

2.1 Heterogeneous topologies

An important part of the LTE standard are the network topologies with a mixture of radio access network nodes, which differ in terms of e.g. physical size, transmit power and connections to the core network. They are referred to as heterogeneous networks [74] and are briefly discussed here.

Heterogeneous networks are the networks with a mix of macro and LPNs, with LPNs distributed throughout the area covered by a macro node. Macro base stations are high-power nodes, deployed in a uniform manner - transmitting at similar power levels, with similar antenna patterns and receiver noise floors [75]. The distance between macro base stations depends on whether the macro node is serving urban, suburban, or rural areas, and their locations are carefully planned. Their deployment is usually a slow and complex process, affected not only by the elaborate capacity and coverage planning but also by the

site acquisitions.

LPNs with their low transmit power and small physical size allow more flexible and cost-effective deployments, and address the challenges associated with the complex and lengthy process of deploying macro base stations. Also, LPNs help address a huge increase in capacity demand, as they enable denser network deployments, where the network is brought closer to users. The LPN deployments are particularly important to meet capacity demands in urban, clustered (hotspot) areas, or in providing coverage in small areas with coverage issues. There are different types of LPNs, such as pico, femto, relay, micro and low-power RRHs. Typically, transmit power in LPNs ranges from 250 mW to 2 W [76], and in some scenarios, it goes up to 5 W [77]. It should be noted that RRHs may be low or high-power nodes. Only low-power RRHs are considered in this thesis.

In heterogeneous networks, a macro topology layer is complemented with a layer of LPNs [74]. LPNs may operate on the same frequency as the macro tier or may use a different frequency. Regardless whether they use the same or different frequencies, heterogeneous networks present a significant shift in how the networks are defined and analysed [78]. Of particular interest to the thesis are the implications for the topology of the network and different backhaul connections, although there are other aspects such as cell-association, mobility, and performance metrics that are impacted [78]. The topology refers to how the nodes are spaced - whether they use a regular, fixed grid, or their location is irregular. Unlike macro nodes, LPNs are not regularly spaced and are typically randomly distributed within a macro cell area. In the remainder of this thesis, the topology layers are referred to as *tiers*. Furthermore, two types of LPNs are considered: namely, low-power **RRHs**, and **small cells**. RRHs are the nodes that enable a physical separation of baseband processing functions, whereas small cells are self-contained nodes. Small cells is a term increasingly seen in the literature and is an umbrella term that incorporates femtocells, picocells and microcells [79]. In this thesis, the term small cells generically refers to picocells or microcells, see Fig. 2.1. Femtocells are not considered, as they are different to picocells and microcells in that they are deployed by an end-user for indoor communication, and use a connection to the core network which is not necessarily provided by the same provider as cellular communication.

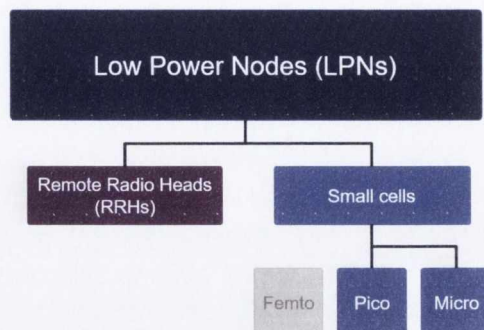


Fig. 2.1 The classification and types of LPNs considered in the thesis.

2.2 Heterogeneity of baseband architectures

The nodes mentioned in the previous section utilise two different types of system architectures. To understand what is involved, it is necessary to focus on the signal processing in a cellular network. Namely, the signal processing in a cellular radio network node is divided into two parts - baseband processing and radio functions. The baseband processing provides interface to the core network and performs all L2 and L3 functions, as well as PHY layer digital processing, namely coding/decoding, modulation/demodulation, channel estimation, resource and antenna mapping. The radio functions include power amplification, filtering, and up/down conversion. From the perspective of signal processing and LPNs, this section discusses two distinct baseband architectures: CBB and DBB, similarly to [80]. The CBB architecture is present in deployments featuring RRHs, whereas DBB architecture is seen in deployments with small cells. They are described next.

2.2.1 CBB architecture

RRHs enable physical separation of the radio and baseband units, with all the baseband functions performed centrally, by the unit typically referred to as *baseband unit* (BBU), also referred to as digital unit (DU). An RRH with co-located or integrated antennas provides the interface to the baseband unit and performs the radio functions¹. The architecture featuring RRHs, therefore, is CBB architecture, with a single interface to the packet core network, see Fig. 2.2. The digital and radio units are connected using high-quality fibre links and a standardised interface². The distance between these two units typically may

¹Besides providing the transmitter/receiver paths, RRHs perform analogue-to-digital, and digital-to-analogue conversion.

²There are few specifications of the interface between baseband and radio units. One is specified by the European Telecommunications Standards Institute (ETSI) as Open Radio equipment Interface (ORI) while the two older specifications are industry-based - Open Base Station Initiative (OBSAI), and Common Public Radio Interface (CPRI) [81].

range up to 15 km [80], but can be extended up to 40 km. This interface is, actually, an internal base station interface [80] and is also referred to as a mobile fronthaul [81]. In 3GPP terminology, the interface is referred to as *ideal backhaul*, as it meets specific, very stringent requirements for bandwidth, latency and jitter - see Table 2.1. The bandwidth requirement depends on the sampling frequency that is the channel width, the number of antennas, the number of sectors, line coding and the sample width [82]. For example, the required throughput for a 20 MHz channel in LTE (single antenna) is 1 Gb/s [83], while in [84] a throughput of up to 10 Gb/s is stated as a requirement. The maximum latency is determined by the response time for fast retransmissions, which in LTE-based systems use Hybrid Automatic Repeat reQuest (HARQ) mechanism³. According to [85], the total fronthaul latency should not exceed 250 microseconds, after accounting for latency on the UL and DL processing and air interface propagation time. In [84], one way latency (which does not include latency in the transport network), is specified to be less than 2 micro seconds. Another important aspect of the CBB architecture is that RRHs are inherently synchronised with the baseband, requiring no additional synchronisation solutions [80].

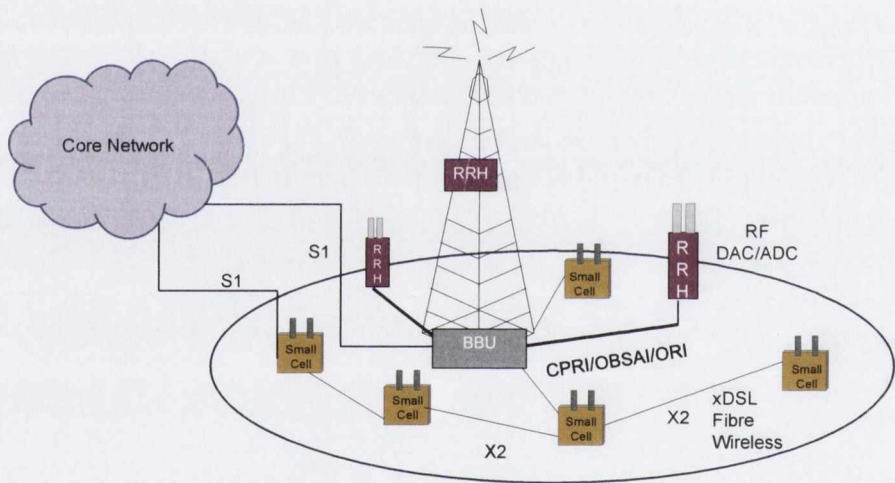


Fig. 2.2 Mix of small cells and RRHs. Small cells use a range of technologies to connect to the rest of the radio network, and the core network. RRHs use fibre connectivity with very high throughput, low latency and low jitter to connect to the BBU. Only BBU provides the interface to the core network.

2.2.2 DBB architecture

Small cells are nodes, each with a full protocol stack and their own antenna, radio and baseband units, and hence fall under a DBB architecture. They each interface the packet core network, as well as other radio access network nodes through standardised LTE interfaces - X2 and S1, respectively, see Fig. 2.2. These interfaces, referred to as mobile backhaul, may

³HARQ is a fast retransmission scheme, which combines error detection and error correction to improve the link quality [71].

Table 2.1 Summary of latency and throughput requirements according to 3GPP.

Non-ideal backhaul requirements		
Backhaul technology	Latency (one way)	Throughput
Fiber-access 1	10-30 ms	10 Mbps-10 Gbps
Fiber-access 2	5-10 ms	100-1000Mbps
Fiber-access 3	2-5 ms	50Mbps-10Gbps
DSL Access	15-60 ms	10-100 Mbps
Cable	25-35 ms	10-100 Mbps
Wireless backhaul	5-35 ms	10-100 Mbps typical, perhaps up to Gbps range
Ideal backhaul requirements		
Fiber-access 4 (RRH)	Less than 2 micro seconds (does not include propagation delay)	Up to 10 Gbps

be provided using a range of technologies - DSL, wireless and non-dedicated fibre. They may also have different characteristics in terms of latency, jitter and throughput [86]. In 3GPP terminology, this is referred to as *non-ideal backhaul*. For latency requirements according to [84], see Table 2.1.

2.3 Main challenges and differences between the architectures

It is evident that the major challenge for the CBB architecture is a costly transport network infrastructure. The required bandwidth increases with the number of antennas, number of sectors and channel width. The latency requirements are very strict, and will also depend on the distance/propagation delay. Jitter requirements are also very stringent [81]. Also, the baseband operation requires an increased level of resilience, compared to the DBB architecture, as the central location serves a greater number of users. Nevertheless, the CBB architecture provides a number of advantages. Firstly, it enables pooling of baseband resources (for connected RRHs), which in itself provides statistical multiplexing gain, compared to the DBB architecture [82]. Secondly, it enables implementation of sophisticated LTE techniques regarding interference management, implemented through interference coordination, advanced scheduling and joint transmission. The features include enhanced Inter-Cell Interference Coordination (eICIC), and Coordinated MultiPoint (CoMP)⁴. Thirdly, the CBB architecture enables a reduction in power consumption through a decrease in

⁴eICIC is an LTE-Advanced feature introduced in Release 10, enabling coordination between the cells in time domain in order to tackle the interference. CoMP is also an LTE-Advanced feature, which enables dynamic coordination of scheduling/beamforming between the cells aiming to reduce the effects of interference, with scheduling performed by a single cell, but tightly coordinated with the neighbouring cells. It also enables

the use of baseband resources and cooling requirements [82] and provides flexibility in placement of RRHs. Finally, the CBB architecture with RRHs is part of the Cloud RAN architecture. Cloud-RAN enables large-scale baseband processing and cloud computing through the centralisation of baseband resources [82].

The DBB architecture with small cells, on the other hand, allows the use of different backhaul technologies and is a less costly transport solution. As such, it allows a more ad-hoc approach to providing capacity where and when needed, without having to meet special requirements on the transport infrastructure. In the context of LTE-Advanced, it also supports the use of features such as CoMP scheduling and eICIC but requires time-alignment between the cells. This means there are additional requirements on the synchronisation accuracy between small cells. Furthermore, in the case of coordinated scheduling (CoMP), potential gains are lower than would be the case with the CBB architecture, as coordination would be typically considered over a longer interval than the transmission interval [80]. Also, considering the trends towards network densification and a high number of LPNs, that is small cells, the amount of signalling over X2 (the interface between the radio access nodes) and S1 (the interface to the core network) needs to be taken into account, as there will be a requirement to increase coordination between the cells.

Finally, it should be noted that besides the above mentioned advantages of the CBB architecture, Cloud RAN enables the use of network function virtualisation techniques. They, although different from data server definition of virtualisation [87] techniques, should allow better management and deployment of radio access nodes, benefiting from common execution environment for radio and core networks and providing better responsiveness. At the same time, it is recognised that it will not be feasible to adhere to the huge bandwidth and strict latency requirements everywhere. Hence, the industry and operators are looking at selective centralisation of Cloud RAN architecture, which considers functional split at different points in the protocol stack (e.g. PHY split, where all PHY processing is done at a remote site) while still enabling many benefits of the Cloud RAN architecture [87], [85].

2.4 Aggregating spectral resources in heterogeneous baseband architectures

Chapter 1 laid out some of the challenges in bringing about a systematic approach to spectrum sharing and concluded with the suggestion to use LTE-Advanced as a basis in achieving this objective. LTE-Advanced has inherent capabilities to deal with the fragmented spectrum resources, supporting both architectures. It does that through Carrier Aggregation

joint processing/transmission, which requires all participating cells to process the data, and coordinate the transmission to the user [80].

and Dual Connectivity. Carrier Aggregation is designed to support aggregation of spectral resources from different LTE bands. Spectral resources are managed through the use of centralised baseband processing and a single MAC sublayer that provides the scheduling function - see discussion in 2.4.1.7. Dual Connectivity is a later addition to the LTE-feature set, applicable to distributed baseband processing, enabling simultaneous use of spectrum resources for a user connected to two nodes, where each node has its own complete user plane protocol stack. The two features, therefore, represent an excellent set to deal not only with the fragmented spectrum, but also with the heterogeneity of topologies and baseband architectures. The following subsections describe the main aspects of the two features.

2.4.1 Carrier Aggregation

Carrier Aggregation is by now a well-defined feature of LTE-Advanced, which enables aggregation of different blocks of spectrum to form larger transmission bandwidths of up to 100 MHz, with peak data rates of 1 Gb/s on the DL and 500 Mb/s on the UL. Each of the aggregated frequency blocks is referred to as Component Carrier (CC). There are a few ways in which CCs can be aggregated. The aggregation can be performed within the same LTE band, using contiguous or non-contiguous CCs - referred to as intra-band Carrier Aggregation. CCs can also be combined using spectrum from different LTE bands, which represents the case of inter-band Carrier Aggregation. These cases are depicted in Fig. 2.3. Intra-band contiguous Carrier Aggregation may be less common given today's fragmented spectrum allocation, making inter-band Carrier Aggregation a necessity for a number of cellular operators. Of particular interest is the inter-band Carrier Aggregation, where CCs may come from LTE bands that are significantly far apart and, therefore, have very different propagation characteristics. Carrier Aggregation is supported on the UL and the DL, as well as in both LTE Time Division (TDD) and LTE Frequency Division Duplex (FDD) systems⁵. It supports aggregation of up to five CCs. Different CCs do not need to have the same bandwidth. To ensure backwards compatibility with the LTE, the CCs have the same width as in LTE: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz [89]. While asymmetric configurations on the UL and the DL are supported, the number of CCs on the UL, however, cannot exceed the number of CCs on the DL [90]. The reason for this is that each UL CC is associated with the DL CC, as the DL CC carries scheduling grants for transmissions on the UL.

Aggregation of carriers has been defined for specific sets of LTE bands. In addition, 3GPP has defined UE's Carrier Aggregation *bandwidth class*, according to the maximum supported number of CCs and aggregated resource blocks. A UE can then support a combination of particular band(s) and bandwidth classes - see for example [91]. It should be noted that

⁵FDD mode separates the UL and DL communication by transmitting in different frequency bands. TDD mode operates using the same frequency band (i.e. channel), and the separation between the UL and DL communication takes place using guard bands in the time domain [88].

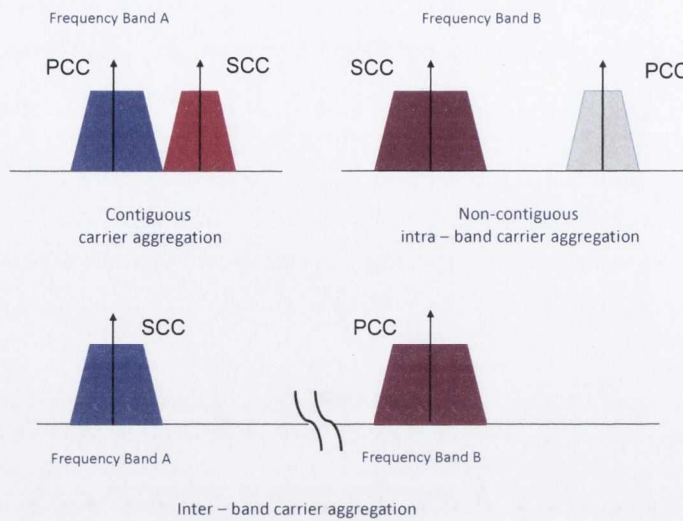


Fig. 2.3 Intra- and inter-band Carrier Aggregation. CCs can be of different widths. Primary component carrier and secondary component carriers are defined per a user.

there are many aspects of Carrier Aggregation feature that may be discussed. They include the implementation of transmitters and receivers, particularly for the cases of non-contiguous intra-band, or inter-band aggregation, the UL operation of Carrier Aggregation, as well as aspects related to the management of CCs, to name only a few. The aim here is to give a brief overview of the main aspects, some of which will be drawn upon in the following chapters.

2.4.1.1 Deployment scenarios

3GPP has identified a number of deployment scenarios where Carrier Aggregation can be used [90]. The most straightforward deployment scenarios are the ones where CCs have similar power levels and come from the same band, Fig. 2.4a. In Fig. 2.4b, cells from frequencies f_1 and f_2 are overlaid, but they belong to different bands i.e. ($f_2 > f_1$). This is inter-band Carrier Aggregation scenario, where f_2 has a smaller coverage due to a greater path loss. Such a case could also be feasible with f_1 and f_2 belonging to the same band, but with different transmit power levels. In Scenario c, f_1 and f_2 cells provide overlapping coverage using separate antennas. By pointing the antennas of certain carriers at inter-sector boundaries, the throughput for cell-edge users can be increased. Another possible deployment scenario is an inter-band scenario where RRHs provide capacity hot spots, Scenario d.

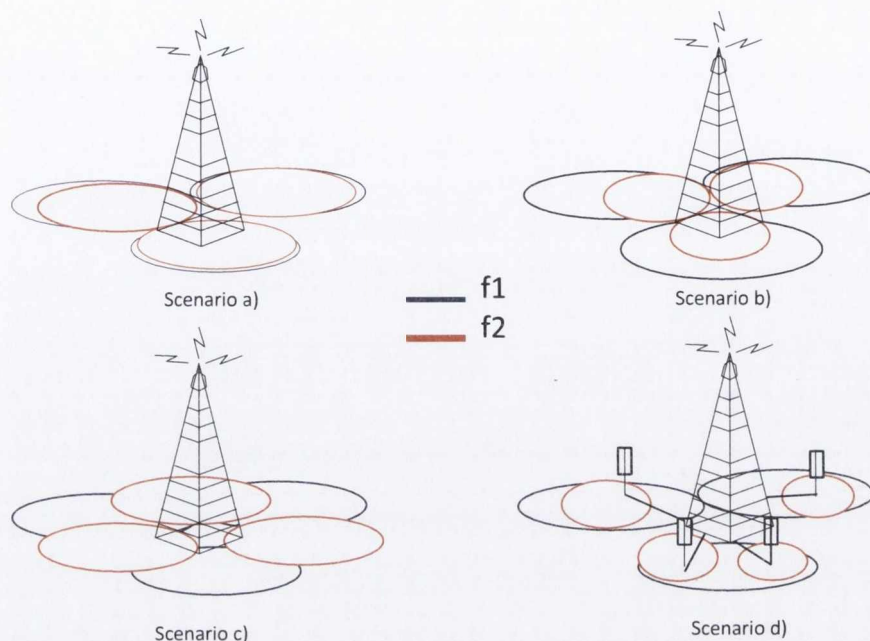


Fig. 2.4 Deployment scenarios as envisaged by 3GPP. In scenarios a), b) and c), both component carriers - f_1 and f_2 - operate on macro nodes. In scenario d), f_1 is employed by macro tier, whereas f_2 is deployed on the tier of RRHs.

2.4.1.2 Protocol impacts

To preserve backward compatibility with LTE carriers, in Carrier Aggregation, each CC maintains its PHY configuration. This means that parameters such as modulation and coding schemes are defined separately, per a carrier. Such protocol architecture allows the use of different MIMO schemes and power settings for different component carriers. Regarding MAC layer, the MAC sublayer responsible for retransmission is set per a component carrier. However, there is a single MAC sublayer, responsible for data multiplexing and packet scheduling. Carrier Aggregation is only exposed to this MAC sublayer, and is transparent to the protocol layers above - Packet Data Convergence Protocol (PDCP) and Radio Link Control (RLC), see Fig. 2.5, according to [71], [92]. Single MAC layer requires centralised baseband processing - the reason Carrier Aggregation is used in the CBB architectures. Finally, it should be noted that the LTE-Advanced Release 10 signalling and protocols specifications are defined in a generic way, supporting both intra and inter-band scenarios on the UL and DL. The RF specifications, however, are band-dependent. They also depend on whether the communication is UL or DL. Therefore, each release defines the RF specification for a particular band and a particular UL/DL combination.

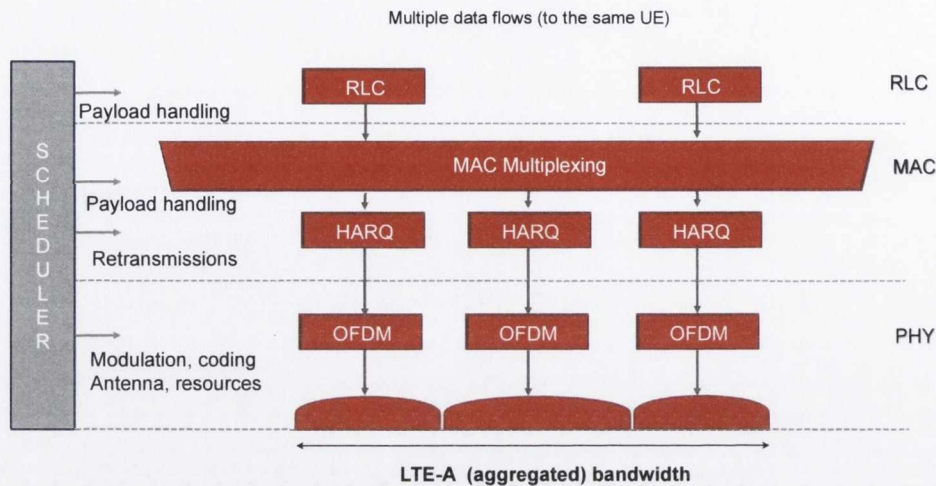


Fig. 2.5 Carrier Aggregation protocol stack - DL. The scheduler, situated in MAC, controls data rate.

2.4.1.3 Primary/Secondary cells

For each LTE-A user, one CC is designated as the primary carrier and is responsible for mandatory functionality, such as security key exchange with the core network or radio link monitoring⁶. The serving cell of Primary CC is called the Primary Serving Cell (PCell) and is the only cell that maintains a dedicated, RRC connection to the network when an UE transmits the data. Other CCs are called the Secondary CCs, and their corresponding cells are Secondary Serving Cells (SCells). It should be noted that PCell and SCell designation is UE-specific. Hence, the same cell can be the primary cell for one UE, and a secondary cell for another UE. The UE aggregation capability determines the number of serving cells that can be configured.

Addition and activation of SCells In Carrier Aggregation, the addition, reconfiguration and removal of SCells is performed by dedicated signalling from the PCell. Fig. 2.6 depicts the addition of an SCell. Once SCells are added, they can be activated, using MAC control elements. The deactivation is also performed using MAC, either through control elements or using the deactivation timer. Hence, the UE does not need to monitor control and data channels of the deactivated carriers. In this way, the UE battery consumption is reduced, as

⁶Radio link monitoring is a function which enables a user equipment (UE) to monitor the link on specific resource elements (pilot signal) when it is in connected mode. The UE can then establish whether it is in synch or out-of-synch with the serving cell. If a radio link failure is reported as a consequence of a number of consecutive out-of-synch indicators, the UE stops the transmission and has to establish Radio Resource Control (RRC) connection again.

well as the amount of required signalling [90]. The PCell can never be deactivated and is only changed during the handover procedure.

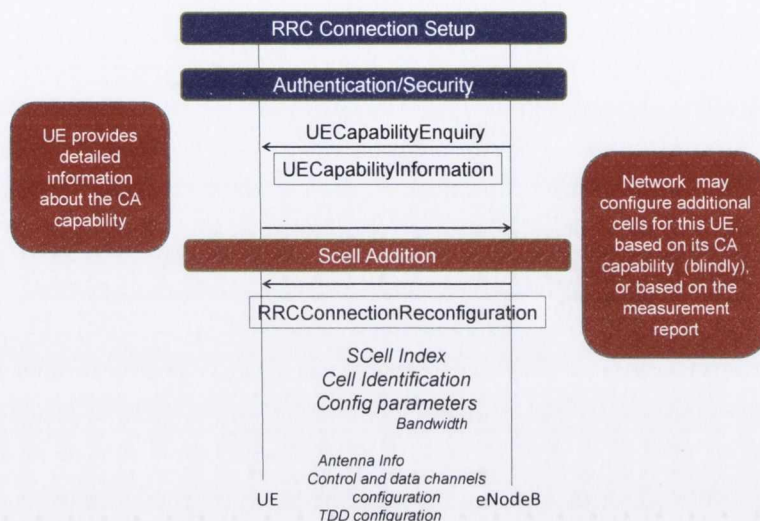


Fig. 2.6 Overview of a signalling flow for the addition of SCell.

2.4.1.4 Tx/Rx architectures

Carrier Aggregation has a significant effect on transmitter (Tx) and receiver (Rx) structures, depending on whether it is contiguous or non-contiguous intra-band aggregation, or inter-band Carrier Aggregation. Clearly, the implementation of baseband and RF structures is much more critical for the UEs than for the base stations. To that end, 3GPP has identified a few Tx architectural options applicable to different scenarios [93], according to where the CCs are combined. For example, the contiguous Carrier Aggregation can be supported by a single baseband and an RF chain. A single baseband requires centre carrier spacing to be a multiple of 300 kHz, as a least common multiple of LTE channel raster of 100 kHz and subcarrier spacing of 15 kHz [93]. Inter-band Carrier Aggregation requires multiple baseband and RF structures. The non-contiguous Carrier Aggregation also requires two baseband chains, with different up-conversion options [93]. On the receive side, either single baseband and RF chain is used for contiguous Carrier Aggregation; otherwise multiple baseband structures and RF chains are required. These, together with the aspects such as receiver intermodulation and spurious emissions are just some of the challenges related to the Tx/Rx structures with the introduction of Carrier Aggregation [94].

2.4.1.5 PHY layer procedures

Synchronisation On the DL of Carrier Aggregation system, the PCell and SCells are transmitted either from the nodes in the same physical location or the nodes at different physical locations, e.g. macro nodes and RRHs. As RRHs obtain their synchronisation from the centralised digital unit, and a user is synchronised in time and frequency with the PCell (transmitted from the macro node), there are no additional requirements on the synchronisation in the case of DL transmission. It should be noted that in the UL, the situation is different, and the use of multiple timing-advance is necessary to compensate for the difference in the path-length in the case of non-collocated cells. Multiple timing advance is introduced in 3GPP Release 11 [95].

Cross-carrier scheduling Carrier Aggregation also supports cross-carrier scheduling, Fig. 2.7, which means that the scheduling information for the DL is not carried by the associated (secondary) CC, but by another CC and is signalled using RRC signalling. For that, a carrier indicator is used on the control channel of the carrier providing the scheduling information [71]. The carrier indicator field (CIF) is appended to Downlink Control Information (DCI). DCI informs the UE about the DL scheduling assignments, UL scheduling grants and power control [71]. When CIF is appended to DCI, cross-carrier scheduling is used, whereby CIF informs the UE which CC is used for transmission of data. UE transmission can be scheduled using control channel only on one CC. Cross-carrier scheduling was initially introduced to tackle interference in deployments with heterogeneous networks, where macro and pico cells operate on the same frequencies. Namely, control channel that carries DCI must be decoded by the UE at a cell-edge. Hence, using the most suitable CCs to carry control channels for macro and small cells should reduce the risk of control channel interference.

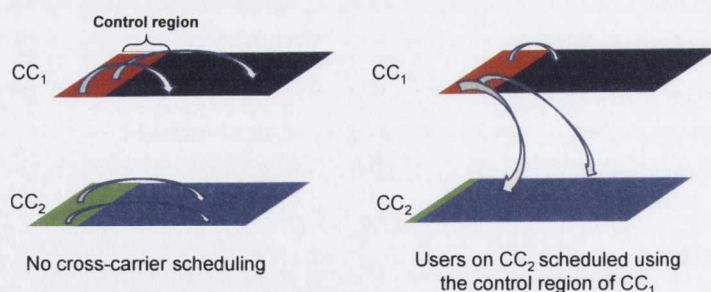


Fig. 2.7 Cross-carrier scheduling. Control region on CC₂ on the right does not carry scheduling assignments for its users.

2.4.1.6 Network modes

As mentioned above, Carrier Aggregation is supported in FDD and TDD modes. In 3GPP Release 12, support for joint FDD-TDD operation is introduced [96]. Support for joint FDD-TDD operation also enables flexibility regarding how the network is configured - namely PCell can be either in FDD or TDD mode.

2.4.1.7 Radio resource management & scheduling techniques

CC configuration In addition to the radio resource management (RRM) function of LTE, responsible for optimum allocation of radio resources to the users, Carrier Aggregation introduces new RRM functionality, which in [92] is referred to as CC configuration. CC configuration, packet scheduling and link adaptation in Carrier Aggregation are depicted in Fig. 2.8, according to [97]. The CC configuration is responsible for assigning users onto

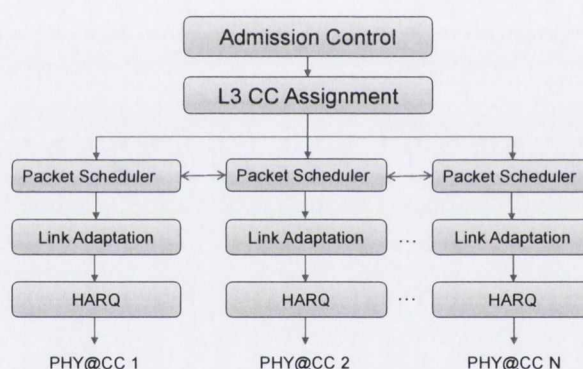


Fig. 2.8 Carrier Aggregation introduces L3 CC assignment component. Link adaptation and fast retransmissions are handled per a CC.

frequency carriers, where a user is assigned to a PCell, based on the signal quality. As PCell is in charge of maintaining the signalling connection to the core network, a user should be assigned to a PCell that provides the best signal quality. Subsequently, additional SCells can be allocated to the user, based on QoS requirements, buffered data and importantly, the load of the frequency carrier. However, in typical LTE-Advanced systems, the aim of a cellular operator is also to maximise the utilisation of all available radio resources. Hence, it is expected that users will be assigned to different carriers to achieve the load-balancing. Other aspects also need to be taken into account in CC configuration, including fairness between LTE and LTE-Advanced users, capabilities of terminals, and power consumption

on the UL [98]⁷. The CC configuration also needs to take into account the deployment scenario and users mobility to reduce the core network signalling overhead [99].

Packet scheduling in Carrier Aggregation Besides CC management functionality, the RRM in Carrier Aggregation enables simultaneous scheduling of users on different CCs, see Fig. 2.8. The scheduler, situated in MAC, is tightly coupled with the CC activation mechanism, as users can be scheduled only on the activated CCs. Scheduling in Carrier Aggregation draws on the scheduling function in LTE systems, with the main task of allocating spectrum resources in a most optimum way. The scheduler is responsible for allocation of resource blocks, which are made of 12 consecutive sub-carriers in the frequency domain and a single 0.5 millisecond-long time slot in the time domain [71]. The scheduling is performed on a 1 millisecond-basis, where only a single user can be assigned to a particular resource block (except in cases of multi-antenna transmission, which is not in the scope of the thesis). Sharing of resource blocks is coordinated by a packet scheduler, situated in the MAC layer, which represents a key element of LTE/LTE-A systems [100]. Closely related to scheduling is the link adaptation, which deals with how to set the transmission parameters to handle variations in the quality of the radio-link, see Fig. Considering that LTE employs fast scheduling, it is particularly important that packet scheduler uses scalable, low-complexity algorithms. Hence, to avoid the complexity associated with non-linear optimisation and consideration of all possible combinations for all users on all resource blocks, packet scheduler computes metric $MT_{i,k}$ for each user i and resource block k and assigns user j that maximises the metric ([100], Eq. (1)):

$$MT_{j,k} = \arg \max_i MT_{i,k} \quad (2.1)$$

Different metrics can be defined, taking into account aspects such as channel quality, throughput, fairness, delay, buffer state [100]. In [100], an excellent taxonomy of schedulers utilised in LTE systems is presented. The authors identify five different types of schedulers, which include combination of channel-aware and QoS aware schedulers, semi-persistent schedulers for Voice over IP (VoIP) and energy-aware schedulers. One of the most straightforward schedulers is Round Robin (RR) scheduler, which assigns resources to users regardless of the channel quality. In this way, RR scheduler provides fairness (in the time-domain), but does not utilise multi-user diversity i.e. the fact that different users experience different fades on different sub-carriers - considered by the channel-aware schedulers. Hence, channel-aware schedulers avail of the channel conditions and optimise frequency resources in time to maximise the system capacity. A widely implemented such scheduler is Proportional Fair scheduler (PF), used for packet scheduling for non-guaranteed bit rate services.

⁷It should be noted that due to the power constraint, CC configuration is of a greater importance on the UL than on the DL [98].

Individual proportional fair (PF) algorithm. PF is an SINR-aware algorithm, meaning that the scheduling is based on SINR values, measured at the user's receiver over the resource blocks [71]. The main idea of the PF scheduling is to schedule users with good instantaneous channel conditions while providing a certain degree of fairness by considering the past throughput for all users, over a sufficiently long period. Hence, a user j is selected according to the following general formula [71]:

$$j = \arg \max_i \frac{r_i}{\bar{R}_i} \quad (2.2)$$

where r_i is the instantaneous rate of user i , and $\bar{R}_i$ is the average user rate over the selected averaging window. PF algorithm has been extended to Generalised PF (GPF) algorithm, by introducing two weighting coefficients α and β that enable tuning of the efficiency and fairness [100]:

$$j = \arg \max_i \frac{[r_i]^\alpha}{[\bar{R}_i]^\beta} \quad (2.3)$$

where $\alpha, \beta \in [0, 1]$. Namely, setting $\alpha = 0$ means that the current channel conditions would not be taken into account and the scheduling algorithm would assign users to the resource blocks based only on the previous throughput. In other words, such setting maximises fairness. On the other hand, with $\beta = 0$, the instantaneous rate only would matter in the scheduling decision - maximising efficiency, but without fairness. With $\alpha = 1$ and $\beta = 1$, GPF algorithm becomes PF.

In terms of Carrier Aggregation systems, two types of packet scheduling algorithms are typically seen for data services - individual Proportional Fair (PF) and Cross-Carrier Proportional Fair (CC-PF) algorithms - see [98] and references therein. Individual PF considers only the radio conditions within a single carrier and allocates users on resource blocks according to the Eq. (2.2) or (2.3).

CC-PF algorithm. CC-PF extends the PF algorithm across multiple carriers. This is a more advanced scheduling scheme, which takes into account the the statistics on all carriers [97], [101]. Hence, for a case with the number of carriers $m > 1$, the user i on k -th resource block on m -th carrier with the best metric MT will be schedule [97]:

$$MT_{i,k,m}(t) = \frac{r_{i,k,m}(t+1)}{\sum_{m=1}^M r_{i,m}(t)} \quad (2.4)$$

where M is the total number of carriers. In this case, the nominator takes into account the instantaneous channel conditions on each RB of each carrier, whereas denominator takes into account previous throughput on all carriers. Hence, CC-PF increases the overall

fairness, but at the expense of an increased computational complexity. Nevertheless, it is shown in [102] that CC-PF maximises utility, defined as a sum of logarithmic throughputs once the carriers are assigned to the users. CC-PF algorithm can also be extended to the Generalised CC-PF form, using weighting coefficients that increase efficiency or fairness [102]:

$$j = \arg \max_i \frac{\alpha(i) \cdot r(i, k, m, t)}{R(i, t)^\beta} \quad (2.5)$$

In this case parameter $\alpha(i)$ depends on the user capability to support Carrier Aggregation. The performance of different algorithms is also highly dependent on the deployment scenario and coverage characteristics of the considered carriers [101].

There are also other scheduling algorithms that operate over multiple carriers. Some of them take into account different aggregation capabilities of terminals, or delay - see the work referred in [98]. It should be noted that the algorithms and their implementation are not specified by 3GPP, and are left open to base station vendors to specify.

2.4.1.8 State-of-the-Art

Carrier Aggregation within LTE-Advanced is a well-established research topic, with a wealth of literature that deals with different aspects of the system. General functionality and system description aspects can be found in [103], [92] and [104]. Thus far, much focus of LTE-Advanced based Carrier Aggregation has been on the radio resource management [97], [101]. In [97], a comprehensive resource allocation framework is analysed, with different load-balancing and scheduling techniques (independent and cross-carrier proportional-fair), and using both - finite and full-buffer traffic models. In [101], based on the performance of independent and cross-carrier proportional-fair scheduling for different deployment scenarios, two techniques for Layer 3 component management are proposed, based on the absolute or relative quality of the additional carriers in relation to the primary carrier. In [105], the CC selection mechanism on the UL is evaluated, using a path loss based threshold to distinguish between power-limited UEs and non-power-limited UEs. In [99], the impact of different component management schemes on the RRC signalling overhead is evaluated in a mobility scenario, using a deployment where component carriers have different coverage (macro cells overlaid with LPNs). In [106], a deployment scenario considering a combination of LPNs - RRH and pico cells is considered. The deployments with RRHs are referred to as inter-site carrier aggregation. Deployments with pico cells are considered as typical HetNet deployments, where macro and pico cells operate on the same frequency. The work shows that inter-site Carrier Aggregation deployment offers a significant gain in low-load situations, and also provides better load-balancing and easier mobility management. In [94], the challenges of terminal implementation for Carrier Aggregation are discussed. Finally, a comprehensive survey of works in Carrier Aggregation, particularly in the domain of radio

resource management, the reader is referred to [98] and references therein. More advanced forms of Carrier Aggregation for Release 12 and beyond are foreseen. A high-level description of Release 12, including Carrier Aggregation can be found in [107]. The associated features include joint LTE TDD-FDD Carrier Aggregation, in Release 12 [108], and a number of additional band combinations and supported carriers on the downlink (DL) and uplink (UL). Furthermore, in the last year, Carrier Aggregation and Dual Connectivity have been a subject of numerous activities within 3GPP, and in the industry. The proposal is to use these features to support the operation in the unlicensed (WiFi) spectrum. The discussion on this part of related work can be found in the Conclusion in Chapter 8.

2.4.2 Dual Connectivity

This subsection describes key aspects of Dual Connectivity of relevance to this thesis. Dual Connectivity is introduced in 3GPP Release 12 to support densification of cellular networks through the use of small cells. The aim with Dual Connectivity is also to enable simultaneous utilisation of radio resources in distributed baseband architectures over a range of backhaul technologies with different throughput, delay and jitter characteristics. Dual Connectivity enables a user to have a simultaneous connection to two nodes, with two individual schedulers, over a range of backhaul technologies. It is applicable when a user is in connected mode, where one node is designated as a master node - a Master eNodeB. The Master eNodeB is responsible for the signalling connection to the core network. The other node is a secondary node - a Secondary eNodeB, which is added as an additional resource by the Master eNodeB. Dual Connectivity requires implementation of two MAC layers in the UE - one for the Master eNodeB, and the other for the Secondary eNodeB [90].

2.4.2.1 Deployment scenarios

Dual Connectivity supports different deployment scenarios, which include co-channel as well as the inter-frequency operation between macro nodes and small cells [84]. A scenario featuring topologies only with small cells is also supported. In this thesis, when referring to Dual Connectivity, the reference is to the scenario where macro nodes and small cells operate on different frequencies, as depicted by the image in the left corner of Fig. 2.9.

2.4.2.2 Protocol impact

Control plane In Dual Connectivity, while each node controls its radio resources, only a Master eNodeB maintains the signalling connection to the core network, as depicted in Fig. 2.10. Secondary eNodeB is added to provide extra resources. The coordination between the Master and Secondary eNodeBs is done using X2 interface.

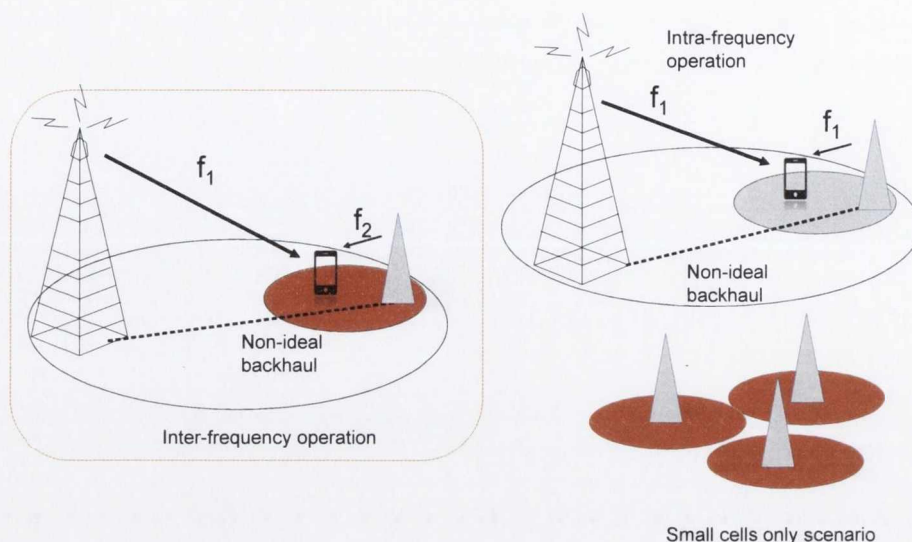


Fig. 2.9 Dual Connectivity scenarios in 3GPP. Macro and small cells may operate on the same, or different frequencies. Small-cells only scenario is also considered.

User plane Dual Connectivity introduces significant changes to the protocol stack on the user plane. Namely, 3GPP has proposed few architectural options in terms of handling the user traffic. One option envisages separate bearers between the core network and a Secondary eNodeB while the other option envisages split bearers between the core and radio access networks. Namely, in LTE, an Enhanced Packet Service (EPS) bearer, which carries traffic with a certain QoS, is a packet flow between a Packet Gateway (P-GW) in the core network and a user [109]. EPS bearer is then mapped onto an Enhanced UTRAN Radio Access Bearer (E-RAB) between the UE and a Serving Gateway (S-GW). In the core network, the EPS bearer is mapped onto S5/S8 bearer between S-GW and P-GW. On the radio access side, E-RAB is further mapped onto a radio bearer between a UE and an eNodeB, and an S1 bearer between the eNodeB and the S-GW. Hence, each service is assigned to a particular EPS bearer, according to its QoS parameters [109]. All services with the same QoS characteristics are assigned to the same bearer [109].

Fig. 2.11 on the left depicts the architectural option in Dual Connectivity with separate E-RAB bearers between a UE and an S-GW. In that case, each S1 bearer is terminated in each of the nodes separately. That is, each node is only involved in the transport of data associated with its bearer. Hence, each node performs its processing - namely, scheduling function and buffering is done separately on each node. This option has certain advantages as it does not require processing of the same packets in different nodes, and the requirements for the transport network infrastructure are low. There are also disadvantages. For example, the utilisation of radio resources is not possible in two nodes for the same bearer. Further,

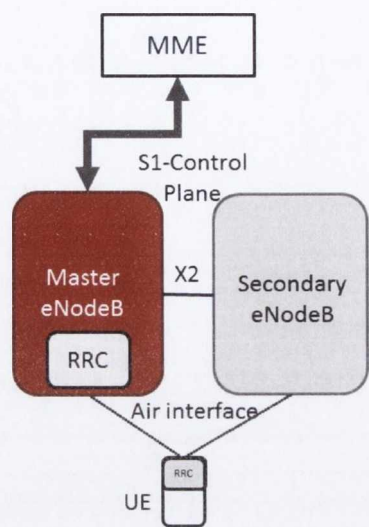


Fig. 2.10 Control plane for Dual Connectivity. RRC messages are only exchanged between the Master eNodeB and UE.

the change of Secondary NB due to e.g. mobility is visible to the core network.

The other specified option is the option where an EPS bearer is split between the Master and the Secondary eNodeBs and is depicted on the right of Fig. 2.11. This option enables spectral resource aggregation between the nodes but requires routing, processing and buffering the traffic between the nodes. Furthermore, to avail of the inter-node spectral aggregation, in this case, there are requirements regarding backhaul performance - it has to offer latency below 30 ms [110]. Given different characteristics of the various types of backhaul solutions, see Table 2.1, the focus of this thesis is the option with the separate bearers, as it does not pose any particular requirements on the backhaul.

2.4.2.3 Master/Secondary eNodeB

Only the Master eNodeB can initiate the addition of a Secondary eNodeB. However, the modification and release of the Secondary eNodeB can be initiated by either of the nodes, which is signalled through the X2 interface.

2.4.2.4 Support for Carrier Aggregation within Master/Secondary eNodeB

Dual Connectivity also enables the aggregation of carriers within each tier - the macro tier or the tier with small cells. When Carrier Aggregation within Master eNodeB is configured, the same principles as outlined in subsection 2.4.1, p. 31 apply. When additional resources (cells) on the Secondary eNodeB (based on the UE measurement report or traffic load) are required, the Master eNodeB may request from the Secondary eNodeB activation of

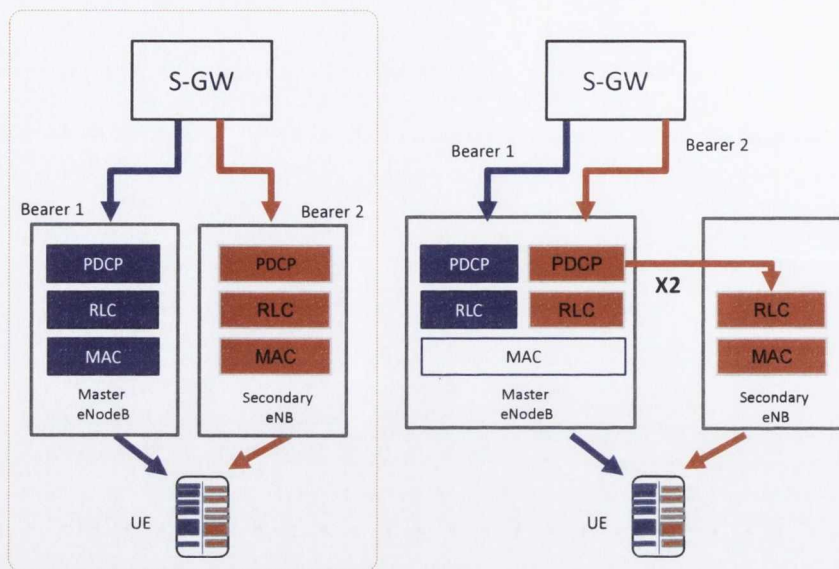


Fig. 2.11 User plane for Dual Connectivity. Separate bearers (left) and split bearer (right) options. With separate bearers considered in this thesis, both nodes have the complete protocol stack below Packet Data Convergence Protocol (PDCP).

additional cells. It is the role of Secondary NodeB to decide whether it can provide these additional radio resources and which cell (within the Secondary NodeB cells) will be the PCell. This cell has to have the UL control channel.

2.4.2.5 Network modes

Dual connectivity supports configuration where Master and Secondary eNodeBs may operate either in the same or different duplex scheme (FDD or TDD) [110].

2.4.2.6 State-of-the-Art

Dual Connectivity is a relatively recent research topic. Most works focus on evaluating the possibilities and impacts of splitting control and user plane traffic between a macro tier and a tier of small cells. For example, in [111], a framework based on splitting control and user plane in MIMO architecture is proposed. The control plane is established using macro tier, whereas small-cells tier used for data traffic. For channel estimation, the work proposes the use of MIMO and user specific reference signals to achieve energy savings and better efficiency. COMP and Dual Connectivity, with split user-control plane architectures, is proposed in [112] to overcome the issues with handovers in mobility scenarios. Energy efficiency using Dual Connectivity is studied in [113], whereas in [114], Dual Connectivity is aided by the database to achieve better energy efficiency. The work in [115] is focused on split-bearer architecture and optimal flow control between a Master and a Secondary

eNodeB in cases when the Master eNodeB has only statistical knowledge of the Secondary eNB queue state. In [116], the authors analyse challenges in the terminal, and on the UL, with the focus on split-bearer user-plane architecture.

2.5 Summary

This chapter described the most important aspects of the three key components used as a basis for this thesis: the heterogeneous topology with a macro tier and a tier of LPNs; two distinct baseband architectures from the perspective of LPNs - CBB and DBB; and two prominent features of LTE-Advanced - Carrier Aggregation and Dual Connectivity. The first part of the chapter focuses on the topology and the baseband architectures, outlining the main challenges and differences between the two. The CBB architecture poses strict requirements in terms of jitter, delay and the required throughput on the interface between the radio and digital unit, and as such is a costly option. However, it provides a number of advantages, such as the implementation of advanced scheduling, joint processing and interference management techniques, as well as pooling of resources. It also provides energy and other efficiencies associated with the centralised processing. From the transport network perspective, the DBB architecture is clearly a more cost-effective solution and provides greater deployment flexibility. However, it poses limits regarding supported features and the gain they can provide. Further, the chapter described Carrier Aggregation and Dual Connectivity - the two features that used through the thesis. Carrier Aggregation provides an elegant solution for the aggregation of spectrum resources from different LTE bands, with different channel widths. It is applicable only in the CBB architectures. Dual Connectivity offers a simultaneous connection of a user to two radio access nodes with distinct schedulers, where each of the nodes have their own user-plane protocol stack. It supports different options regarding user plane handling, and also requires additional signalling between Master and Secondary eNodeBs to provide the core network with the information regarding the radio resources on the Secondary eNodeB. Dual Connectivity is only applicable to the DBB architectures. Dual Connectivity also supports the aggregation of spectral resources in accordance with the Carrier Aggregation feature.

The next chapter turns to defining the spectrum sharing framework and the overall challenges and outlines specific challenges this thesis addresses.

Chapter 3

The Sharing Framework

The last chapter described the key characteristics of Carrier Aggregation and Dual Connectivity, as defined in LTE-Advanced. It is clear that they are powerful tools for dealing with fragmented spectrum and supporting different baseband architectures. This chapter outlines the proposed framework, including the spectrum-sharing model, different baseband architectures and how the two features underpin the whole framework. As outlined in Chapter 1, the framework concentrates on DL communication. The chapter starts with Section 3.1, which describes the most important aspects of the framework, whereas Section 3.2 outlines challenges in developing such a framework. Section 3.3 provides the summary.

3.1 The main propositions of the framework

Given the primary objectives the framework is set out to address - namely, embedding spectrum sharing into LTE-Advanced system and providing attainable methodology that will encourage spectrum sharing, the following are the main propositions:

- Carrier Aggregation and Dual Connectivity should be used as the basis for the framework as they provide flexibility in addressing the heterogeneity of spectrum. The features enable aggregation of spectrum resources from different frequency bands. The aim of the framework is to broaden the type of spectrum the LTE-Advanced standard considers. Namely, in addition to spectrum exclusively owned by a cellular operator, the framework should also employ shared spectrum. Furthermore, the intention is to consider shared spectrum resources that are intrinsically different in a number of aspects. They should reflect distinct features of different spectrum sharing models, such as spectrum availability, access rights, permitted power-regime, interference protection, and usage fee.
- The framework should address both CBB and DBB architectures, particularly in the light of future cellular network deployments featuring heterogeneous networks with a

variety of transport network solutions. Carrier Aggregation and Dual Connectivity should be ideally suited as they support the two baseband architectures.

- The framework also proposes to introduce a mechanism that deals with two typically competing objectives - QoS, and cost of spectrum. Both aspects are of particular importance to cellular operators. QoS should be defined in terms of the end-user performance metric for a specified service. Hence, it is directly related to the QoS that is planned and offered by a cellular operator [117]. The framework, therefore, proposes to use an end-user performance metric and appropriate target values that the network should deliver. The mechanism should also consider that the exclusivity regarding transmission in certain spectrum sharing models envisages usage fee.

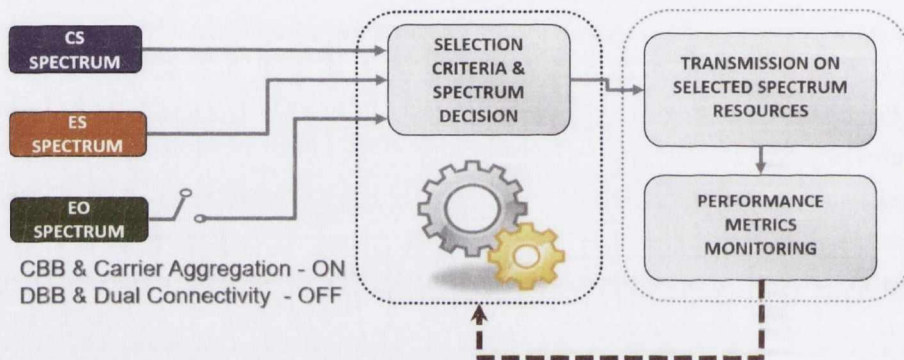


Fig. 3.1 The main concept of the proposed framework. Spectrum resources considered in the selection criteria depend on the baseband architecture. The objective and selection criteria determine how the shared carriers are used.

Fig. 3.1 depicts the main concept of the proposed framework. The following subsections describe in more details its main propositions.

3.1.1 Spectrum classes

The framework proposes a three-tier spectrum approach, where spectrum resources belong to what are referred as different *spectrum classes*, first introduced in [73].

- EO spectrum where a single entity i.e. a cellular operator is licenced to transmit in a given block of spectrum (channel)¹, in a particular area, typically for several years. The cellular operator controls the radio resources entirely within its channel. This type of spectrum use is the most prevalent in cellular communications today.

¹The terms *block of spectrum* and *channel* are used interchangeably in this thesis.

- ES spectrum class provides an exclusive right to transmit, enforced through a centralised control of access to spectrum by a spectrum manager or a spectrum broker. The spectrum manager is responsible for radio resource management to maximise e.g. revenue [118]. In this case, a single entity, i.e. a cellular operator, leases a block of spectrum, for a specified (short) period of time - seconds, minutes, or hours. The access to spectrum envisages a usage fee. In return, the cellular operator is guaranteed the in-channel and adjacent-channel interference protection. The transmission power regime may be high-power. An example of this architecture may be found in [119], where a spectrum broker coordinates a short-term spectrum lease applicable to a region as small as the area covered by a single base station.
- CS spectrum class provides no guarantees on the availability or the quality of spectral resources. A number of entities may access the same block of spectrum, free of cost. Power levels may be determined by the number of entities accessing spectrum, but are usually low. Although there may be a limit on the number of entities transmitting in the channel, there are no guarantees on the interference levels. This approach embraces a number of variations of *commons*, or *licensed shared use* [120], [40], but without defining the rules for access to the medium.

It should be noted that each spectrum class, as defined within the framework, should not be considered only with respect to a single band or a channel within the band. On the contrary, it is envisaged that each spectrum class should contain a number of bands and corresponding channels. Particularly, it is expected that the proposed classification regarding the ES and CS spectrum classes is broad enough to incorporate different bands currently identified for spectrum sharing, as well as future spectrum sharing bands. In other words, it is envisaged that there will be a one-to-many mapping between the shared spectrum class and the bands/channels. The thesis, however, focuses on a single ES and a single CS band, particularly on a single channel within each band.

3.1.2 Topology & spectrum employment

The spectrum-sharing framework embraces different topologies - macro only, or a topology with a heterogeneous network, featuring a mix of macro cells and LPNs. In this thesis, of particular interest is heterogeneous network topology, where LPNs are either RRHs (CBB architecture) or small cells (DBB architecture). The proposed employment of spectrum within different architectures is summarised below.

3.1.2.1 Employment of EO spectrum

It is recommended that the EO spectrum be used on a macro tier in both baseband architectures. The macro tier should provide the functionality found in the current networks,

i.e. *as is*. The frequency carrier of the EO spectrum, within the framework, is referred to as *principal carrier*. All users should have access to this carrier, which is suitable for providing mobility and coverage, but should also be used for data transmission. Principle carrier, hence, should provide:

- synchronisation between a macro cell and all terminals in the cell
- basic system information for UEs to access the cell
- control signalling related to scheduling and transmission acknowledgements
- cell-specific (pilot) signals needed for channel estimation, also used as a basis for basic procedures such as cell search and handover²
- spectrum resources for data transmission.

In addition, the framework proposes that the principal carrier in the CBB architecture should also carry the additional, control information related to the shared carriers. This is further discussed in Chapter 7.

3.1.2.2 Shared spectrum employment

In the framework, the frequency carriers of the shared spectrum resources are referred to as shared carriers. They should be deployed on the tier of LPNs - RRHs and small cells.

CBB architecture In the CBB architecture, LPNs are RRHs, and the baseband processing is done centrally, with a single MAC sublayer. Hence, in the framework, the spectrum resources from the ES and CS classes are proposed to be employed on the tier of RRHs. The existing Carrier Aggregation mechanism of adding and activating SCells, explained in the previous chapter (see p. 34), should be reused to facilitate the addition and subsequent activation of a number shared carriers. In this architecture, the spectrum resources from all spectrum classes should be aggregated and scheduled according to a defined scheduling metric.

DBB architecture In the DBB architecture, Master and Secondary eNodeB implement each their own scheduler. In the framework, it is proposed that macro node should operate as Master eNodeB, and will be referred to as a master node. Similarly, small cells should act as Secondary eNodeBs, and will be referred to as secondary nodes. Hence, in the framework, master and secondary nodes should each implement their own, separate scheduler. The

²Channel estimation is used for coherent demodulation, which is the demodulation used in LTE/LTE-Advanced systems. On the other hand, cell search is one of the basic operations in cellular communications, which enables the terminal to synchronise with a cell and obtain the cell identity. It is also required to support mobility. Handover refers to a process of changing the cell that provides control and data channels when a user is in *connected state*. It follows the cell search procedure [71].

existing mechanism in Dual Connectivity should be used to request the activation of shared carriers on small cells. Furthermore, the framework considers the option with separate bearers to be of interest, as it allows the use of any backhaul solution, as discussed on p. 41. This means that, for a particular service, a user could utilise only spectrum resources from either a master or a secondary node. As the framework focuses on the performance of a single service with the shared carriers, the users within the framework could, therefore, avail of the spectrum resources from the secondary nodes only. For the purpose of control signalling to and from the core network, the users would still use a master node, utilising appropriate Dual Connectivity mechanisms. The framework also recommends that within the secondary nodes, the aggregation of resources between ES and CS spectrum takes place.

3.1.2.3 Network mode

From the perspective of the network operating mode, the proposed spectrum sharing model and topologies within the framework should support operation in both - FDD and TDD mode, as well as a mixture of FDD and TDD modes. Namely, both duplex options have advantages and disadvantages. FDD mode is more suitable for symmetrical applications, as spectrum is paired. Furthermore, as there is no time delay in the transmission/reception, the FDD mode reduces delay for MAC and HARQ [88]. Also, due to a presence of a typically large guard band, the UE-UE interference is negligible, as well as the interference from one base station to another. However, FDD has a number of disadvantages. Firstly, FDD requires paired spectrum and a large guard band between UL and DL bands, which does not utilise spectrum resources in a best possible way. It also requires extra spectrum planning and is not suitable for asymmetrical applications. Furthermore, one of the big disadvantages of the FDD mode is that it requires channel state information, which also has to be quantised in the receiver before it is reported to the transmitter. This not only contributes to a significant signalling overhead but also degrades the fidelity of information regarding the channel state [88]. Finally, FDD requires more expensive hardware - separate local oscillators for UL and DL, sharp filters and duplexer [88]. TDD mode, on the other hand, operates using unpaired spectrum and, therefore, enables a more flexible spectrum utilisation and asymmetric allocation of spectrum resources. Secondly, TDD does not require channel feedback and quantisation of channel state information due to the existing reciprocity of the channel response on the UL and DL [71]. This leads to better optimisation of transmit parameters, although it may not always provide the transmitter with a complete knowledge of the channel conditions. However, one of the greatest disadvantages with TDD is a requirement for the radio frame synchronisation to avoid the base station-base station interference and UE-UE interference. The guard interval between UL and DL transmissions, in this case, needs to cater for the propagation delay of the largest cell. Clearly, the larger the cell is, the greater is the required guard interval. There are also other disadvantages with TDD. They include a delay for MAC and HARQ, as well as outdated channel information,

which can be an issue in time-varying channels [88].

Given the above, the framework recommends a mixture of FDD and TDD modes, as one of the most suitable options. Namely, the FDD mode should be more appropriate for the EO spectrum due to its wide adoption for the licensed bands and support for continuous transmission. FDD mode is also better suited to a greater cell size. On the other hand, from a shared spectrum perspective, the TDD mode may be more advantageous as it should not require a paired spectrum to support UL and DL communication. Furthermore, TDD mode should be more appropriate for LPNs due to their smaller cell size. Hence, the framework proposes setting in a mixed FDD/TDD mode, but it does not preclude other solutions - e.g. pure FDD mode. It should be noted that the analysis of the framework in the thesis focuses on the pure FDD mode.

3.1.3 Spectrum selection mechanism

At the core of the framework is a proposition to use the alternative shared spectrum resources, in addition to the EO spectrum. Such a proposition should also include a methodology for a cellular operator that defines *how* to utilise the shared spectrum. Clearly, such a methodology should take into account that i) the CS band may be available and is free - but provides no guarantees on the quality of spectrum resources; ii) the ES spectrum provides guarantees on the availability and the exclusivity of transmission, but at a cost. Also, the methodology should also take into account QoS that a cellular operator plans to offer. The methodology, hence, should be about defining the objective and criteria for selection of shared spectrum resources. The recommendation is that the method, referred to as *spectrum selection mechanism*, is centred around minimising the cost of shared spectrum for the cellular operator, while meeting target QoS. As the cost of the ES spectrum may envisage other, ancillary cost, such as the cost of providing the interface towards a spectrum broker, or administrative fees, it is recommended that the cost of ES spectrum include the cost of access to the spectrum band only. Furthermore, the cost should be directly proportional to the amount of spectrum required. In this way, within the framework, the objective then translates into minimising the amount of spectrum resources coming from the ES spectrum while meeting the required QoS. Certain QoS aspects are addressed in Chapter 4 while Chapters 6 and 7 define and analyse QoS requirements in more detail.

3.2 Challenges in developing the framework

It is evident that there are many challenges in developing the proposed framework. They relate to different facets of the spectrum selection mechanism, as well as to the overall impact of the considered architectures. Broadly, they can be classified into three groups.

The first group of challenges relates to characterising the shared spectrum and is described below.

- One of the challenges includes shared spectrum access architecture, where ES and CS spectrum classes, by definition, are expected to have different ways of accessing and releasing spectrum resources. They are also likely to use different spectrum access techniques. In developing the framework, certain assumptions are made about the spectrum access architecture. For example, in the ES band, a centralised spectrum manager/broker, which controls the access to spectrum is envisaged. This is a typical centralised spectrum management approach discussed in many works that consider dynamic spectrum management, for example, [121], [122]³. The assumptions are also made about the CS band. They also draw, in the main, on the proposed spectrum sharing models, such as TV White Spaces [47], [46] and CBS [61], where the use of a database is stipulated.
- Spectrum modelling, which enables evaluating different classes of shared spectrum to select appropriate spectrum resources, is also one of the challenges. Spectrum modelling requires appropriately characterising the ES and CS spectrum and drawing on cognitive radio functions, detailed in e.g. [45]. In the context of the proposed sharing model, modelling spectrum envisages addressing aspects such as: identifying spectrum bands for sharing; characterising their availability and the interference; characterising the cost of bands; and determining appropriate transmission parameters, such as permitted power, channel widths, and others.

Hence, for the first group of challenges, the aspects related to the shared spectrum architecture are substantively covered in the literature and are not analysed further in the thesis. On the other hand, characterising shared spectrum is fundamental to the spectrum selection mechanism and the simulation-based analysis in the thesis. It is therefore addressed first, in Chapter 4.

The second group of challenges pertains to the analysis and performance of specific topologies, supported by Carrier Aggregation and Dual Connectivity. Hence, they also include challenges related to the spectrum selection mechanism, considered within the context of the identified topologies. Furthermore, there is a coinciding challenge concerning the best way to model the system. Hence, the challenges include:

- QoS criteria - identifying the type of services the framework should address, and adopting the appropriate performance metric. Again, parallels to the spectrum decision functions in cognitive radio and cognitive radio networks can be drawn on

³Also see discussion in [45]. In [123], the signalling procedures for the centralised spectrum management in future cellular (LTE-Advanced based) networks that incorporate dynamic spectrum access are proposed.

- see, for example, [124], [45], [125]. Furthermore, within the framework, the QoS criteria also need to reflect the fact that multi-user scenarios should be analysed. Therefore, addressing this challenge should answer the questions on which service is considered [126], how the performance metric reflects a multi-user scenario, and what are the requirements to achieve the required performance.
- Resource management - tightly coupled with the challenge on the QoS criteria as it directly affects the performance of a cellular system. The proposed spectrum sharing model features heterogeneous spectrum resources. There is, therefore, a challenge regarding scheduling algorithms that should be used within the framework.
- Modelling the framework addressing the questions of what methods to use - i.e. should analytical methods be used or if the framework should be modelled using simulations. System-level simulations are proposed to be used.
- Control plane aspects, relating to a question of how is the control plane affected in the framework and how it refers to the architectures with LPNs.

All challenges outlined within Group 2 are intrinsic to the questions the thesis and the framework should address. Chapter 4 addresses initial aspects related the QoS. The challenges of the QoS criteria and resource management are dealt with in Chapters 6 and 7. Chapter 5 addresses one of the tools for the system level simulations, whereas control plane aspects are dealt within Chapter 7.

There are other challenges that the proposed framework poses. They include issues related to the implementation, the hardware aspects - particularly RF structures, as well as regulatory challenges. These challenges are beyond the scope of the thesis.

3.3 Summary

In this chapter, the spectrum sharing framework that is central to the thesis is presented. The framework is set to provide a comprehensive and systematic approach to spectrum sharing by using a three-tier model that embraces different forms of spectrum. The framework provides wider transmission bandwidths by reusing Carrier Aggregation and Dual Connectivity of LTE-Advanced. It incorporates spectrum resources from the prevalent EO spectrum class, and two different classes of the shared spectrum - ES and CS. The ES spectrum class is an example of the centralised spectrum sharing model, offering short-term leases of spectrum and guarantees on spectrum quality. The CS class is a case of open access spectrum but does not provide guarantees on the availability, or quality of spectral resources. Furthermore, the framework is set to address and evaluate heterogeneous networks with different baseband architectures. This not only means that the framework supports spatial densification through

the use of LPNs, but that it addresses the underlying transport network requirements. This is one of the major aspects that need to be considered in networks featuring LPNs. Finally, at the core of the framework is the spectrum selection mechanism, which aims to address QoS requirements, while minimising the cost of acquiring spectrum resources from the ES spectrum. It is evident that the challenges in developing such a framework are significant. This thesis addresses some of them. It seeks to answer key questions stemming from the challenges dealing with spectrum modelling, objective and selection criteria, topologies and modelling the framework. The initial analysis, described in the next chapter, aims to address certain aspects of spectrum modelling and QoS.

Chapter 4

Spectrum Characterisation

This chapter explores some of the challenges associated with the characterisation of the shared spectrum classes. Furthermore, the objective is to address certain aspects of the spectrum selection process. The chapter considers a simple scenario, where ES and CS spectrum classes lay in the same band and where few spectrum properties in the CS band are singled out and considered - namely, the availability and interference. Regarding selection criteria, the focus is on signal-to-noise (SNR) and signal-to-noise-and-interference (SINR) aspects. The chapter is organised in the following way: Section 4.1 outlines the aspects considered in the chapter and describes spectrum characterisation, whereas Section 4.2 presents the spectrum selection process. Section 4.3 sets out the system model, including input parameters. Section 4.4 describes the results, while Section 4.5 concludes the chapter.

4.1 Attributes & characterisation of spectrum classes

The ES and CS shared spectrum classes discussed in the previous chapter reflect two distinct features of the spectrum sharing models - the exclusivity of transmission and common/open access. Clearly, for a cellular operator, the preference would always be to use ES spectrum that would provide it with complete control over the radio resources and with guarantees for the interference protection. However, the ES spectrum comes at a cost. Therefore, for a cellular operator, there would always be trade-offs regarding cost and QoS that need to be balanced. To understand the trade-offs, it is necessary to characterise the two spectrum classes. Spectrum characterisation requires firstly identifying the appropriate attributes of the shared spectrum and then describing them. In this section, key attributes of the two shared spectrum classes are considered.

4.1.1 Frequency bands

To remind the reader, the ES spectrum class in the proposed spectrum sharing model should have an exclusive right to transmit, granted by a spectrum broker. The access to spectrum

envisages a usage fee. The CS spectrum class provides no guarantees on the availability or the quality of spectral resources. Different entities may access this spectrum, free of cost. Furthermore, as the thesis builds on system-level simulations rather than on an analytical model, the spectrum characterisation requires selecting specific frequency bands. In this chapter, the ES and CS spectrum classes are chosen to be in the same frequency band at 2 GHz. In this way, the analysis is entirely focused on the difference in the quality of the two types of spectrum resources and avoids dealing with differences related to the path loss. Also, the focus of the thesis is on LTE-based systems, which as the multiple access mechanism use a combination of OFDM and time division. Namely, a frequency band is divided into a number of resource blocks, which are the units of resource allocation in LTE/LTE-Advanced systems. Each user is allocated a number of resource blocks within the transmission time¹. Hence, considering the above, it is envisaged that both - the ES and CS spectrum bands consist of a number of resource blocks, whereby each user is allocated a certain number of resource blocks.

4.1.2 Availability of shared spectrum

According to one of the central premises of the thesis, the ES band is entirely available to the cellular operator. It should be noted that this assumption is valid within a period specified by the spectrum manager. The thesis does not consider the time aspect of spectrum availability. For the CS band, its availability is analysed through the availability of its resource blocks. Their availability, however, is not guaranteed and can be described as a random process. Characterising spectrum availability by using a statistical model is one of the fundamental cognitive radio functions. Hence, any one of the various models describing spectrum occupancy developed for cognitive radio networks, see for example [127], [128] and the ones referred in [129], may be used to represent the availability of the CS resource blocks. In this chapter, the model presented in [127] is adopted, as it characterises the probability of channel availability using Beta distribution. Beta distribution from [127] is selected to reflect the non-identically distributed, independent probabilities of the availability of resource blocks. In other words, the probability of availability of each resource block is different, which may better reflect a more realistic scenario, particularly when considering channels in various shared bands. Also, in [127], Beta parameters are validated through spectrum measurements in two different locations. Furthermore, Beta distribution may cover a broad range of shapes that characterise channel availability, depending on the values of the shape parameters - see Eq. (4.3).

¹In LTE systems, in the frequency domain, the resource block is a group of 12 consecutive subcarriers, which stand 15 KHz apart, making a single resource block 180 kHz wide. In the time domain, the resource blocks are defined over a single slot of 0.5 milliseconds. The resource allocation takes place on a subframe-by-subframe basis, where two time-slots make a subframe (1 millisecond).

4.1.3 Interference

Interference - co-channel and adjacent channel - is one of the most important factors to model, as it is a primary reason for a capacity reduction. In the proposed framework, it is one of the main differentiating factors between the ES and CS bands. The focus of the thesis, however, is on co-channel interference². The spectrum sharing framework differentiates between intra- and inter-system interference. Intra-system interference relates to the interference caused by the transmitters that belong to the same entity e.g. a cellular operator. This type of interference can be controlled using methods such as ICIC of LTE, which is based on the fractional frequency reuse³.

Hence, within the framework, both bands suffer from intra-system interference. Besides, in the CS band, inter-system interference is also present - caused by the transmitters that belong to different entities. A particular challenge in modelling the interference in the CS band is related to the fact that it requires a defined access protocol/etiquette. In [130], two ways of modelling the interference between heterogeneous systems are discussed from the information-theoretic perspective. One treats interference as additive noise, whereas the other one uses Listen Before Talk (LBT) mechanism employed in WiFi networks. In the thesis, interference is treated as additive noise. A user connects to the node that provides the highest received power, whereas transmission by all other (non-serving) nodes is treated as interference. This particular model is adopted as it is utilised in cellular systems. It also does not require defining any particular access mechanism or coordination between the nodes.

In this chapter, a simplified model is adopted to evaluate the effects of the difference in the interference levels experienced by the two spectrum classes. The assumption is that the ES spectrum is characterised by the effects of noise only, as the cellular operator entirely controls the spectrum band. It is, therefore, considered that intra-system interference is below the noise floor. In the CS spectrum, the effects of inter-system interference are characterised by inter-cell interference within the operator's network.

²In the remainder of the thesis, the term interference refers to co-channel interference unless stated otherwise.

³ICIC is a mechanism defined in LTE Release 8, which enables the exchange of information between the cells regarding the transmit power on particular resource blocks. This information can be used by the neighbouring cells to coordinate the scheduling of cell-edge users [71]. ICIC is based on fractional frequency reuse, which entails splitting the coverage area of a cell into regions, which use different sub-bands for the transmission. The cells' neighbouring areas do not use the same sub-bands to avoid the interference for cell-edge users. Typically, different power levels are used in the various regions of the cell.

4.1.4 Cost of shared bands

The basic premise of the spectrum sharing framework concerning the cost of shared bands is used throughout the thesis: the ES spectrum envisages a usage fee, whereas the CS band is free.

4.1.5 SNR/SINR distributions

The quality of spectrum in this chapter is reflected entirely through SNR/SINR distributions. In the ES spectrum, the SNR distribution illustrates the distance-dependant path loss (between a base station and a user), including the effects of noise and log-normal shadowing⁴. In the CS band, in addition to the effects of path loss, shadowing and noise, inter-cell interference is considered. The computed SNR/SINR distributions, hence, represent wide-band values, which means that they are constant over all resource blocks. Namely, no small-scale fading effects are analysed in this or other chapters - see the discussion in the following section. The computation of SNR/SINR distributions is performed using Matlab. Namely, Monte-Carlo simulations are run to compute signal, noise and interference levels of a random user, using equally-spaced macro transmitters. Path loss is calculated according to the path loss formula in [77] for 2 GHz frequency. Accordingly, the shadowing is modelled as a log-normal random variable, with zero mean and standard deviation specified in [77]. Besides, shadowing also includes correlation between the links that originate from the same base station. Namely, shadowing in a network is not independent, as different paths may encounter the same obstacles [132]. The formula used for shadowing correlation in the simulator is given in Chapter 5, p. 74. Finally, the interference at each user is calculated as the sum of received powers from all non-serving transmitters in the network.

4.2 Spectrum selection process

The spectrum selection draws on one of the primary functions of cognitive radio - the *spectrum decision*, which is responsible for selecting the most suitable spectrum block for transmission [126]. Namely, as discussed in [133], different criteria and techniques can be applied for spectrum decision (selection). Criteria or objective may, for example, be aimed at maximising spectrum efficiency or minimising spectrum-switching delay [126], or minimising cost. The techniques range from heuristic approaches to optimization-based spectrum selection (linear and non-linear programming) to game-theory, fuzzy-logic, and others.

In this chapter, a two-stage selection process is considered. The objective is to present

⁴Large-scale effects typically refer to the combined effects of deterministic path loss in relation to distance and variations about the mean received power. Variation is described using log-normal distribution - hence, it is referred to as log-normal shadowing [131].

the operator with a choice of options when to use a particular shared spectrum band. Hence, the operator can decide whether the conditions in the CS band are satisfactory and worth exploiting instead of using a costlier option with the ES band. It should be noted that it is expected that spectrum selection process in the framework takes place on a significantly longer time-scale than that of e.g. the transmission interval in LTE. Hence, in the thesis, small-scale fading effects are not considered. Namely, they reflect themselves as fast variations in power due to delay-spread caused by multipath effects and time-variant behaviour due to motion [131]. As multipath effects can be deemed averaged out over the considered period and, at the same time, mobility is not analysed in the thesis, small-scale effects are not included in the analysis.

4.2.1 Stage 1

Stage 1 entails a computation of the availability of the CS spectrum. To that end, a threshold for the probability of availability of a resource block is introduced, denoted as ξ and used later in the analysis. The CS band, rather its resource blocks and their availability are used as input to this stage of the selection process. Resource blocks with the probability of availability lesser than the threshold are not considered. Hence, a cellular operator, at the output of this stage of the process, considers only resource blocks with the probability of availability greater than the selected threshold value. The threshold value, on one hand, reflects the availability of the CS band while, on the other hand, it represents the system's capability to exploit more of free resources. By setting a high threshold value, the system is configured to access only resource blocks with a high probability of availability. A low threshold means that the system is accessing less reliable resource blocks, but at the same time, it has the flexibility to use more free resource blocks, even if they have a high probability of being occupied by another entity. The threshold value should not be considered static, but should be dynamically changed by a cellular operator, depending on e.g. traffic demand or another parameter, specified by the operator.

4.2.2 Stage 2

Stage 2 envisages comparison of the quality of two bands using spectral efficiency as a metric. Hence, as input to this phase of the process, the computed SNR and SINR distributions, according to subsection 4.1.5, p. 60, are used. Further, this stage entails computing achievable capacity and *spectral efficiency equivalent* q , which is a relative measure of the quality of the two spectrum classes.

4.2.2.1 Achievable capacity & spectral efficiency equivalent

Based on the obtained SNR/SINR distributions, the achievable capacity is computed for each of the spectrum classes. The achievable capacity is maximum (Shannon) capacity [134]

that can be reached and does not take into account the aspects such as finite code-length and set of modulation techniques [135]. The achievable capacity in the shared spectrum classes reflects the difference between the quality of the two bands through SNR/SINR distributions. It also needs to take into account the fact that a random variable characterises the availability of the CS band. Considering that the probability of availability is computed for a single resource block, the achievable capacity represents capacity per a resource block. Also, *spectrum efficiency equivalent* per a resource block gives an average number of resource blocks from the CS band needed to achieve the same capacity as provided by a single resource block in the ES band⁵. The higher the *spectral efficiency equivalent* is, the higher is the number of resource blocks needed from the CS band to achieve the capacity of a resource block in the ES spectrum. Also, Stage 2 computes the minimum required SINR in the CS band ensuring that the CS band has a sufficient number of resource blocks of considered availability. Figure 4.1 depicts the proposed two-stage selection process.

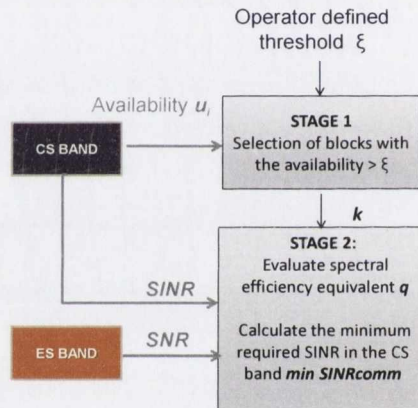


Fig. 4.1 The proposed process for the selection of CS resource blocks. Depending on their availability and quality, a cellular operator can decide should the additional resources from the ES band be resorted to.

4.3 System model

Here, all of the above-explained aspects are put together, and system model, including input parameters, are presented. The following notation is used:

- ξ - availability threshold below which the CS resource blocks are not considered
- k - the number of resource blocks from the CS band with probability of being free that is greater than a predefined threshold ξ

⁵Normalised capacity i.e. capacity per a resource block and spectral efficiency per resource block are equivalent terms, used interchangeably.

- $SINR_{cs}$ - SINR value from the SINR distribution in the CS band
- SNR_{es} - SNR value from the SNR distribution in the ES band
- B - bandwidth of a single resource block
- C_{es} - capacity of each resource block in the ES band
- $C_{i,cs}$ - capacity of i -th resource block in the CS band
- q - spectral efficiency equivalent i.e. an average number of resource blocks from the CS band needed to achieve the same capacity as provided by a single resource block from the ES band
- u_i - probability of availability of an i -th resource block in the CS band
- N - total number of resource blocks in the CS band.

4.3.1 Spectrum bands - the characterisation

SNR/SINR Distributions. Subsection 4.1.5, p. 60, explained how the SNR and SINR distributions are modelled. Namely, in the ES band only the effects of path loss, log-normal shadowing and noise are taken into account. Hence, the SNR_{es} for user u , served by the transmitter l is computed as:

$$SNR_{es_{u,l}} = \frac{P_{tx} \cdot L_{l,u}}{N_{th}} \quad (4.1)$$

In the CS band besides the effects of path loss, log-normal shadowing and noise, intra-system interference is also included. The $SINR_{cs}$ for user u , served by the transmitter l is computed as:

$$SINR_{cs_{u,l}} = \frac{P_{tx} \cdot L_{l,u}}{N_{th} + \sum_{\substack{j=1 \\ j \neq l}}^M P_{tx} \cdot L_{j,u}} \quad (4.2)$$

where

- P_{tx} - transmit power of each macro node
- $L_{l,u}$ - path loss (including log-normal shadowing) and antenna gains on the link between the serving cell l and a user u
- N_{th} - thermal noise in the receiver
- $L_{j,u}$ - path loss (including log-normal shadowing) and antenna gains on the interfering link between all non-serving cells j and a user u
- M - total number of cells considered.

4.3.2 Selection process

4.3.2.1 Stage 1

Here, a statistical model is employed to obtain all resource blocks from the CS band, with the probability higher than ξ . Beta distribution is used to describe the probability of a resource block being free u_i . The general form of Beta distribution is given by

$$pdf(x; \alpha, \beta) = \frac{x(1-x)^{\beta-1}}{B(\alpha, \beta)} \quad (4.3)$$

where

$$B(\alpha, \beta) = \int_0^1 t^{\alpha-1} (1-t)^{\beta-1} dt.$$

The number of resource blocks k from the CS band with a probability of being free u_i that is greater than a predefined threshold ξ is given by

$$k = \sum_{i=1}^N y_i \quad (4.4)$$

where

$$y_i = \begin{cases} 1 & \text{if } u_i \geq \xi \\ 0 & \text{otherwise} \end{cases}$$

4.3.2.2 Stage 2

Stage 2 uses SNR/SINR distributions and computes achievable capacity and *spectral efficiency equivalent*. The capacity on each resource block in the ES band is given by a well known Shannon capacity formula [134]:

$$C_{es} = B \cdot \log_2 \cdot (1 + SNR_{es}) \quad (4.5)$$

In the CS band, the capacity of resource block i is offset by the probability of availability u_i . Namely, the computation of capacity here draws on the cognitive radio channel capacity, Eq. (1) in [126], where capacity is offset by the time a cognitive radio user does not transmit due to sensing and switching delay as it is required to vacate the channel. In this chapter, the probability of availability can be seen as a portion of time when a resource block is not available. The capacity on a resource block i can then be written as:

$$C_{i,cs} = u_i \cdot B \cdot \log_2 \cdot (1 + SINR_{i,cs}) \quad (4.6)$$

Spectral efficiency equivalent q . Based on the computed values of $C_{i,cs}$ and C_{es} , q is calculated. As previously mentioned, the resource block capacity in the CS band $C_{i,cs}$ is a function of not only the $SINR_{cs}$ values, but also the threshold values ξ , selected in

Stage 1. In other words, $C_{i,cs} = C_{i,cs}(SINR_{cs}, \xi)$, whereas in the ES band $C_{es} = C_{es}(SNR_{es})$.

Minimum SINR. In Stage 2, minimum $SINR_{cs}$ is also computed, given the different values of the threshold for the probability of availability. In other words, for $SINR_{cs}$ for which $q > k$, the CS band does not have the required number of resource blocks. Hence, minimum required $SINR_{cs}$ across a range of values SNR_{es} is computed to determine the $SINR_{cs}$ for which $q \leq k$.

4.3.3 Input parameters

4.3.3.1 Spectrum bands - the characterisation

The $SINR_{cs}$ and SNR_{es} distributions for both spectrum classes are computed using a Matlab-based simulation tool, referred to as HetNet, which simulates deployment of nodes and users in OFDMA/LTE networks. HetNet is described in detail in the next chapter - Chapter 5. In this chapter, equally spaced macro transmitters, with uniformly distributed users are considered in the ES and CS spectrum.

Parameters used in computation of SNR/SINR In both, ES and CS spectrum band spectrum of 10 MHz is considered. It should be noted that the number of resource blocks takes into account 10% guard band, which is used in LTE systems [77]. The main parameters used in the simulation are given in Table 4.1.

Table 4.1 Summary of the parameters used in the simulation.

Simulator model	
Spectrum	50 resource blocks over 10 MHz, 2 GHz
BS TX power	46 dBm
BS Antenna pattern/gain	Directive antenna, 3GPP model [77] / 14 dBi
UE antenna pattern/gain	Omnidirectional antenna / 0 dBi
Propagation model	
Channel model	3GPP Macro, case 1, [77]
Log-normal shadowing - standard deviation	8 dB

Computed SNR/SINR Distributions Figure 4.2 depicts the cumulative distribution function (CDF) obtained from the ES and CS bands, by performing simulations as per parameters in Table 4.1. As expected, the average user in the ES band experiences significantly better SNR, as this was a 'noise-only' band. There, the median SNR is 32 dB, whereas in the CS band, 32 dB is the best experienced SINR. The median SINR in the CS band is 8 dB.

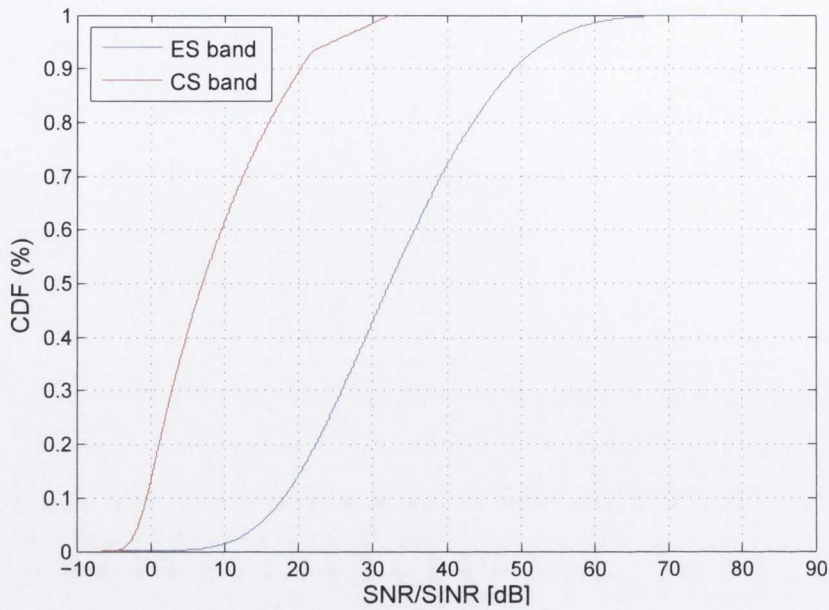


Fig. 4.2 CDFs of SNR/SINR in the ES and CS bands

4.3.3.2 Selection process

Beta Parameters and Threshold Values The Beta distribution parameters are estimated based on the mean and standard deviation obtained from a set of spectrum measurements in [127], where $\alpha = 0.4046$ and $\beta = 0.859$. The number of resource blocks over which the probability of availability is set to 50, which with the guard band of 10% equates to 10 MHz bandwidth. Also, three pre-defined threshold values of ξ are observed: 0.5, 0.7 and 0.9.

4.4 Results & discussion

4.4.1 Stage 1

The number of resource blocks k are calculated for three different values of $\xi = 0.5, 0.7$ and 0.9 , and according to Eq. (4.4). The corresponding computed values are $k = 14, 8$ and 3 . Hence, the probability of availability reflecting the medium and high likelihood of availability are considered. The case when the probability of availability is below 0.5 is not analysed. Clearly, the higher the availability threshold value, the lower is the total number of resource blocks in the CS band that a cellular operator can consider.

4.4.2 Stage 2

Spectral efficiency equivalent q Figure 4.3 depicts the average q , given $SINR_{cs}$, and computed using Eq. (4.4) and selected values of ξ . Notably, $q = q(SINR_{es}, SINR_{cs}, \xi)$, i.e.

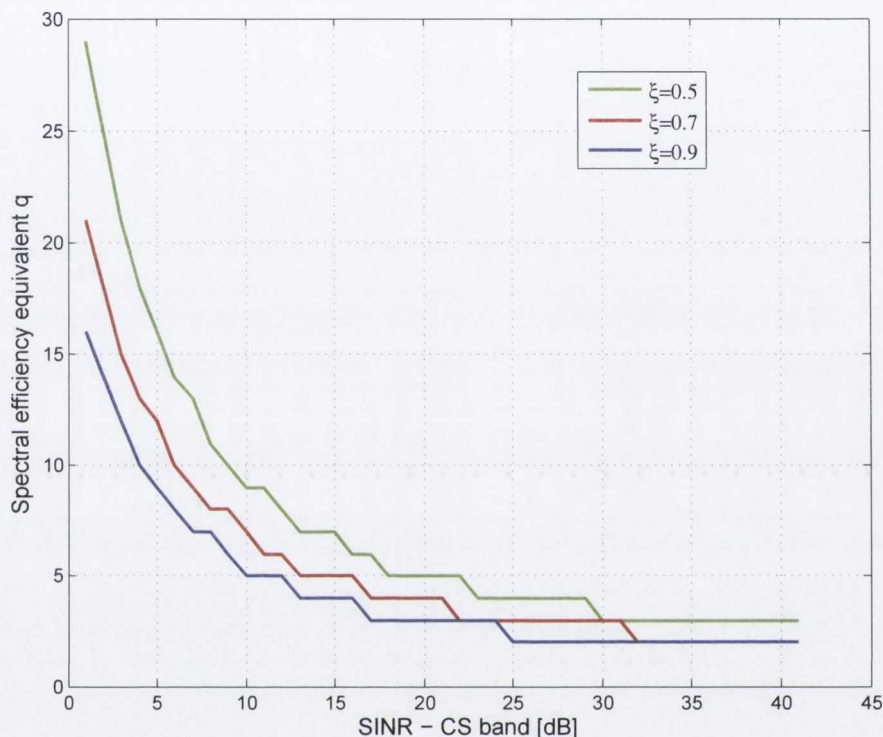


Fig. 4.3 The ES spectral efficiency equivalent for different values of probability thresholds

q depends not only on the quality of spectrum in both bands but also on the value of the availability threshold. Also, it can be observed that:

- For low values of $SINR_{cs}$, the average q is much higher i.e. many more resource blocks from the CS band are needed to achieve the same capacity as in the ES band, whereas as $SINR_{cs}$ increases, q decreases.
- Given the SNR_{es} , the resource block spectral efficiency is proportional to the availability probability threshold ξ . The higher the likelihood of availability, the lower is q and vice versa. Results in Figure 4.3 refer to the observed set of 50 resource blocks. However, different values for the observed set do not change the relationship between q and the $SINR_{cs}$, depicted by Figure 4.3.

Minimum SINR in the CS band The minimum required $SINR_{cs}$ is calculated for all values of SNR_{es} . They represent the number of resource blocks that is $\leq k$ and is required

to achieve the capacity of the ES band. Fig. 4.4 depicts the results. It can be observed

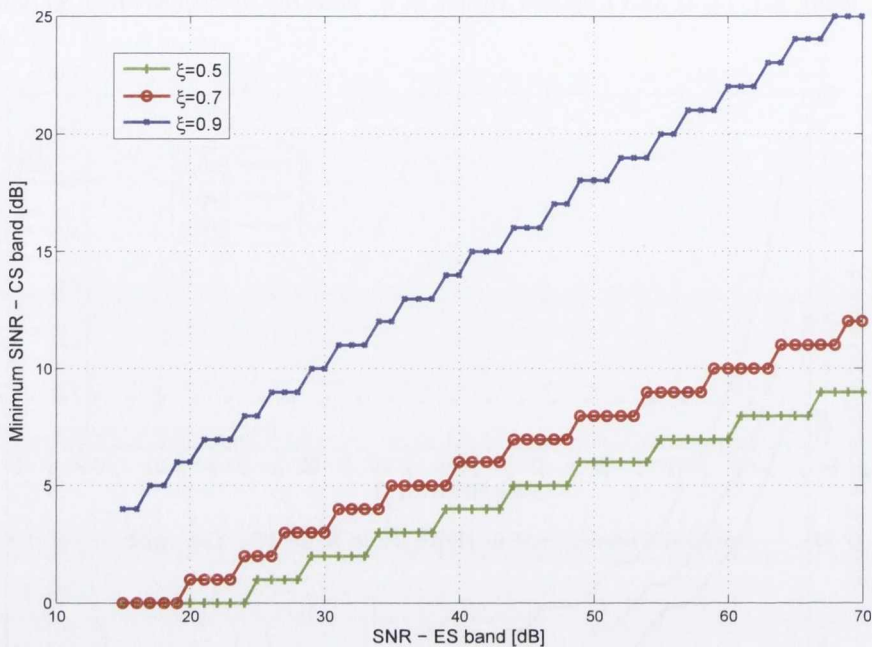


Fig. 4.4 Minimum SINR required to use the CS band

that for $\xi = 0.5$ and $\xi = 0.7$, and lower values of SNR_{es} , there is no requirement on the minimum $SINR_{cs}$ for a majority of locations in the cell if the required SINR value above 0 dB is considered. Namely, in LTE systems, for a user to be able to decode the signal from a base station, SINR should be greater or equal to a predefined value that can be -5 dB, or even lower (see Sections 13.3 and 13.4 in [71]). For the purpose of this analysis, the value of 0 dB value is adopted. Hence, as average user experiences SINR that is ≥ 0 dB, there is no additional requirement on the minimum value of $SINR_{cs}$ required to meet the ES band capacity. Hence, in general, the lower the threshold ξ , the lower is the minimum $SINR_{cs}$ across a range of values SNR_{es} for which $q \leq k$. For example, for the median in the ES band of $SNR_{es} = 32$ dB, the minimum required $SINR_{cs}$ with $\xi = 0.9$ is 11 dB, whereas with $\xi = 0.5$ the required minimum is $SINR_{cs} = 2$ dB. This is a significant difference in the minimum $SINR_{cs}$, especially considering that it refers to the CS band. For higher threshold values, minimum $SINR_{cs}$ is greater and rises quicker with the increase of SNR_{es} , compared to the lower threshold value. This proves a trade-off between the probability threshold and the minimum $SINR_{cs}$: if the system accepts the lower likelihood of a resource block being available, it can use a lower minimum value of $SINR_{cs}$ to acquire the resource blocks from the CS band.

4.5 Summary

This chapter explores the challenges associated with identifying and characterising the major attributes of the two shared spectrum classes, and analysing the selection process. Therefore, a very specific scenario featuring macro tier only, where two shared spectrum classes lay in the same frequency band is considered. The considered scenario, hence, enables focusing on the shared spectrum attributes, and the selection process. The two most important attributes are adopted for the shared spectrum classes: the availability and quality of spectrum measured through SNR/SINR and spectrum efficiency equivalent. In line with the constructs of the spectrum sharing framework, the ES class is considered available, but at a cost. In the case of the CS band, free access to spectrum is envisaged, but with no guarantee of the availability, i.e. the availability is described using a random variable. The decision to avail of the CS band is made based on the statistical data, more precisely the probability of availability. The selection process uses SINR distributions, as a best-suited measure of the conditions in the two spectrum classes. Furthermore, the spectrum selection process is expected to take place on a significantly longer time-scale than that of the transmission interval in e.g. LTE. Hence, it was concluded that the small-scale effects are not central to the framework and are, therefore, not specifically analysed. Besides, to characterise the fact that in addition to intra-system interference, the CS band experiences inter-system interference, the ES band is represented as a 'noise-only' band while the CS band experiences noise and interference. In that way, a proxy measure of the quality of spectrum in the two bands is obtained. In the proposed two-stage spectrum selection process, the cellular operator controls the availability threshold setting and evaluates the quality of spectrum resources from the CS band. To unify the two aspects - the probability of availability and the SNR/SINR in the two bands, the concept of the ES band spectral efficiency equivalent is introduced. The spectral efficiency equivalent represents an average number of resource blocks in the CS band required to achieve the capacity of a resource block in the ES band. Although this is a simple scenario, interesting insights are obtained: for example, considering that the CS band fluctuates in terms of its availability, the probability threshold can be considered the cellular operator's design parameter that acts as a measure of spectrum reliability. On the other hand, it also defines the system's flexibility to accept a less reliable spectrum in return for less stringent requirements on the minimum required SINR in the CS band.

Finally, there are few aspects of particular importance that need to be noted. Firstly, while considering the individual resource blocks is suitable for this analysis, of interest for the framework are the channels within designated shared frequency bands, as opposed to resource blocks. Namely, decision-making per a resource block creates considerable challenges for the OFDM-based system, as each resource block would create side-lobes since subcarrier orthogonality and synchronisation between different entities cannot be assumed

[136]. Furthermore, there would also be implications regarding complexity and the associated overhead, especially as the number of resource blocks grows. For these reasons, in the next chapters, it is the channels typically found in LTE systems that are considered, instead of resource blocks. Secondly, while the analysis in this chapter considers the SNR/SINR for the two spectrum classes, this is confined to a single band. Dealing with these aspects, as well as with different topologies requires providing the appropriate Matlab environment featuring also LPNs. This topic is addressed in the next chapter.

Chapter 5

Simulation Tool for the CBB Architecture - HetNet+

The last chapter focused on spectrum characterisation and certain aspects of spectrum selection criteria. The challenge now is to explore how Carrier Aggregation and Dual Connectivity can be extended to include different, shared spectrum classes. As the thesis focuses on simulating certain performance aspects of the baseband architectures that use the two features, the purpose of this chapter is to describe the simulator used for the analysis. Specifically, the chapter describes the simulator for the CBB architecture and Carrier Aggregation - HetNet+. HetNet+ extends the scope of an existing Matlab-based simulator, called HetNet, designed by a researcher within the group. HetNet is aimed at simulating heterogeneous networks and small cells, using single frequency carrier. Hence, although it represents a good basis, HetNet required significant extensions to support the simulations for the CBB architecture. Considering that the objective was to reuse, to a greatest possible extent, the existing functions and modules, it is important to understand scenarios, radio resource management techniques and performance metrics supported by HetNet and on which HetNet+ builds. Hence, Section 5.1 describes the main, relevant functions of HetNet simulator, while Section 5.2 describes the extensions and capabilities of HetNet+. Section 5.3 provides the summary of the chapter.

5.1 Overview of HetNet simulator

5.1.1 Supported scenarios

HetNet simulator is a Matlab-based system-level simulation tool, intended for simulating the DL communication in OFDMA/LTE-based networks in FDD mode. It also uses Matlab object-oriented programming for implementing certain classes e.g. cells, users, antennas. HetNet supports simulations of homogeneous, heterogeneous and small cell networks. In homogeneous network setup, 19 macro nodes are placed in a regular hexagonal grid (2

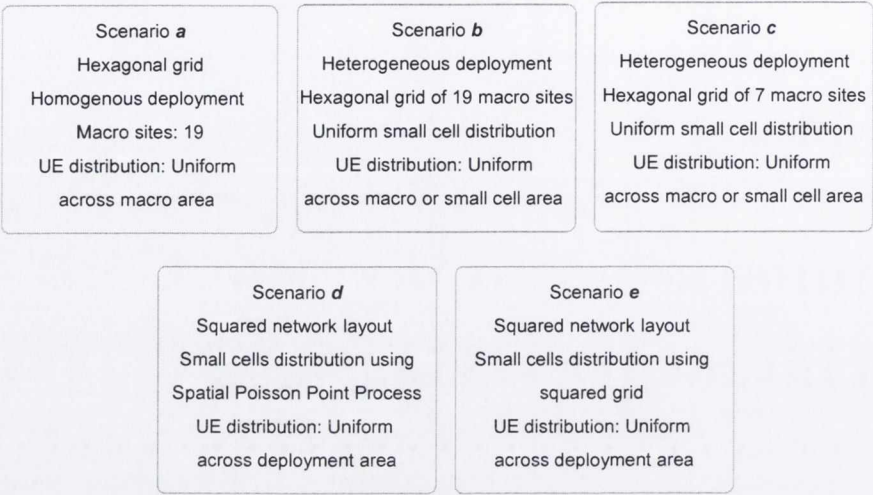


Fig. 5.1 Outline of the scenarios supported by HetNet simulator

rings), where each node supports three cells (sectors). The distance between the nodes is determined by the inter-site distance for a particular environment - i.e. urban, or suburban. The distances follow the recommendations for each specific environment, according to [77]. In the case of a heterogeneous network, in addition to the macro topology tier, the LPNs, specifically picocells, are distributed across the macro cell area, using a uniform distribution, following the constraints on the distance between the nodes and users. As per the users, they can be distributed uniformly across the macro-cell area or in a clustered deployment, where a percentage of all users are clustered within the picocell area. The distances between the nodes and users are depicted in Table 5.1. Finally, in the case of small cells networks, the cells are placed according to spatial, homogeneous Poisson Point Process (SPPP)¹. The SPPP model does not impose any constraint on the distance between the points in the process i.e. the nodes. In these cases, only the minimum distance between a user and a cell is adhered to. Fig. 5.1 summarises all the scenarios, as supported by HetNet simulator.

In all scenarios, the wrap-around technique is implemented. The wrap-around technique treats the boundary region as contiguous [138], and avoids edge-effects in the simulation. It allows for computation of interference effects for all users, without introducing a bias towards particular users (i.e. users located in outer cells).

¹SPPP provides a model that is described by the density of points in an area. The number of points in a given area is a Poisson random variable, determined by the density and the area size [137].

Table 5.1 Minimum distance between the nodes and UEs in homogeneous (macro-only) and heterogeneous network scenarios according to 3GPP

Minimum distance	(m)
Macro nodes Inter-Site Distance (Urban environment)	500
Macro nodes - Pico cells	≥ 75
Distance between pico cells	≥ 40
UE - macro nodes	≥ 35
UE - pico cells	> 10
UE distribution	All UEs uniformly distributed over macro area
	Percentage of UEs uniformly distributed over picocell area, remaining users over the macro cell area

Table 5.2 Relevant channel models

	Macro	LPN
Model 1	$PL(dB) = 128.1 + 37.6 \cdot \log_{10}(d)$	$PL(dB) = 140.7 + 36.7 \cdot \log_{10}(d)$
Model 2	$PLLOS(dB) = 103.4 + 24.2 \cdot \log_{10}(d)$	$PLLOS(dB) = 103.8 + 20.9 \cdot \log_{10}(d)$
Model 2	$PLNLOS(dB) = 131.1 + 42.8 \cdot \log_{10}(d)$	$PLNLOS(dB) = 145.4 + 37.5 \log_{10}(d)$

5.1.2 Antenna models

Macro cells and LPNs (picocells and small cells) use different antenna patterns. In the case of macro nodes, there are three sectors per a node. A directional antenna serves each of the sectors. In the case of LPNs, an omnidirectional antenna pattern is used. UEs also use omnidirectional antenna pattern. Antennas patterns and parameters are specified in [77].

5.1.3 The channel model

HetNet simulator is set to the carrier frequency of 2 GHz. In the case of heterogeneous networks, both the macro tier and the tier of picocells operate on the same frequency. The simulator implements path loss and log-normal shadowing, specified for macro cells and outdoor LPNs according to [77]. Two DL path loss models are implemented in the simulator. They are depicted in Table 5.2. Model 2, as illustrated by the table distinguishes between Line of Sight (LoS) and Non-Line-of-Sight (NLoS) cases. The distance in the path loss formulae are given in km. The probabilities for LoS and NLoS are calculated according

Table 5.3 Probability of LoS for macro nodes and LPNs (urban environment)

Probability for LoS Macro - UE	$0.018 \cdot \min(\frac{0.018}{d}, 1) \cdot (1 - \exp(-\frac{d}{0.063}) + \exp(-\frac{d}{.063}))$
Probability for LoS LPN - UE	$0.5 - \min(0.5, 5 \cdot \exp(-\frac{0.156}{d})) + \min(0.5, \exp(-\frac{d}{0.03}))$

to the formulae in Table 5.3. For each link, the path loss is computed as

$$PL(dB) = PL_d(dB) + X_\sigma(dB) \quad (5.1)$$

where PL_d (dB) represents a deterministic component of path loss, which depends on the distance. X_σ is a normal variable with zero mean and standard deviation $\sigma - \mathcal{N}(0, \sigma)$, representing shadow fading component in dB, which reflects variation about the mean. For macro-cells, the shadow fading deviation of 8 dB is used, while in the case of LPNs, the value of 10 dB is applied. As discussed in Chapter 4, p. 60, shadowing includes correlation between the links that originate from the same base station as different paths may encounter the same obstacles [132]. In HetNet, shadowing correlation (SC) is calculated as

$$SC = \sqrt{.5} \cdot Z_n + \sqrt{.5} \cdot Z_l \quad (5.2)$$

where Z_n and Z_l represent Gaussian random variables $\mathcal{N}(0, \sigma)$. They are associated with the location of users and nodes - macro base station and LPNs.

5.1.4 Traffic model

System level simulators typically use two types of traffic models for best-effort traffic: full-buffer and File Transfer Protocol (FTP) traffic model [77]. The full buffer traffic model envisages continuous transmission, whereas with FTP traffic model users arrive in the cell and download/upload files of the specified size. Users arrivals are characterised according to Poisson distribution.

In the simulator, the full buffer traffic model is supported in all the scenarios.

5.1.5 Radio resource management

Radio resource management is responsible for efficient utilisation of radio resources. It encompasses aspects such as admission control, load balancing, frequency reuse schemes and scheduling algorithms. The simulator supports different frequency reuse schemes, which determine the assignment of frequency resources in the spatial domain. It also supports different scheduling algorithms. Only frequency reuse scheme 1 is considered in this thesis, which means that all the available bandwidth is used throughout the cell. Furthermore, of particular relevance are the scheduling algorithms, as they determine how radio resources

(resource blocks) are allocated within the transmission interval². Below is a brief description of the relevant scheduling algorithms as implemented in the simulator.

5.1.5.1 RR algorithm

RR algorithm allocates resource blocks to the users, regardless of their channel quality. The algorithm assigns each user a given number of resource blocks, which is a function of the total number of available resource blocks i.e. $N_{totalRBs}$ and the number of users at a particular transmission interval. The number of users at each transmission interval N_{uesTTI} is determined as a minimum between the total number of users in a cell and the maximum number of users that can be served in a transmission interval i.e. $N_{uesTTI} = \min(N_{users}, N_{usersTTI})$. The algorithm works in a circular way; consequently, all users are scheduled either in the current transmission interval or one of the subsequent intervals. Considering that $N_{totalRBs}$ is not necessarily a multiple of N_{uesTTI} , the users that are given an additional resource block are randomly chosen among the users allocated in the current allocation round.

5.1.5.2 PF algorithm

PF algorithm allocates resources that take into account two competing criteria - namely, fairness and the channel quality. Different from the RR algorithm, and as previously noted in Chapter 2, p.37, PF provides a trade-off between the users instantaneous conditions and their past throughput.

HetNet simulator implements two metrics considered with the PF scheduler:

- The past user throughput on a resource block is given as:

$$R_i(t) = (1 - \alpha) \cdot r_i[t - 1] + \alpha \cdot r_i[t] \quad (5.3)$$

where t is the discrete time, or a transmission interval, $r_i[t]$ is the actual throughput experienced by user i at time t , and α is the coefficient that measures the importance of the previous throughput.

- The second metric takes into account channel quality through an estimated user throughput in the next scheduling interval $\hat{r}_{i,l}(t + 1)$ on each resource block:

$$MT_i(t) = \max_i \frac{\hat{r}_i[t + 1]}{R_i[t]} \quad (5.4)$$

²In LTE, this is referred to as Transmission Time Interval (TTI) and as mentioned in Chapter 4, it is 1 ms long.

Consequently, the algorithm computes the matrix containing the value of MT , for each user on each resource block. The user with the highest value of MT on each resource block is the user to be scheduled by the cell.

5.1.6 Link-level model

System level simulations typically rely on the simplified link-level models, as it is practically infeasible to simulate the link and system level simultaneously. However, the simplified link-layer models also need to be accurate enough to reflect on a radio link performance. Therefore, system level simulators normally include link measurement and link performance models [139]. Link measurement measures the quality of the link and takes into account:

- network layout
- channel and antenna models
- shadow fading
- small-scale fading
- frequency reuse
- power-allocation
- scheduling algorithms and
- other (PHY layer) parameters.

Based on the measurement model, a link performance model provides performance metrics. Link performance models for multi-carrier systems with fast resource scheduling and link adaptation, such as LTE-based systems, typically use a mapping function to obtain and calculate the so-called effective SINR. The effective SINR can account for instantaneous channel and interference conditions on a set of sub-carriers. It also accounts for multiple antennas at transmitters and receivers, together with spatial processing techniques, such as beamforming [139]. Look-up tables, obtained from the Additive White Gaussian Noise (AWGN)³ link-level simulations, are then used to map effective SINR to the expected Block Error Rate (BLER) for the purpose of system performance evaluation. The link-layer mapping functions and look-up-tables make the link-to-system interface.

HetNet simulator addresses previously discussed supported scenarios, channel models and radio resource management techniques. It is, therefore, particularly suited for evaluation of coverage, SINR statistics and throughput. However, it does not implement link-to-system

³AWGN channel is the channel impaired by the influence of thermal noise in the receiver and is normally used as a baseline in evaluating the the link performance [131]

interface. Instead, it uses modified, upper-bounded Shannon formula for spectral efficiency (or normalised throughput), according to [135]. It also takes into account the guard band and guard-time for LTE systems in frequency and time domains respectively. The formula also takes into account the implementation loss in SINR due to finite code length. These aspects are not discussed further in this chapter. Chapter 7, subsection 7.2.5.2, p. 116 provides more details on how some of them are incorporated into the framework.

5.2 HetNet+

The primary goal with HetNet+ is to enable system level simulations with additional frequency carriers on the DL in the CBB architecture, while relying on the existing supported scenarios, functions and classes of HetNet. The following subsections describe additional scenarios, initialisation of cells and users, and the channel model introduced in HetNet+.

5.2.1 Supported scenarios

HetNet+ supports simulations of two different types of topologies - homogeneous and heterogeneous network topology. In homogeneous networks, a tier of macro cells deployed on a hexagonal grid employs different carriers and is denoted Scenario *f*, Fig. 5.2. However, as discussed in Chapters 1 and 2, future deployments are expected to feature a mixture of topologies with equally-spaced macro nodes and irregularly spaced LPNs [4]. For that reason, of particular interest to the thesis are deployments with a macro tier and a tier of LPNs that each employs different carrier. Therefore, HetNet+ introduces Scenario *g*, where a fixed number of LPNs is distributed across a hexagonal macro grid area, using uniform distribution. This scenario is the primary focus of the analysis for the CBB architecture.

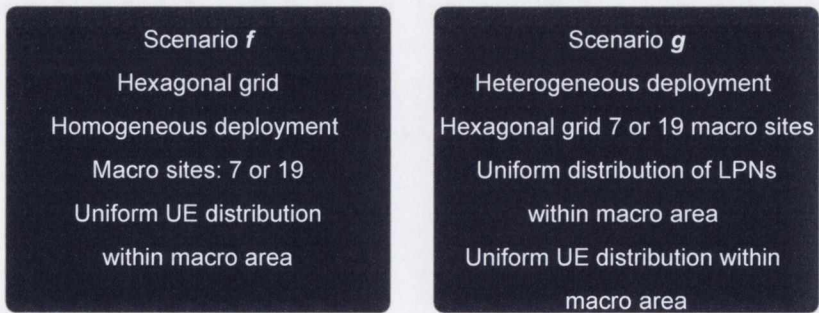


Fig. 5.2 Additional scenarios in HetNet+

5.2.2 Main simulation flow

Fig. 5.3 depicts the main flow in HetNet+, where red shaded boxes depict functions associated with the principal carrier, whereas navy shaded boxes indicate those related to the additional, ancillary carriers. All shaded boxes represent extended modules/features. Clearly, additional, that is ancillary carriers, are treated as extra cells and for each carrier, the cell initialisation is performed separately. Cells may employ different channel models, which facilitates the use of a wide range of frequencies. Regarding protocol structure, as Fig. 5.4 illustrates,

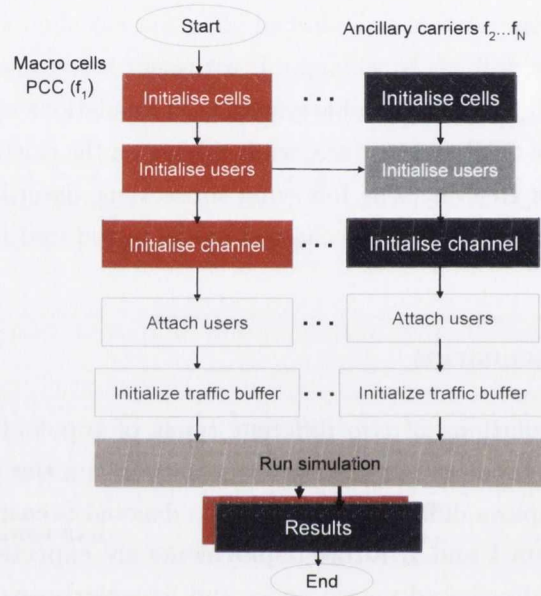


Fig. 5.3 High-level overview of the main HetNet+ flow

additional carriers are activated on Layer 3. EO spectrum is always set as PCC for all users. All other carriers are additional carriers and can be used, depending on the user capability. Layer 2 uses (existing) scheduling algorithms to schedule users on resource blocks that now belong to different frequency carriers. Link layer deals with the link measurement, according to the specified deployment, channel model and scheduling technique. Performance is considered for each link separately. Each user capable of Carrier Aggregation can avail of a wider transmission bandwidth. Retransmissions are not implemented, which is also the case with HetNet simulator.

5.2.3 Initialisation of ancillary cells

Additional that is ancillary frequency carriers are new cells in the simulator. The principal carrier on frequency f_1 is used as a primary carrier for all users and should always be employed on macro cells. At the same time, the total number of carriers is fixed in the *configFile*. Also, a separate configuration file *additionalConfigFile* is created, which contains



Fig. 5.4 HetNet+ uses existing link models and scheduling algorithms

all the parameters of a particular carrier, such as power, bandwidth, antenna gain and others. This approach allows flexibility in setting different attributes to different carriers, as depicted by Fig. 5.5. In case where a homogeneous macro-tier only (Scenario *f*) is of interest, the

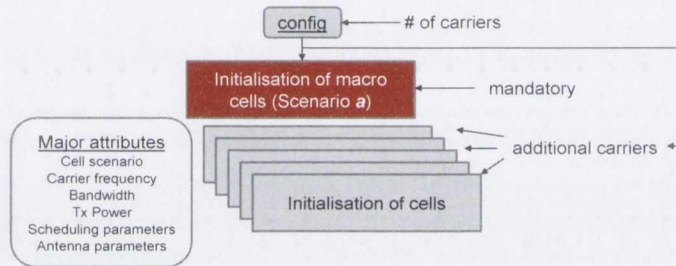


Fig. 5.5 The introduction of ancillary carriers is analogous to the activation of secondary carriers as defined in LTE-Advanced. All major attributes are set separately per a carrier.

cells on the additional carriers are initialised using function *initializeMacroHomogScenario()*.

5.2.4 Initialisation of users

The distribution of users is set to uniform across the macro cell area. All users connect to frequency f_1 . To simulate a scenario where users have different Carrier Aggregation capabilities, parameter *additionalConfig.percentage* determines a percentage of users that have the capability to connect to a particular frequency. Users without Carrier Aggregation capability are randomly selected using new function *initializeUsersMultipleFreq*. The distance between the users and all the nodes is as per the values outlined in Table 5.1, according to [77].

5.2.5 Extended Hata channel model

One of the main additions to HetNet simulator is the new channel model. Namely, HetNet simulator uses formulae based on empirical values, according to [77], obtained for the

Table 5.4 Extended Hata path loss formulae

Distance (km)	d	Environment	Frequency f (MHz)	Median Path Loss PL (dB)
$d < 0.04$				$PL = 32.4 + 20 \cdot \log(f) + 10 \cdot \log(d^2 + (H_b - H_{ue})^2/10^6)$
$d > 0.1$		Urban	$30 < f \leq 150$	$PL = 69.6 + 26.2 \cdot \log(150) - 20 \cdot \log(150/f) - 13.82 \cdot \log(c) + (44.9 - 6.55 \cdot \log(c)) \cdot \log(d)^\alpha - a(H_{ue}) - b(H_b)$
$d > 0.1$		Urban	$150 < f \leq 1500$	$PL = 69.6 + 26.2 \cdot \log(f) - 13.82 \cdot \log(c) + (44.9 - 6.55 \cdot \log(c)) \cdot \log(d)^\alpha - a(H_{ue}) - b(H_b)$
$d > 0.1$		Urban	$1500 < f \leq 2000$	$PL = 46.3 + 33.9 \cdot \log(f) - 13.82 \cdot \log(c) + (44.9 - 6.55 \cdot \log(c)) \cdot \log(d)^\alpha - a(H_{ue}) - b(H_b)$
$d > 0.1$		Urban	$2000 < f \leq 3000$	$PL = 46.3 + 33.9 \cdot \log(2000) + 10 \cdot \log(f/2000) - 13.82 \cdot \log(c) + (44.9 - 6.55 \cdot \log(c)) \cdot \log(d)^\alpha - a(H_{ue}) - b(H_b)$
$0.04 < d < 0.1$				$PL = PL(0.04) + [(\log(d) - \log(0.04)) / .3979] \cdot [PL(0.1) - PL(0.04)]$

operation at 2 GHz. To cover a range of frequencies of interest, the Extended Hata model for frequencies 30 MHz - 3 GHz is introduced. It is an empirical model, based on the original Okumura model, initially developed for Non-Line-Of-Sight (NLOS) paths in the urban environments typical of mobile services. In practice, it is suitable for distances up to 40 km. For distances $d < 40\text{m}$, this model uses free-space path loss formula. Extended Hata formulae are used for distances $d > 100\text{m}$, whereas for the distances in-between the two values, interpolation between these two models is used. Although Extended Hata model is primarily suited for transmitter heights found in deployments with macro cells, it is selected as one of most widely-available channel modes. Furthermore, as stated above, it covers a range of frequencies of interest.

In the simulator, the Extended Hata model with standard deviation, as implemented in [140] is used⁴. Table 5.4 depicts Extended Hata path loss formulae, where

⁴The module is dated April 2011, and it is the same one used in the simulation tools by ECC, except for the calculation of standard deviation. To remind the reader, the ECC is European agency that undertakes activities and develops policies, according to the European and international legislations.

$$a(H_{ue}) = (1.1 \cdot \log(f) - 0.7) \cdot \min(10, H_{ue}) - 0.76 + \max(0, 20 \cdot \log(H_{ue}/10))$$

$$b(H_b) = \min(0, 20 \cdot \log(H_b/30)).$$

Here, H_{ue} and H_b represent heights of the UE and the base station, respectively, and $c = \max(H_b, 30)$. Standard deviation follows the recommendation from [140].

5.2.6 Radio Resource Management

All existing static spectrum reuse schemes can be used in all Carrier Aggregation configurations. The focus of the thesis is on the frequency reuse 1 only.

5.2.6.1 Scheduling algorithms

As discussed in Chapter 2, scheduling in Carrier Aggregation systems can be performed separately - per a component carrier, or using cross-carrier scheduling, see for example [97], [101] and discussion in Chapter 2, p. 37. In the simulator, RR and PF schedulers continue to be used in the extended version of the simulator as they are. The allocation of resource blocks is then performed separately on each of the carriers.

5.3 Summary

This chapter describes key aspects of HetNet simulator and its extension HetNet+, selected as one of the main tools for modelling the framework. HetNet+ is built in a way to preserve the main structure, and reuse as much as possible classes, functions and modules of HetNet simulator. HetNet+ is extended to support the CBB architecture, where macro-tier is used as a basis and operates using the principal carrier. The users are distributed uniformly across macro cell area and attach to the additional cells that provide the strongest signal. The ancillary cells may operate at a macro tier or tier of LPNs. The existing scheduling algorithms enable scheduling of users within each carrier. The simulator also introduces extensively used Extended-Hata channel model that covers a range of frequencies of interest. Particularly, the Matlab module developed by Ofcom is used as the implementation of the Extended Hata model. With all the essential elements of the framework in place, the next chapter turns to the evaluation of the proposed framework. The focus is on the CBB architecture in heterogeneous network setup using two spectrum sharing models as illustrative examples for the framework - TV White Spaces and LSA.

Chapter 6

CBB Architecture Analysis

Chapter 4 considered the macro topology tier only and focused on characterising different aspects of shared spectrum bands. This chapter examines the sharing framework for the CBB architecture, using Carrier Aggregation. The QoS is defined, and the chapter analyses how the combination of EO, ES and CS spectrum can deliver specific QoS for different densities of RRHs and the network load. The chapter begins by reminding the reader of the main characteristics of the CBB architecture. Section 6.2 defines the overall scenario, including shared spectrum attributes. This section also presents selection criteria that incorporates the methodology for the QoS metric computation. Section 6.3 presents the results and analysis. Section 6.4 includes the discussion on related work while Section 6.5 concludes the chapter.

6.1 A brief reminder of the CBB architecture

In the CBB architecture, LPNs are RRHs, and the baseband processing is performed centrally. Consequently, as discussed in Chapter 2, subsection 2.2.1, 27, the CBB architecture requires strict adherence to stringent requirements on throughput, delay and jitter. With heterogeneous networks, this means that the spectral resources from both tiers - macro and the tier of RRHs are aggregated to provide wider transmission bandwidths using Carrier Aggregation mechanism. In Carrier Aggregation, for each user, there is a designated primary carrier responsible for essential functionality, including maintaining the signalling connection to the core network. Other component carriers are secondary carriers and are added as extra resources using dedicated signalling. Each carrier is configured separately with regard to transmission parameters, such as power, modulation and coding, and the number of transmission layers. The multiplexing of data is done on a MAC sublayer, as depicted in Fig. 2.5, p. 34. Also, for all carriers, there is a single scheduler, which can e.g. optimise radio resource allocation taking into account channel state for users across different carriers. The scheduler can also assign resources to the users according to the metrics calculated for each carrier separately.

6.2 The framework

6.2.1 Topology

In this chapter, a heterogeneous network with two tiers and centralised baseband processing is considered. The two tiers comprise of a macro and a tier of RRHs. According to the proposed framework, the principal carrier is EO carrier that operates on the macro layer. The tier of RRHs employs shared, CS and ES carriers. Fig. 6.1 depicts the topology of the scenario featuring randomly distributed RRHs. Users are also distributed randomly over the (macro) cell area, following the constraints on the minimum distance to macro nodes and RRHs according to [77].

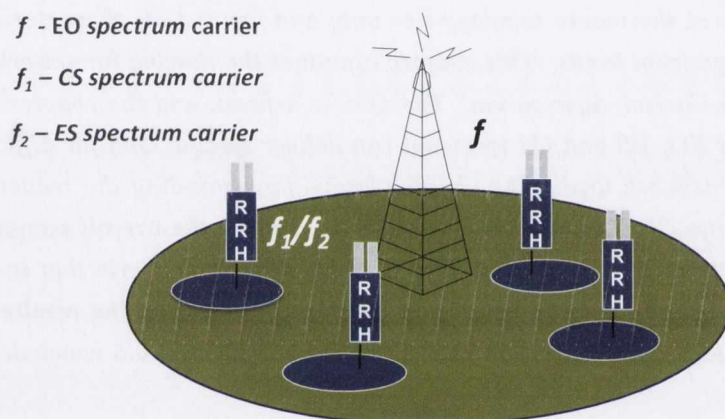


Fig. 6.1 Deployment scenario considered in this chapter, with different RRH densities. RRHs employ shared carriers. Users are distributed throughout the macro cell area.

6.2.2 Spectrum characterisation

The analysis in this chapter considers three spectrum bands. The 2 GHz band is adopted for the EO band, as it is typically used by the cellular operators for LTE systems. It is also the frequency carrier used in [77] for LTE system level simulations. For the shared spectrum, in principle, any band could be selected. This chapter draws on spectrum bands that have commonalities with the ES and CS classes. Given that, the LSA band at 2.3 GHz is adopted as the ES band, whereas the TV White Spaces is used as the CS band. Hence, apart from serving as realistic examples of the shared spectrum bands, they also provide a mix of spectrum resources with different propagation characteristics, which adds to the richness of the analysis.

To remind the reader, LSA is a spectrum sharing framework developed on the European level, currently targeting 2.3-2.4 GHz band [62]. The LSA framework features the

LSA Repository, which is a database containing the information on spectrum opportunities, and the LSA Controller, which controls the access to spectrum in frequency, spatial and time domains. The LSA spectrum band features two sharing entities - an incumbent and a sharing licensee, typically a cellular operator. The transmission is binary by definition - either the incumbent or the cellular operator is permitted to operate in the specified frequency-location-time area. Hence, once an operator becomes an LSA licensee in the specified frequency-location-time area, it has the exclusivity of operation, as it was operating in its own band, but has to adhere to the agreed transmission parameters such as transmit power, transmission mask or spurious emissions [66]. On the other hand, TV White Spaces is a well-defined and documented spectrum sharing model, proposed in Europe and the US. In Europe, it incorporates the UHF TV band at 470-790 MHz [47], and in the US, it is the band at 470-698 MHz [46]. Both, FCC and CEPT/Ofcom documentation provide detailed descriptions of the model, see [46] and [47]. A geo-location database provides access to spectrum, ensuring interference protection for the incumbents - the DTT users and PMSE. The database provides the information on the available channels, and transmission parameters such as maximum emissions, out-of-band emissions, time validity and other parameters [46], [47], [48].

6.2.2.1 Availability & cost of shared bands

In this chapter, and as discussed in Chapter 4, subsection 4.1.2, p. 58, the analysis in the thesis considers that the ES band is available to the operator for a specified period. It should be noted that in the case of LSA, the availability of LSA spectrum is not guaranteed, as a cellular operator may be requested to vacate the band due to the appearance of the incumbent. The cellular operator may then be reassigned another LSA channel, if available, or may have to wait until the incumbent leaves the band. These aspects are not considered in the thesis. As per the CS spectrum, in this chapter, a geo-location database signals the availability of the band. Hence, the CS spectrum availability can be considered in binary terms - the band is available or not. In this chapter, only the case when the CS band is available is considered.

Cost of shared bands In line with the proposed sharing framework, the use of the ES band comes at a cost, which is directly proportional to the required bandwidth. The CS band is free.

6.2.2.2 Power levels

The permitted power levels are different for the ES and CS bands, as described below.

ES band In the ES band, the cellular operator has the flexibility in operating in a low or a high-power regime. Since of interest here are the LPNs, only the low-power operation is analysed. The power level is selected to be at a top range of a typical LPN¹.

CS band In the CS band, the power is not fixed and permitted power level setting depends on whether it is the FCC or CEPT/Ofcom model that is adhered to. This chapter follows the CEPT/Ofcom model; explicitly the recommendations by Ofcom for the protection of DTT service, as outlined in [48]². The CEPT/Ofcom TV White Spaces model allows power to be scaled upwards and downwards, depending on the spatial and frequency distance of a TV WSD from the DTT receivers at a TV coverage edge. On the other hand, in the FCC model, for a co-channel and adjacent channel operation outside the separation distance that is calculated based on the antenna height and other parameters, a TV WSD may emit at maximum power for a given device type. Below, a summary of calculations of the permitted power levels for the DTT service protection, according to [48] and [47], is presented.

Power levels in TV White Spaces The emission limits for a TV WSD operating on a particular channel are calculated based on the quality of DTT coverage and a TV WSD location. The calculations are based on *location probability*, which is the probability of a successful TV reception. It is a metric used for planning of DTT networks and is typically calculated on a pixel-based grid for every 100 m by 100 m pixel. It reflects the useful DTT signal level compared to power levels of DTT interferers. Hence, *location probability* for a DTT receiver, in the case where no TV WSD operates, is calculated as:

$$q_1 = Pr\{P_s \geq P_{s,min} + \sum_{k=1}^K r_{U,k} P_{U,k}\} \quad (6.1)$$

Eq. (6.1) is given in a linear domain. Here, P_s is the received power of the wanted DTT signal, $P_{s,min}$ is the reference receiver sensitivity level, $P_{U,k}$ is the power of k-th unwanted DTT signal, and $r_{U,k}$ is the protection ratio for k-th DTT-DTT signal, which depends on the frequency offset between a DTT interferer and a DTT victim [48], [47]. It should be noted that according to [48], a pixel is considered served by DTT if $q_1 \geq 0.7$, hence for $q_1 = 0.7$, the pixel is at the edge of DTT coverage. By allowing TV WSDs to transmit, there is a degradation in the location probability, which then becomes

$$q_2 = Pr\{P_s \geq P_{s,min} + \sum_{k=1}^K r_{U,k} P_{U,k} + r(\Delta f) \times G \times P_{IB}^{WSD}\} \quad (6.2)$$

¹The power is set to 5 W - see for example [141] for a range of power levels found with LPNs.

²Calculations relating to the PMSE service protection are also detailed in [47], as well as in [48]. They are, however, not considered in this chapter.

Here, $r(\Delta f)$ is the protection ratio of a DTT receiver for a given frequency offset between the TV WSD and DTT receiver, G represents the coupling gain between a TV WSD location and a DTT receiver, and P_{IB}^{WSD} is the maximum permitted emission of a TV WSD³. The permitted power levels for TV WSD on each channel, therefore, depend on the acceptable degradation of DTT coverage quality, given the DTT receiver sensitivity and the spatial and frequency separation between the TV WSD and DTT receivers⁴. The worst case for the WSD power levels occurs when TV WSD and DTT receivers are located in the same pixel, as this is the case when the coupling gain is highest. It is referred to as a reference geometry [48].

Finally, it should be noted that the above calculations for TV WSD power limits assume a single TV WSD device per a pixel in a given channel. In [47], in cases where multiple TV WSDs operate on the same frequency, or frequency that has the same potential in terms of interference to the DTT receivers, the reduction of power by a value of fixed parameter i.e. *interference margin* is suggested. Interference margin, therefore, takes into account the aggregate interference from multiple TV WSDs operating in a given area at the same time. The value of interference margin is calculated as $10 \cdot \log(N)$, where N may be based on the number of potential or active TV WSDs [52]. Consequently, in [47], a fixed value for interference margin of 3 – 6 dB is noted, allowing for 2 – 4 multiple interferers, respectively. In addition to the two outlined options for calculating the interference margin, the third option in [52] aims to minimise its value by taking into account the actual power at which TV WSDs emit. Hence, in this case, there is no unnecessary restriction on the power of TV WSDs. However, this option adds to the computational complexity. In [48] few possible approaches as to how to deal with the interference from multiple TV WSDs are also discussed. They include a direct reduction in the permitted power levels and a rule-based reduction, which in a geo-location database would relate the maximum allowed power to the number of TV WSDs that can transmit in a given area/channel.

This work. Returning to the subject of power in the CS band in this chapter, firstly note that a TV WSD here is represented by an RRH, operating on a TV WS channel. For the purpose of further analysis, the maximum and minimum power levels are taken from the illustrative examples when a TV WSD and the DTT receivers are located in the same or immediate adjacent pixels, and where the location probability exceeds 0.7 [48]. The illustrative minimum and maximum⁵ emission level examples in [48] refer to the first

³The coupling gain depends on the distance between a TV WSD transmitter and a DTT receiver i.e. the path loss, as well as on the antenna gain and angular and polarisation discrimination [48], [142]. Maximum emission refers to EIRP.

⁴It should be noted that coupling gain cannot be precisely calculated based on the actual separation between the WSD and DTT receivers, since the exact location of DTT receivers is not known.

⁵It should be noted that Ofcom has preserved this cap on the maximum permissible WSD power in its latest statement [9].

adjacent channels to the DTT transmitting channel⁶. In this work, the power scaling is applied to reflect the possibility of multiple entities operating in the same channel. They are referred to as "foreign" entities. Hence, the following cases are considered:

- *No power sharing with "foreign" entities.* This is the case when each RRH can use all the available power, allocated to it by the geo-location database. The power level depends on the DTT coverage quality, as depicted by Table 6.1.
- *Sharing power with other, "foreign" entities.* In this case, there is a number of other entities sharing the spectrum with the operator's RRHs. A number of power levels are considered to reflect a broad range of a number of "foreign" entities. Power scaling is applied as a reduction from the maximum and minimum levels that correspond to good and poor DTT service areas, see Table 6.1.

	No "foreign" entities (no power scaling)	Sharing with "foreign" entities (power scaling applied)
Good DTT service area (Maximum considered emission)	✓	✓
Poor DTT service area (Minimum considered emission)	✓	✓

Table 6.1 All power options are considered in the CS band.

6.2.2.3 Path loss

As discussed in Chapter 4, subsection 4.1.5, 60, one of the most important aspects of spectrum characterisation is evaluating quality of spectrum through the SINR distribution. Evidently, the SINR distribution of a random user is affected by the received power levels, noise and interference levels. Besides the dependence on the transmitted power levels, the received power is also affected by the path loss, including log-normal shadowing. Path loss can be notably different when CS and ES channels lie in spectrum bands that are wide apart, as is the case in this analysis, with the CS band operating at 626 MHz and ES band at 2.3 GHz - see Fig. 6.2. As can be seen from the figure, the path loss between these bands differs between 11 and 18 dB across a range of distances seen typically in urban deployments. Path loss is calculated using the Extended Hata model in both cases.

⁶In a given example, the DTT channel is 40. In this chapter, channel 40 is adopted as the TV WS channel, that is the channel of the CS band.

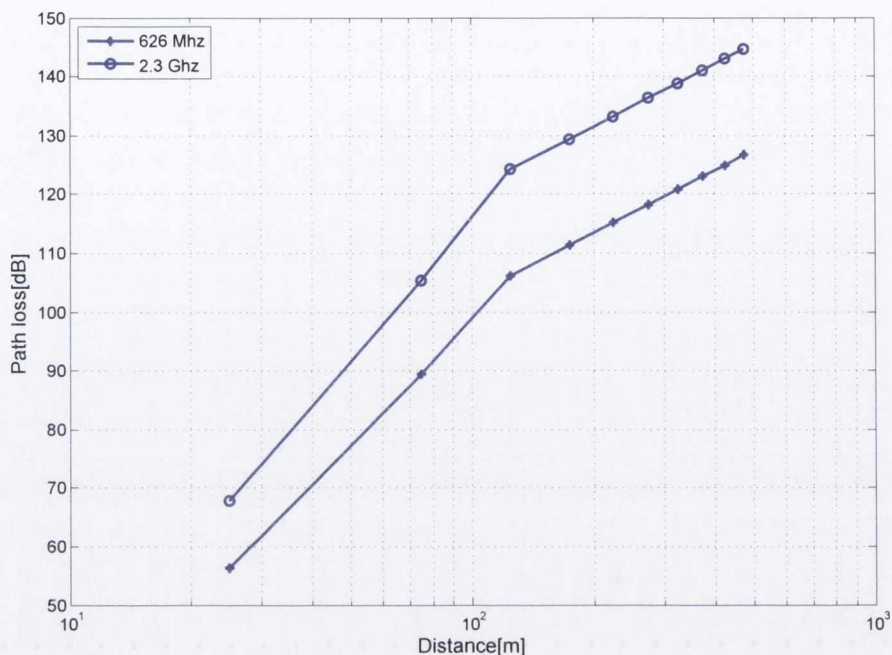


Fig. 6.2 Path loss in urban environment with Extended Hata model (transmitter height of 5 meters).

6.2.2.4 Interference

Also discussed in Chapter 4 is interference - see subsection 4.1.3, p. 59. Two types of co-channel interference may occur in the considered spectrum bands in this analysis. They are inter-system and intra-system interference. Intra-system interference occurs between operator's neighbouring nodes on each tier. Hence, intra-system interference is considered in all bands - EO, ES and CS. Inter-system interference occurs in the CS band only, as other networks can also use its free spectrum resources. However, this chapter does not deal with inter-system interference. The interference by "foreign" networks/entities is included in the analysis of the CS band in the next chapter (Chapter 7).

6.2.2.5 Bandwidth

In the UHF TV band in Europe, the channel width is 8 MHz. Hence, in this chapter, this is the channel width adopted for the CS band⁷. In the ES band, it is envisaged that spectrum is accessed using channels of a particular width. The adopted nominal channel width is 5 MHz, which follows the channel width of the LSA-designated LTE band 40 at 2.3 – 2.4 GHz. There, only the channel widths that are multiples of 5 MHz are supported [66]. Hence, in

⁷ Although LTE does not include support for 8-MHz wide channels, an 8-MHz channel could be obtained by aggregating contiguous 3 and 5 MHz channels.

this analysis, the channels that are multiples of 5 MHz are considered - e.g. 5, 10, 15, .. MHz. Note that, in certain cases, it may not be possible to provide large contiguous chunks of spectrum, e.g. 20 MHz. Therefore, in these instances, it would be required that instead of one e.g. 20 MHz carrier, the cellular operator uses spectrum resources from e.g. two 10 MHz carriers. This would require support for non-contiguous Carrier Aggregation in transmitters and receivers. Also, the total number of carriers should also be taken into consideration, as it should not exceed the supported number of component carriers⁸.

6.2.3 Selection criteria for spectrum requirement decision

The objective criterion in this framework is about minimising the cost for a cellular operator, which is a linear function of the amount of spectrum required from the ES band. Hence, minimising the cost to the operator translates into minimising the bandwidth from the ES spectrum the cellular operator resorts to. At the same time, the aim is to provide certain QoS for the users and hence, the operator needs to adhere to the constraints posed by the QoS requirements. The QoS metric may include e.g. peak data rate, which is the data rate experienced in good radio conditions when no other users utilise the radio resources [71]. Of interest, however, here are the cases when users experience different channel conditions, but also share the radio resources with other users. This data rate, calculated above the MAC layer is typically referred to as user throughput [71]. Note that within this chapter, the user throughput is calculated as explained in the following subsection and takes into account some aspects of the link-level overheads, but it does not include any overhead above the MAC layer. The throughput calculations will be further discussed in Chapter 7, subsection 7.2.5.2, 116. Also, note that the terms rate and throughput are interchangeably used.

For calculation of spectrum requirement from the ES band in this chapter, the conventional QoS metrics is considered - the 50%-ile and lowest 5%-ile throughput of a user. In this chapter, a user refers to an average user that can take any position within a macro cell while adhering to the distance constraints to all types of nodes. Hence, the median throughput represents a median throughput user experiences across all carriers. Accordingly, a cell-edge throughput is a cell-edge throughput across all carriers. This can be written as

$$R_k + R_{1,k} + R_{2,k} \geq R_{th,k} \quad (6.3)$$

where $k \in m, e$ denotes whether the equation refers to the median or cell-edge values. R_k , $R_{1,k}$, and $R_{2,k}$ refer to median or cell-edge user rate in the EO, CS and ES bands, respectively, whereas $R_{th,k}$ is the target median or cell-edge user throughput.

⁸The number of CCs currently supported by the 3GPP standard is 5 [89]. Future releases are expected to support up to 32 carriers [143].

Hence, if the CS band cannot meet the target QoS requirements, the cellular operator also resorts to the ES band. Pictorial representation of this concept is given in Fig. 6.3.

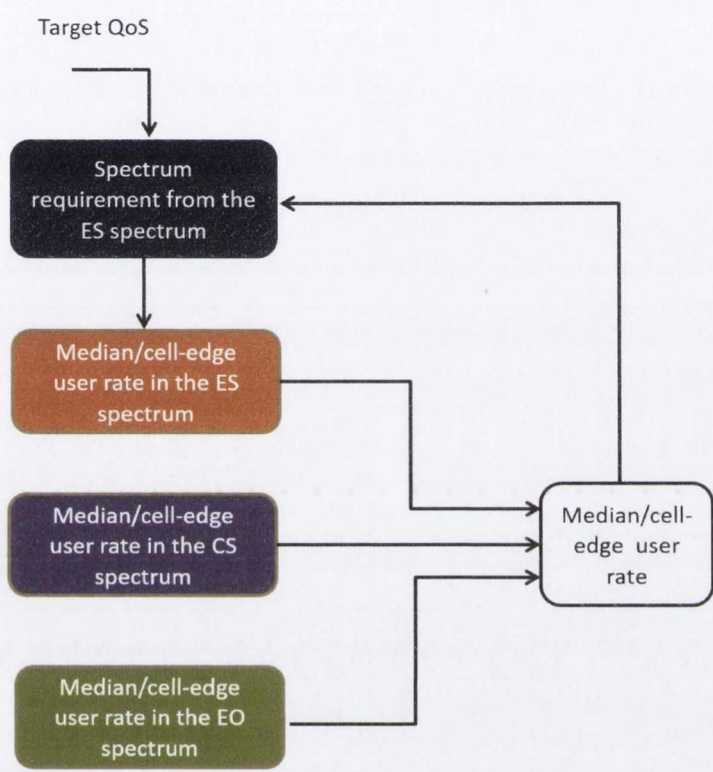


Fig. 6.3 Median and cell-edge user throughput across all spectrum bands determine the requirement from the ES spectrum.

6.2.3.1 Link rate computation

Link rates on each carrier are affected by the number of resource blocks allocated to each user and by the spectral efficiency (normalised throughput). The bandwidth allocated to a user depends on the total number of users and the scheduling scheme. Per-a-carrier PF algorithm, described in Chapter 5, is used for allocation of resource blocks in each of the spectrum bands and takes into account fairness and channel conditions within each frequency carrier. The spectral efficiency is determined by the SINR levels and is calculated according to the modified Shannon formula [135]. The SINR levels are affected by the transmit power levels, path loss, antenna gains, log-normal shadowing, noise, and the inter-cell interference.

The SINR of random user u , on cell i on any carrier, is calculated as:

$$SINR_{u,i} = \frac{P_{tx} \cdot L_{i,u}}{N_{th} + \sum_{\substack{j=1 \\ j \neq i}}^N P_{tx} \cdot L_{j,u}} \quad (6.4)$$

where

- P_{tx} - transmit power (assumes that all cells use the same transmit power)
- $L_{i,u}$ - path loss (including log-normal shadowing) and antenna gains on the link between serving cell i and user u
- N_{th} - thermal noise
- $L_{j,u}$ - path loss (including log-normal shadowing) and antenna gains on the interfering link between cell j and user u
- N - total number of cells per a tier, which operates on a particular frequency carrier.

6.2.4 Outline of the model

Given all of the above-discussed aspects, the model can be summarised in the following way:

- The scenario considered herein is a case of a heterogeneous network with the CBB architecture in an urban environment. HetNet+ simulator is used for modelling the framework, i.e. what is defined in Chapter 5 as *Scenario g*. Namely, macro cells are placed on a hexagonal grid, whereas RRHs are deployed uniformly across the macro cell area. Different density of RRHs per macro is considered.
- The EO band operates at frequency f on a macro tier. CS and ES bands operate at frequencies f_1 and f_2 , respectively. They are both employed by the tier of RRHs.
- The distribution of users is uniform, with the constraints on the minimum distance to macro cells and RRH, according to [77]. All users support aggregation across all carriers.
- Performance is evaluated in terms of median and cell-edge user throughput, across all carriers. A number of parameters affect the performance. A range of values is considered for RRH density, the number of users in the macro cell area and power levels in the CS band.

Power levels Power in the CS band is considered using the illustrative minimum and maximum power for TV WSDs, according to [48]. Furthermore, power levels are reduced for a range of values to reflect the case when the CS band is shared with a

different number of "foreign" entities, as discussed in subsection 6.2.2.2, 86. Hence, the cases when only operator's RRH operate on a given channel, as well as the cases when "foreign" entities are present on the channel are considered. In areas with good DTT service, maximum emission levels can be applied, whereas in the areas with poor DTT service (at the edge of DTT signal coverage), RRHs can only emit at low levels. In these cases, the EIRP levels should not exceed the selected value, which is 11 dBm, as DTT receivers cannot sustain additional levels of interference from TV WSDs⁹. Table 6.1 depicts power options in the CS band. In the EO band, a typical transmit power is considered [77]. In the ES band, the power level is set at a top value found typically with LPNs.

- The targets for median and cell-edge user throughput are selected to depict the spectrum requirements. The chosen values are in broad alignment with the gains seen in Carrier Aggregation systems, such as [97] and [101].
- In the ES spectrum, the spectrum requirement is computed to ensure the median/cell edge throughput, calculated according to the above meets the target rates. Only multiples of 5 MHz channels are considered.
- Finally, the effects of reducing the target throughput on spectrum requirement from the ES band are also analysed.

6.2.5 Input parameters

This subsection outlines the values of the main parameters used in this work.

6.2.5.1 Parameters applicable to all bands

Table 6.2 lists the parameters common to all bands.

6.2.5.2 EO and ES band parameters

Tables 6.3 and 6.4 depict other main parameters used for the EO and ES bands, respectively.

6.2.5.3 CS band parameters

For the CS band, Table 6.5 outlines the EIRP levels for the considered cases as per earlier discussion in this and subsection 6.2.2.2, 86.

⁹Ofcom also considers the edge of DTT coverage for a WSD with high out-of-block emissions, where permitted EIRP level is -7 dBm. This case is not considered.

Table 6.2 Input parameters used in all bands

Common Parameters for all bands	
Propagation model	
Channel model	Extended Hata [140]
UE antenna pattern/gain	Omnidirectional antenna / 0 dBi
Link-level model	
Link-level abstraction	Upper-bounded LTE Shannon’s capacity [135]
Traffic model	
Traffic model	Full buffer
User scheduler	
Scheduler	Individual Carrier Proportional Fair

Table 6.3 Input parameters used in the EO band

EO Spectrum	
Spectrum	50 resource blocks over 10 MHz @ 2 GHz
BS TX power	46 dBm
BS Antenna pattern/gain	Directive antenna, 3GPP model [77] / 14 dBi
Deployment Scenario	
Macro deployment - 19 sites	Urban environment, 3GPP model [77]

Table 6.4 Input parameters specific to the ES band

ES Spectrum	
Spectrum	25 resource blocks over basic unit of bandwidth of 5 MHz @ 2.31 GHz
Tx power	37 dBm
BS Antenna pattern/gain	Omnidirectional antenna, 3GPP model [77] / 5 dBi
Deployment Scenario	
RRH deployment	1, 2, 3 and 4 RRHs per macro cell

Table 6.5 Permitted EIRP levels in the CS band for different cases

	EIRP per RRH (no power scaling)	EIRP per RRH (power scaling applied)
Maximum permitted emission (good DTT service area)	36 dBm	27, 18 and 9 dBm
Minimum permitted emission (poor DTT service area)	11 dBm	9 and 5.5 dBm

Table 6.6 Other input parameters specific to the CS band

CS Spectrum	
Spectrum	40 resource blocks over 8 MHz @ 626 MHz (UHF Channel 40)
TX power (including scaling)	36, 18, 11 and 5.5 dBm
BS Antenna pattern/gain	Omnidirectional antenna / 0 dBi
Deployment Scenario	
RRH deployment	1, 2, 3 and 4 RRHs per macro cell

6.3 Results

6.3.1 CS band effects

In this subsection, the results obtained for cell-edge and median user throughput using spectrum resources in the EO and CS bands are depicted. Hence, the term throughput here refers to the combined throughput from the two bands. The performance is analysed in relation to the power levels and sharing in the power domain, according to the cases depicted in Table 6.5.

No "foreign" entities. The combined median user throughput from the EO and CS band is illustrated in Fig. 6.4 while Fig. 6.5 depicts the 5%-ile user rate. In both cases, the x-axis represents the number of users per a macro cell. Further, both figures illustrate the instances when RRHs operate at maximum EIRP of 36 dBm and minimum EIRP of 11 dBm. Firstly, it should be noted that all changes that relate to the combined user throughput come as a result of a change in the parameters of the CS band, as for a given number of users in a macro cell, the rate provided by the EO band is constant. Secondly, the throughput increase due to a higher power, given all the other parameters, is more

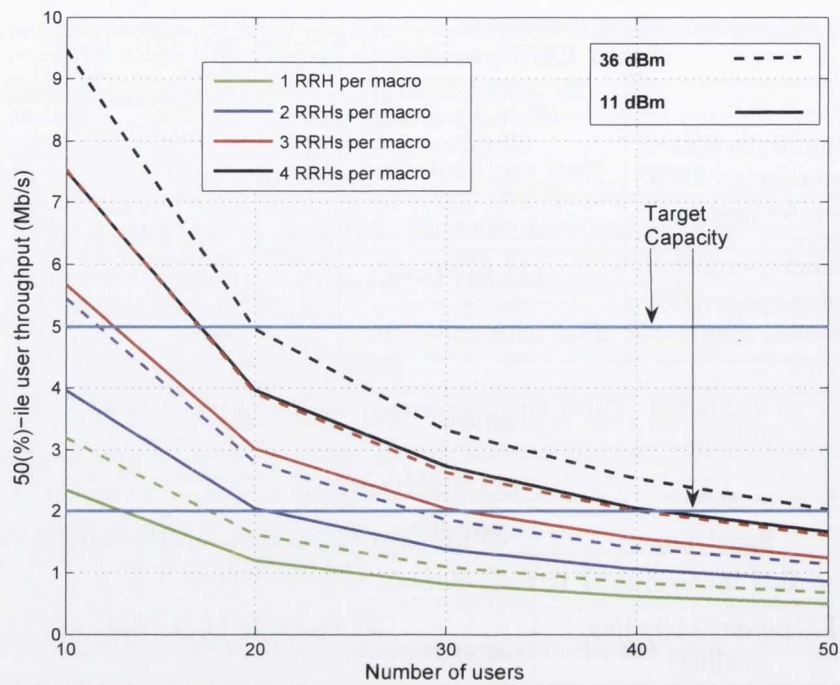


Fig. 6.4 Combined median user rate for the maximum and minimum considered power levels. There is no power sharing with other spectrum users/entities. X-axis represents the number of users per macro cell. Y-axis represents 50%-ile user throughput.

significant in the case of a lower RRH density. For example, for a single RRH per a macro cell, see Fig. 6.4, the performance improvement between poor and good DTT service area is 36%. For the case of 4 RRHs per macro, the performance gain due to a higher transmission power is 26%, given 10 users per macro cell. As the number of users increases, this trend mainly remains, but the overall performance is degraded. Hence, for the combined median user throughput in the EO and CS bands, the performance improvement when RRHs are in a good DTT service area compared to a poor DTT service area ranges approximately between 23% and 36%, depending on the RRH density and the number of users. The case for a cell-edge throughput, Fig. 6.5, follows the same trend. However, the improvement in the combined throughput due to a higher power is more significant - for one RRH per macro cell and 10 users, the improvement is 45%, whereas it is 37% for the case of 4 RRHs per macro. It is also interesting to observe the effects of the RRH density. It is evident that the increase in the number of RRHs results in a huge rise in the median and cell-edge throughput. For example, with 30 users in the cell, in a good DTT service area (with the maximum permitted power of 36 dBm), the increase in the combined median user throughput is 194%. The increase in the combined median user throughput due to higher RRH density when RRHs operate in a poor DTT service area (with minimum considered

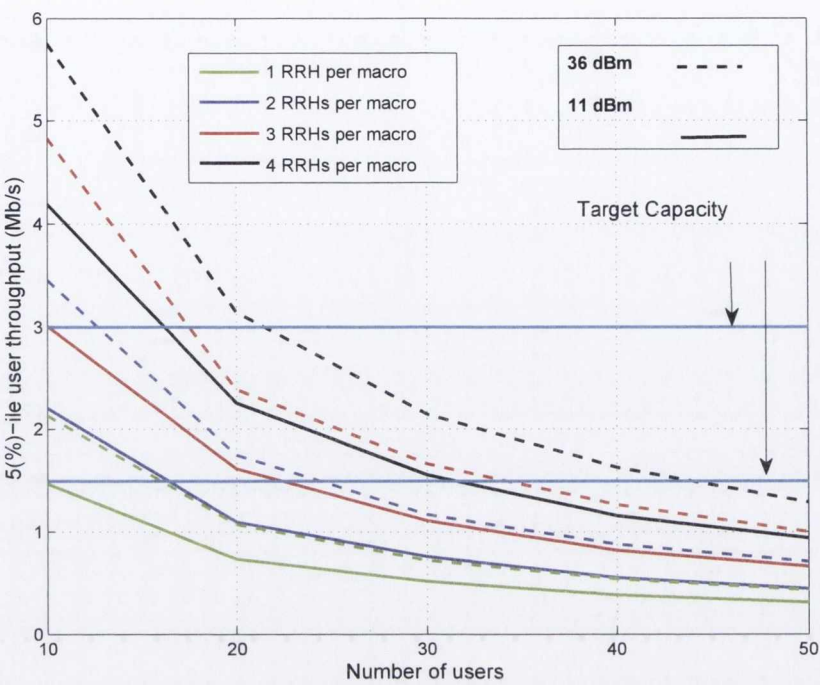


Fig. 6.5 Combined cell-edge user rate with RRH power set to the maximum and the minimum considered levels. There is no power sharing with other spectrum users/entities. X-axis represents the number of users per macro cell. Y-axis represents 5%-ile user throughput.

power of 11 dBm) is even greater - 240 %. A similar trend is observed for the combined cell-edge user throughput. With 30 users in the cell, and maximum power of 36 dBm, the increase in the combined cell-edge user throughput is 199%, whereas with the power of 11 dBm the throughput increase is 205%. The tremendous improvement in the user rate comes primarily as a result of the spatial spectrum reuse, as well as due to the improved SINR.

Finally, the figures also clearly depict the effect of the network load. With the increase in the number of users, the throughput decrease is consistent across the range of cell densities, and for minimum and maximum power levels. With the load increasing from e.g. 10 to 30 users, the decrease in the combined median and cell-edge throughput is in the range 62 – 66%. Increasing the load from e.g. 30 to 50 users reduces the rate between 38 and 40%.

Multiple "foreign" entities. Fig. 6.6 depicts the median user throughput when RRHs share spectrum with other, "foreign" entities. Maximum and minimum considered power levels are scaled, according to Table 6.5. The focus is at the performance difference when RRHs are in a good DTT service area (EIRP=18 dBm), and the case of a poor DTT service area (EIRP=5.5 dBm). Here, the improvement in the performance due to a higher transmit power in a good DTT service area is more noticeable with a higher RRH density. The trend

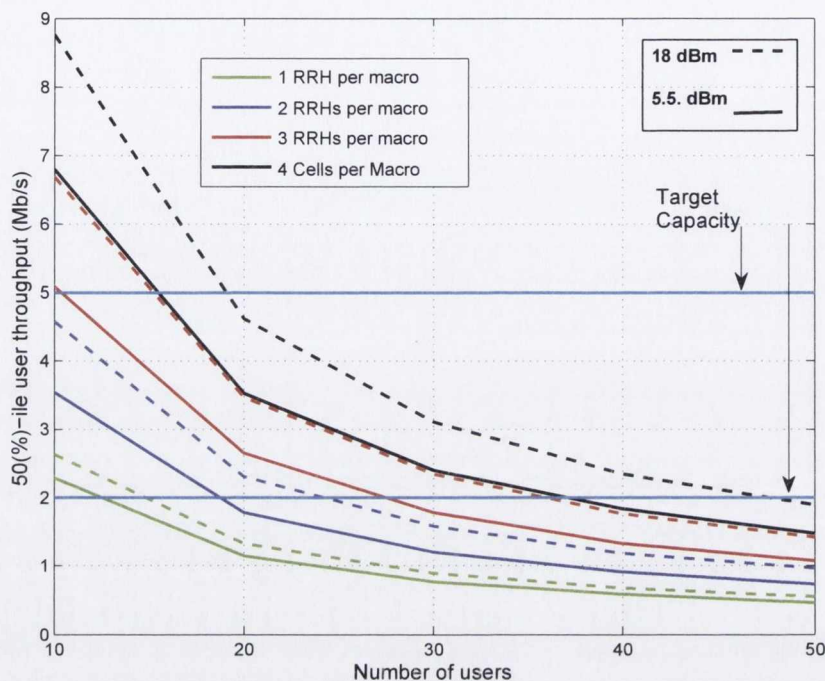


Fig. 6.6 Combined median user rate for the case when the operator has to share spectrum with other, "foreign" entities. Power levels are scaled when RRHs are in a good (18 dBm) and a poor DTT service area (5.5 dBm).

can be explained by the fact that the interference levels are lower due to the lower power levels. They are, hence, not offsetting the gain obtained by the higher RRH density. For example, for 20 users, the increase in the median user rate due to a higher power for the case of 4 RRHs is 30%. In the event of a single RRH per macro area, the improvement is 16%. When compared with the case when there are no "foreign" entities, Fig. 6.4, the biggest difference can be observed in the performance with low RRH densities - the maximum power of 36 dBm provides 22% improvement, compared to the case of 18 dBm, and around 42% when 5.5 dBm per RRH is used.

Tremendous increase in throughput due to a greater RRH density can be observed in this case as well. For example, when power is 18 dBm, and there are 20 users in a cell, the increase in the number of RRHs from 1 to 4 results in median throughput increase of 246%. This increase is 209% when RRH power is at 5.5 dBm.

The same trend of throughput decrease resulting from an increase in the number of users in the macro cell area, seen in Fig. 6.5 and Fig. 6.4, is observed in this case as well.

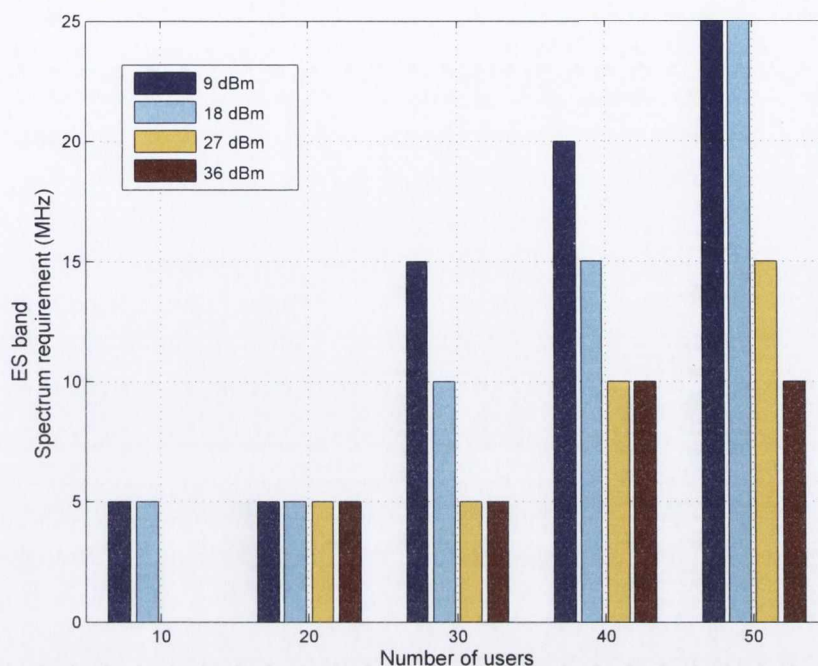


Fig. 6.7 Spectrum requirement for the median user target throughput of 5 Mb/s in a good DTT service area - cell density 2

6.3.2 Spectrum requirements from the ES band

In this subsection, the additional spectrum requirement in the ES band is computed for the cases when EO and CS bands cannot satisfy target cell-edge and median user throughput. The spectrum requirement when selected values are 2 and 5 Mb/s for the median user throughput, and 1.5 and 3 Mb/s for the cell-edge user throughput are depicted. Similar values can be seen in the literature evaluating the gains due to Carrier Aggregation, see for example [97], [101]. The additional spectrum, in block units of 5 MHz, as outlined in Table 6.4, is computed taking into account that CS resources are also used, according to Equation 6.3. Here, some of the results are depicted. They refer to the RRH density 2, and the target rate of 5 Mbps for the median user throughput, and 1.5 Mbps for the cell-edge user throughput.

- *Good DTT service area (maximum emission level).* Fig. 6.7 depicts the spectrum requirement from the ES band, with different permitted power levels, depending on whether the RRHs share spectrum with other entities. It can be observed that for 10 users, only in cases when there are other, "foreign" entities in the CS band, when the permitted power level is below or equal to 18 dBm, the additional spectrum from the ES band is required. As the number of users increases to 20 and more, all cells will require additional spectrum, regardless whether they may be the only entities transmitting in the area, using maximum permitted power. The spectrum requirement

is naturally higher the greater the load on the network, but it is different depending on whether there are "foreign" entities or not. For example, in the case where cellular operator's RRHs use maximum EIRP of 36 dBm, the maximum spectrum requirement is 10 MHz. The spectrum requirement goes up to 25 MHz for the cases when the spectrum is shared and power is reduced to 18 dBm or 9 dBm.

Particularly, the impact of the number of users on spectrum requirement can be seen in Fig. 6.8. In this case, there is no requirement for the additional spectrum from the ES band for any of the power levels, if the number of users is 10. As the number of users increases, the spectrum requirement is increasing, but slower for the cases when RRHs transmit at higher power. It increases by 5 MHz, only for the case of 50 users, and 9 dBm power level.

It should also be noted that in both - Fig. 6.7 and Fig. 6.8 at 27 dBm, the spectrum requirement is the same as for 36 dBm, except for the case of 50 users (Fig. 6.7) .

- Poor DTT service area (minimum considered emission level). Fig. 6.9 depicts the results for poor DTT service area. As the network load increases, the spectrum requirement from the ES band increases linearly for the case of 5.5 dBm, whereas its increase is more gradual for e.g. 11 dBm up to 30 users. In all cases, for the highest load - with 50 users per a macro cell, 25 MHz is required from the ES band.

Finally, Fig. 6.10 illustrates the impact the lowering the target rate has on the spectrum requirement from the ES band. The flexibility to reduce the minimum user rate and, therefore, degrade the QoS is quantified in percentages of the minimum throughput reduction. By reducing the target rate, the spectrum requirement from the ES band can be significantly lowered and ultimately the cost to the operator, especially in the case of a high network load. Particularly, the requirement for 9 dBm case and cell density 2 for the median user throughput is depicted. It can be observed that as the target rate decreases, the impact of the network load (i.e. the number of users) decreases - note the variance of the bars in each column. In this instance, by reducing the target user rate by, e.g. 5 or 10% for the cases of 30 and 40 users, the spectrum requirement is reduced by 5 MHz. When the target rate is decreased by 30%, no additional spectrum is required for a lightly loaded network. Also, the reduction for high-load scenarios is significant - it drops from 25 MHz to 10 MHz. However, reducing the minimum user rate so substantially is unlikely to be considered by cellular operators due to a potentially significant deterioration of user experience.

6.3.3 Analysis

The results presented above are affected by many interrelated factors. They include the number of RRHs, the network load, channel bandwidths, propagation characteristics of

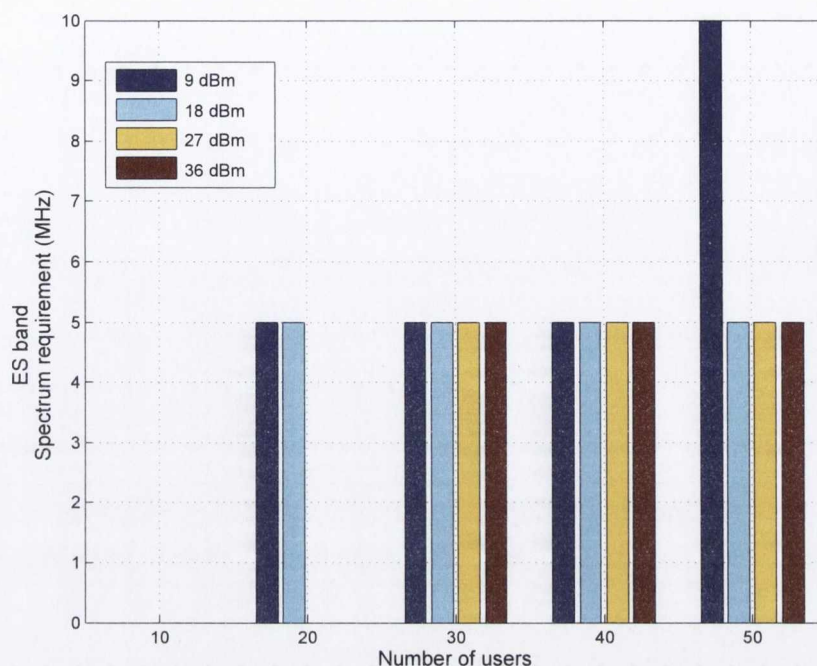


Fig. 6.8 Spectrum requirement for the cell-edge case with target throughput of 1.5 Mb/s in a good DTT service area. The case with 2 RRHs is shown.

the considered carriers, their power and interference levels. Of particular interest are the effects the shared carriers have on the user performance with a given topology using Carrier Aggregation as a basis. It is evident that the propagation characteristics of the 620 MHz carrier lend themselves to offer notable improvement in the user throughput using the permitted power levels and the channel bandwidth of 8 MHz. Firstly, the results show that when there is no power sharing (no other entities), the difference between transmitting in a poor and good DTT service area depend on the topology. The improvement by transmitting in a good DTT service area (using 36 dBm) compared to transmitting in a poor DTT service area (11 dBm) is better with a low density of RRHs. In that case, the benefit of a higher power is more pronounced (36% improvement for the case of a single RRH vs. 23% increase in the case of 4 RRHs, see Fig. 6.4). This effect also occurs for the cell-edge users. There, however, the improvement in throughput with respect to permitted power levels (11 dBm vs. 36 dBm) is greater than in the case of median-user throughput. With other "foreign" entities operating on the channel, that is when power scaling is applied, a good DTT service area with a higher density of RRHs offers a more significant improvement compared to a poor DTT service area (30% for 4 RRHs vs. 16% for a single RRH). This different pattern is a direct result of smaller SINR difference in the case of power scaling for a lower RRH density (i.e. smaller SINR difference between 18 and 5.5 dBm, compared to 36 dBm vs. 11 dBm). Hence, the topology i.e. the density of RRHs is a major factor that affects the gain when comparing poor and good DTT service areas, with or without sharing/power scaling.

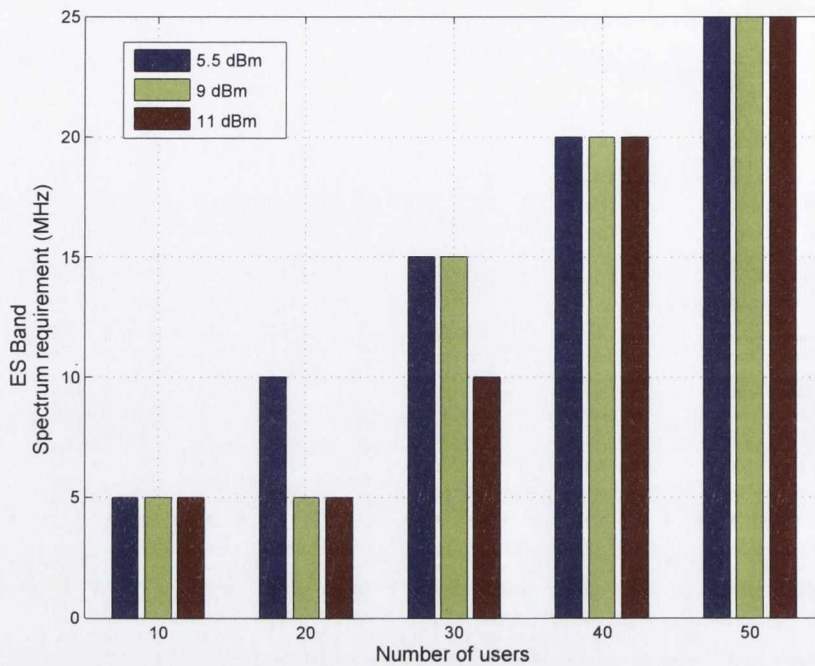


Fig. 6.9 Spectrum requirement for median user target throughput of 5 Mb/s in a poor DTT service area. The case with 2 RRHs is shown.

The results also show that with a carrier with good propagation characteristics such as 620 MHz carrier, similar rates and almost the same spectrum requirement may be obtained when operating below the maximum permitted power, by using, for example, 27 dBm. Further, if the formula for interference margin, discussed in 6.2.2.2, is applied, it means that having up to 7 "foreign" entities in a good DTT service area practically does not result in a change in spectrum requirement.

Besides power, the chapter also considers the effect of the number of users and target rates on the spectrum requirement, for a given RRH density. As results in subsections 6.3.1 and 6.3.2 show, the number of users has a significant impact on the throughput in both median and cell-edge user case, as changing the load in the network directly affects the amount of resources a user gets. By reducing the minimum target rate, the reduction in spectrum requirement is most noticeable for the medium and high number of users, but at a cost of a potentially significant deterioration of user experience.

6.4 Related work & state-of-the-art

This section presents state-of-the-art in the areas of TV White Spaces and LSA that address some of the aspects analysed in this chapter.

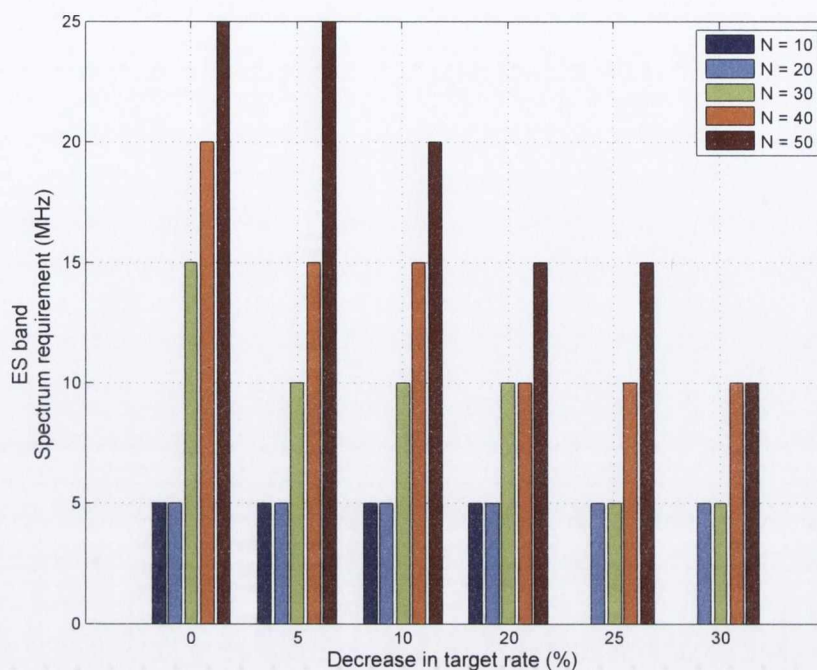


Fig. 6.10 Flexibility is characterised in terms of QoS reduction. The impact on the spectrum requirement is shown (9 dBm).

6.4.1 TV White Space

The area of TV White Spaces has seen a significant amount of research over the years. Some works address the availability and the capacity of TV White Space, e.g. [50], [144], while a number of them explore the available capacity if a secondary network is a cellular network. In [145], an overview of coexistence challenges between different secondary networks is given, while the authors in [146] conclude that not only the transmission power need to be considered, but also the secondary transmission density. In [147], multiple secondary cellular systems that transmit at a border of TV protection area are analysed. The authors propose a centrally managed interference control algorithm to maximise the sum power spectral density under the constraint of aggregate co-channel interference. Maximising the number of mobile and portable devices, while considering the co-channel and adjacent channel interference as a constraint is analysed in [148].

Interesting analysis of the capacity available in TV White Spaces and its suitability for cellular network requirements is given in [149]. The paper presents an extensive assessment of the cellular network capacity provided by the TV White Spaces in Germany. It considers scenarios of a stand-alone and the offloading LTE network operating in the available TV White Space and finds in both cases the uplink being the limiting factor due to the DTT interference the base stations would be subjected to. However, while the stand-alone scenario

does not provide the satisfactory outage probability that would be required to fulfil cellular network requirements, the paper finds that a significant capacity gains can be achieved in the offloading scenario (compared to using the dedicated spectrum), particularly in the urban areas.

In [150] – a femtocell architecture and implementation/prototype that enables simultaneous use of licensed and unlicensed spectrum i.e. the TV White Spaces in indoor femtocell deployments is presented. By using the dedicated spectrum, the proposed architecture deals with the spatial-temporal variations in the availability of a particular TV White Space channel, with the aim to minimise disruption to the users by switching to the licensed spectrum. The disruption caused by vacating a channel and finding a new, suitable channel can in cases of high interference reach between 60 to 120 seconds. In addition, the proposed architecture employs a central TV White Space channel coordinator, responsible for assigning the most suitable channel to the femtocells, as well as collaborative spectrum sensing function for detection of available TV White Space channels. Experimental results show a significant increase in system performance – i.e. in UDP and TCP throughput, compared with the alternative - using only White Space channels.

6.4.2 LSA

The use of Carrier Aggregation, as well as other LTE/LTE-Advanced mechanisms such as cell-reselection and inter-frequency handover, are discussed in the context of supporting the LSA in [151]. In [152], the use of LSA spectrum, combined with Carrier Aggregation, is analysed. The authors consider the use of interference maps on the UL to estimate the impact on the incumbent. The CCs using the LSA spectrum can be activated based on the cell load, but only if UEs in the cell do not cause interference to the incumbent greater than the predefined threshold. The interference effects on the LSA incumbent and the region of operation for the LSA licensee with different operational parameters - in the case of macro and small cells deployment are also analysed in [153]. Through system level simulations, the authors show that a deployment with small cells may enable smaller separation distances between the incumbent and an LSA licensee, for a particular interference threshold. In [154], a mathematical model that characterises service unreliability of the LSA spectrum is developed, focusing on the mean number of users that do not have access to the service. The performance for cell-edge users in a system with distributed antennas and fractional frequency reuse, where only a single cell can avail of LSA spectrum is analysed in [155]. The use case and the trade-off in using the LSA spectrum in the architecture with massively distributed antennas are evaluated in [156]. Other works address architectural aspects. For example, in [157], the challenges of the framework as currently defined are presented. They include the challenges associated with having to vacate the LSA spectrum due to the appearance of an incumbent, as well as challenges related to the management of protection

zones, where interference levels have to be determined in order not to exceed a predefined interference threshold. The authors also briefly discuss possible future directions with LSA - notably, the use of small cells and millimetre frequency bands. In [158], the LSA concept extended to millimeterWave spectrum is proposed. The authors mainly discuss particular aspects of millimeterWave and briefly outline factors that need to be taken into account to expand the LSA into the operation at these frequencies. They include better spectrum availability information within the LSA Repository and a broadened role of LSA Controller to manage dense deployments of small cells.

6.5 Summary

This analysis addresses a number of aspects in the sharing framework with the CBB architecture. From spectrum perspective, two important spectrum sharing bands are used, with certain characteristics that match well the framework's spectrum sharing classes. For the CS spectrum, the TV White Spaces model is adopted, as one of the recent and detailed models, which enables *common* spectrum use, with variable availability and permitted power levels. The power levels depend on a particular channel, and spatial and frequency distance of any number of entities using TV WS. The ES band follows the LSA framework, which provides the *exclusivity* in spectrum access and allows different power regimes, but also has variable availability. The analysis in this chapter, however, focused on the case when both - TV WS and LSA channels are available. Namely, the objective was to gauge the gains from using the CS spectrum and evaluate the cost, that is the required bandwidth from the ES band, for a given QoS target. To the richness of the study contributes the fact that shared carriers exhibit very different propagation characteristics - at 620 MHz and 2.3 GHz. Furthermore, the scenario in this chapter addresses topology of particular interest for the framework - it combines macro cells, which employ EO spectrum, together with different densities of RRHs. The main performance metrics i.e. the median and cell-edge user throughput across different carriers are used for evaluation, and determine the spectrum requirement. In the CS band permitted power varies; hence, illustrative maximum and minimum power levels corresponding to good and poor DTT service areas are used. Besides, power scaling reflects the fact that a number of entities share the band. The results show that a carrier with good propagation characteristics such as 620 MHz carrier provides significant gains to the user rates. Besides, the improvement that comes with operating in a good DTT service area, when there is no power scaling, is more pronounced for a low density of RRHs. However, similar rates may be obtained when operating below the maximum permitted power, by using, for example, 27 dBm. It means that sharing in the power domain in the area with good DTT service does not have a significant detrimental effect on the performance, as long the power levels do not drop more than 10 dB. These findings, of course, do not take into account any additional interference as a result of sharing between the different entities.

Furthermore, the results show that the RRH density is of paramount importance when providing performance gains - the throughput increases in the range of 190 – 240% are seen. A significant effect of the network load on the performance and spectrum requirement is also illustrated - evident as the number of users in the system directly affects the amount of resources each user gets, regardless of the scheduling metric. The target rate is another important factor that determines the spectrum requirement. It is shown that when the operator has the flexibility of lowering the target rate, the bandwidth requirement, and consequently, the cost for the operator may be significantly reduced, particularly in high load cases. The flexibility can, therefore, be considered as the operator's design parameter that, depending on the requirements, manages the trade-off between the QoS and the cost.

This chapter addressed many challenges that the framework set out to quantify and answer. It also illustrated the complexity of interaction between different parameters that affect such a framework. At the same time, it highlighted the need to analyse the framework considering the effects of a higher density of LPNs as well as the impact of inter-system interference in the CS band. Hence, Chapter 7 endeavours to deal with these aspects, looking at both - CBB and DBB architectures.

Chapter 7

Analysis of the Complete Sharing Framework

The last chapter presented an extensive analysis of the sharing framework for the CBB architecture using Carrier Aggregation. This chapter broadens the analysis also to include the DBB architecture with Dual Connectivity and the impact the backhaul technologies have on the sharing framework. The chapter examines the spectrum requirement from the ES spectrum to deliver the specified QoS targets for low, medium and dense deployments of LPNs and different network load. A range of conditions in the CS band is incorporated into the analysis, including transmissions by "foreign" interferers. The major aspects of control plane are also considered. The effects of the identified parameters are formalised through sensitivity analysis. The chapter starts with a brief outline of both baseband architectures. Section 7.2 guides the reader through the overall scenario, including the employment of selected spectrum bands on different tiers and spectrum characterisation. This section also explains the methodology and gives a mathematical formulation of the calculation of spectrum requirement from the ES band. Section 7.3 describes the system parameters, whereas Section 7.4 presents the results. Sensitivity analysis and the associated discussion is given in Section 7.5. Section 7.6 discusses the key findings and concludes the chapter.

7.1 A brief reminder of the two architectures

CBB Architecture & Carrier Aggregation. In this architecture, LPNs are RRHs and the baseband processing is done centrally. The spectral resources from both tiers - macro and the tier of RRHs can be aggregated using Carrier Aggregation mechanism. In Carrier Aggregation, for each user, a single component carrier (CC) is designated as a primary carrier. Primary carrier is responsible for mandatory functionality, including maintaining the signalling connection to the core network. Other CCs are secondary carriers, added as extra resources using dedicated signalling. In Carrier Aggregation, there is a single

scheduling function. The scheduler can optimise radio resource allocation based on different scheduling metric, which may, for example, take into account channel state for users across different carriers. Furthermore, Carrier Aggregation enables cross-carrier scheduling¹, which facilitates transmission of scheduling information by a carrier different from the carrier that transmits user traffic. As discussed in Chapter 2, subsection 2.2.1, p.27, the CBB architecture requires a strict adherence to the stringent requirements on throughput, delay and jitter.

DBB Architecture & Dual Connectivity. Small cells are LPNs in this architecture, which relies on Dual Connectivity mechanism to achieve a simultaneous connection to two nodes. In Dual Connectivity, one of the nodes is designated as a Master eNodeB, and the other node is a Secondary eNodeB. Regarding the user plane, each node implements the whole protocol stack, including the scheduler. The 3GPP standard [90] defines two possible architectural options for handling the user traffic. The architectural option of interest in the thesis is the option where for a particular service, a user can be connected either to a macro-tier or a tier of small cells. This option, as discussed in subsection section 2.4.2.2, p.41, does not pose requirements on the latency introduced by the backhaul link and supports any backhaul solution. However, in this case, it is not possible to aggregate spectral resources across the tiers. Still, the aggregation of carriers within each tier is possible. In that case, at least one cell in the Secondary eNodeB has to have a configured UL CC with the UL control channel [90]. As per control plane, a Master eNB, responsible for control signalling towards the core network, may be implemented either on a macro tier or a tier of small cells. The Master eNodeB initiates the addition of a Secondary eNodeB, which is signalled through the X2 interface. In case the Secondary eNodeB can admit the request, its radio resources are provided to the user. Master and Secondary eNodeBs are connected over the X2 interface and use a range of backhaul technologies. These technologies may introduce a delay that ranges from few to several dozen milliseconds - see Table 2.1, p. 29.

7.2 The framework

7.2.1 Overall scenario

This chapter also features EO, ES and CS spectrum classes. In this chapter, however, both baseband architectures within the framework are considered. The EO carrier is employed by a macro tier, in both architectures. The ES and CS carriers are employed by the tier of LPNs - RRHs, or small cells. In addition, in this chapter, other (cellular) systems that operate on the same channel in the CS band using LPNs are considered. This chapter, as the previous one, refers to them as "foreign" interferers. By allowing multiple other entities to operate in the band should illustrate the increased levels of interference expected in this band.

¹See Chapter 2, subsection 2.4.1.5, p. 36.

Fig. 7.1 depicts the topology of the scenario. The LPNs are distributed randomly, with the constraints on the minimum distance between all types of nodes (macro and LPNs) as outlined in [77]. Further, the scenario analyses different LPN densities and a fixed number of users, clustered around LPNs. The users are deployed within the specified distance from the LPNs, according to [77]. Such a configuration, therefore, reflects a typical deployment of LPNs in high-traffic (hot-spot) areas. The remainder of users is randomly distributed over the entire (macro) cell area, including an area in proximity to an LPN. All users are distributed following the distance constraints to macro nodes and LPNs, according to [77].

To summarise, the scenario in this chapter incorporates:

- macro cells operating using the EO carrier
- operator's LPNs (RRHs and small cells) that employ shared spectrum - ES and CS carriers
- "foreign" low power interferers in the CS band
- a fixed number of users, clustered around LPNs - the remainder of users is distributed throughout the cell.

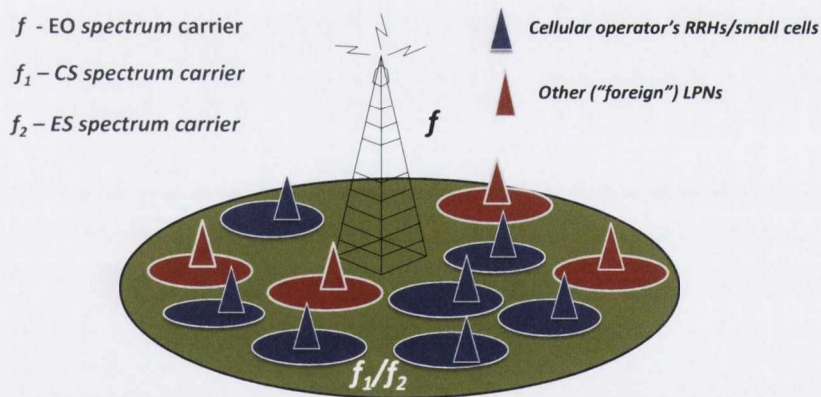


Fig. 7.1 Deployment scenario with different RRH/small cell densities, featuring operator's and "foreign" LPNs. LPNs employ shared carriers. A fixed number of users is clustered around LPNs, whereas the remainder of users is distributed across the whole macro cell area.

7.2.2 Control plane & signalling aspects

Chapter 3 described how the framework proposes to use macro tier to provide mobility and coverage. The previous chapters did not analyse signalling aspects from the perspective of

shared carriers. This subsection describes how the framework considers certain aspects of control plane, which are also used later in the analysis.

7.2.2.1 EO spectrum

The EO spectrum employed by the macro tier provides the functionality found in current networks:

- synchronisation signals for the purpose of synchronisation between a macro cell and all terminals in the cell
- basic system information required by the terminals to access the cell
- control signalling carrying scheduling information and transmission acknowledgements concerning the UL transmission
- cell specific (pilot) responsible for cell search, channel quality measurements and channel estimation for coherent demodulation
- spectrum resources for data transmission.

7.2.2.2 Shared spectrum

Regarding control plane and signalling aspects on the shared carriers, the framework proposes a solution that would, to a certain extent, reduce the amount of signalling carried by the LPNs. The split between the user and control plane in heterogeneous networks was, among first, introduced in [159]². In the sharing framework, pilot signals and scheduling transmissions are proposed to be handled as described below.

Pilot (cell-specific reference) signals. In LTE, Cell-specific Reference Signal (CRS) is the basic signal that facilitates channel measurement and channel estimation for coherent demodulation. The CRS signal can be transmitted only on 1, 2, or 4 antenna ports. In the framework, pilot signals should be transmitted from every carrier - EO, ES and CS bands - in both architectures, to facilitate channel quality measurements and channel estimation for coherent demodulation. It should be noted that a new type of reference and demodulation signals are introduced as a part of 3GPP Release 10 to support more than 4 transmit layers

²A small cell that carries no or very little signalling is in [159] referred to as *Phantom Cell*. From the control plane perspective (i.e. the RRC signalling), Phantom Cell is managed by a macro node. Phantom Cell, however, has a data path to the core network [159]. Based on the Phantom Cell concept, the 3GPP Release 12 introduces "cell on/off" mechanism [90], which allows turning the downlink transmission of a cell on and off, for the purpose of load balancing, interference management and energy saving. Such a cell may only transmit a periodic discovery signal [90], [86], which the UE may be configured to measure for the purpose of radio resource management.

and non-codebook-based precoding³. Within this chapter, CRS is utilised. The solution based on CRS is suitable as a single transmission layer is considered, and the CRS signal provides the required functionality for all carriers.

Scheduling transmissions. In the CBB architecture with Carrier Aggregation, the proposal is that the EO spectrum reuses the existing mechanism of Carrier Aggregation - i.e. cross-carrier scheduling - to provide control information regarding scheduling transmissions on the shared carriers. In the DBB architecture with Dual Connectivity, the proposal is that each shared carrier provides control information regarding scheduling transmissions, albeit with a smaller number of symbols.

7.2.3 Spectrum characterisation

The main spectrum attributes used in this analysis are outlined below.

Spectrum bands As in the previous chapters, the 2 GHz band is considered for the EO band, using the main parameters as per [77]. For the shared spectrum, this chapter studies the case when two classes are situated in the same, high-frequency band. For that, the 3.5 GHz band is adopted. While the bands used in Chapter 6 - i.e. TV White Spaces and 2.3 GHz - could have been analysed in this chapter as well, the 3.5 GHz band is chosen as higher frequencies are of interest, particularly in the context of LPN deployments. Furthermore, certain aspects of the sharing framework match well with the FCC sharing model in the CBS band, which is the 3.5 GHz band in the US⁴. The parallel between the sharing framework and the CBS is, however, illustrative, as the sharing framework envisages a more dynamic manner how e.g. ES spectrum is accessed, compared to the current rules for PAL⁵.

³Namely, CRS, introduced in Release 8, does not support 8 transmit layers, envisaged by Release 10 and subsequent releases. Furthermore, CRS can only be used in the codebook-based antenna precoding, where receiver must know vector of weights applied to the symbols in each transmission layer. For these reasons, in 3GPP Release 10 and later releases, as a complement to the existing CRS-based solution, Channel State Information - Reference Signal (CSI-RS) and UE-specific Demodulation Reference Signal (DM-RS) are introduced. They are used to measure channel quality and for channel estimation for the purpose of coherent demodulation, respectively. CSI-RS supports up to 8 transmission layers and non-codebook precoding, where a receiver does not require the knowledge of the precoding matrix. CSI-RS also introduces less overhead due to a reduced time/frequency density. CSI-RS needs to be used together with DM-RS, which is a reference signal intended for demodulation for a specific UE. It is transmitted only in the resource blocks designated for transmission to that UE. Furthermore, to avail of the DM-RS signals and minimise the overhead related to control and discovery signals (pilot and synchronisation), a new carrier type is considered for an inclusion into a 3GPP standard. Such a carrier, therefore, would fit well with heterogeneous deployments with Carrier Aggregation and Dual Connectivity as it would reduce the overhead carried by the LPNs [160].

⁴To remind the reader, the CBS band uses as a basis a three-tier sharing model. The GAA tier has the lowest priority in spectrum access and no interference protection from the upper two tiers - incumbent and Priority Access. On the other hand, PA Licensee has the exclusive license for transmission in the specified temporal, spatial and frequency domains, and enjoys interference protection from the GAA tier. The Priority Access tier, however, has to accept interference from the top-tier (incumbent federal users and fixed satellite stations). The FCC has finalised the rules on the band in April 2015.

⁵The PALs are authorised to use spectrum resources in a particular channel in a single census tract for three years.

Availability of the shared bands In this chapter, for the CS band, the channel availability is analysed in binary terms - the channel is either available or not available. The ES band is considered available.

Cost of shared bands One of the major differences between the two shared spectrum classes is the cost of accessing the shared spectrum. The ES band envisages a usage fee, which is proportional to the requested amount of spectrum. The CS spectrum is free.

Power levels In the EO band, power is the same as in the previous chapters and according to [77]. The power levels for the ES and CS bands are according to rules in [61] for permitted power/emission levels for GAA and PA tiers in urban areas. They are, however, applied differently. In the ES band, fixed (maximum) power and antenna gain, as stipulated by [61], are adopted. In the CS band, different power levels, which scale up to the maximum permitted power/emission level, are considered.

Path loss and shadowing calculations The channel model specified in [77] is used for calculation of path loss and shadowing for all bands. The channel model covers the frequency range from 2 to 6 GHz and a range of environments. It uses different formulae for Line of Sight and Non-Line of Sight communication. In the EO band, the urban macro cell model for 2 GHz frequency carrier is used, whereas in the case of shared bands, urban microcell model is used. The microcell model is appropriate for LPNs in the framework, as it applies to local and metropolitan areas, where the antennas of the cells (and the terminals) are assumed to be outdoors and below the rooftops of the surrounding buildings [77].

Interference As mentioned throughout the thesis, interference is treated as additive noise and is calculated based on the transmit power and path loss including shadowing. In this chapter, users in the EO and ES band experience interference from the operator's LPN nodes. In the CS band, users experience additional interference from "foreign" LPNs.

7.2.4 Selection criteria for spectrum requirement decision

Here, the main aspects related to computing the additional spectrum from the ES band are described. In line with the constructs of the framework, this is the amount of spectrum a cellular operator needs to lease to provide a certain minimum QoS. The objective is to minimise the cost for the operator. Hence, the operator resorts to the ES spectrum only if the target QoS cannot be met by using free, CS spectrum and the EO spectrum. Considering that a decision on the amount of required spectrum by the cellular operator is expected to be made on a significantly longer time-scale than that of resource scheduling, the QoS is defined as an average throughput for a typical user. Given that, it is envisaged that spectral resources are allocated using the simplest form of scheduler i.e. the RR scheduler, which is

different from the analysis done in the previous chapter. The objective is therefore to minimise the amount of bandwidth w , which the cellular operator can lease for a specified period.

The bandwidth minimisation is subject to a constraint on the mean rate from all tiers a typical user can access. Namely, in this chapter, a typical user is a user that can take any position within a (macro) cell while adhering to the distance constraints to all types of nodes. Furthermore, at least a fraction of positions will be within 40 m from an LPN, depending on the density of LPNs. Typical user's SINR distributions, for each spectrum band, are obtained by performing a large number of simulation runs over a spatial domain, where a user connects to the strongest node, whereas transmission from other nodes is treated as interference. It is envisaged that the typical user supports Carrier Aggregation and Dual Connectivity.

Given this, three aspects affect this constraint:

- The first aspect relates to setting the target throughput. While there are many possibilities to adopting the target throughput for such a network, in this analysis, the target throughput is measured through a gain for a typical user with respect to the throughput achieved in a macro cell, similarly to [161].
- The second aspect relates to the difference between the two architectures. For the CBB architecture, the amount of spectrum from the ES band is determined by the throughput the typical user experiences combining the EO, and CS band, if the CS band is available. Hence, in this case, inter-tier spectral resource aggregation is possible, as depicted in Fig. 7.2 (left). For the DBB architecture, the spectrum requirement is solely determined by the rate in the CS spectrum, if the CS band is available. In this case, there is no inter-tier spectral resource aggregation, as the right-hand side of Fig. 7.2 depicts.
- The third aspect to consider is the potentially different coverage in the ES and CS bands. Namely, coverage in the CS band depends on the power levels and the number of "foreign" interferers. Namely, should the *SINR* in this band fall below certain minimum value typically considered in the LTE systems, denoted as β^6 , the spectrum requirement should be computed based on the throughput in the ES spectrum only. Hence, the throughput in the CS band is taken into account in the calculation of spectrum requirement only if a probability of the typical user being able to access the CS band is greater than some predefined *access threshold* δ . On average, this probability is equivalent to a percentage of users in the CS band with $SINR \geq \beta$. Therefore, the CS band affects spectrum requirement only if a percentage of users within its

⁶This is the minimum *SINR* value required to decode the pilot signal, also discussed in Chapter 4.

coverage is $\geq \delta$. It should be noted, however, that in the spectrum requirement calculations, the *access threshold* has not been introduced for the purpose of ensuring that low-power nodes provide coverage. That role belongs to the macro tier. The threshold is introduced to ensure that when both shared spectrum bands are utilised, the spectrum decision is not based only on a small percentage of users that can access the CS band. Instead, the decision should be based on a sufficient number of users that can access both bands. Considering that the analysis shows that the ES spectrum provides a high probability of coverage even in the case of a low density of LPNs, there is no requirement for the threshold to be applied for the ES band.

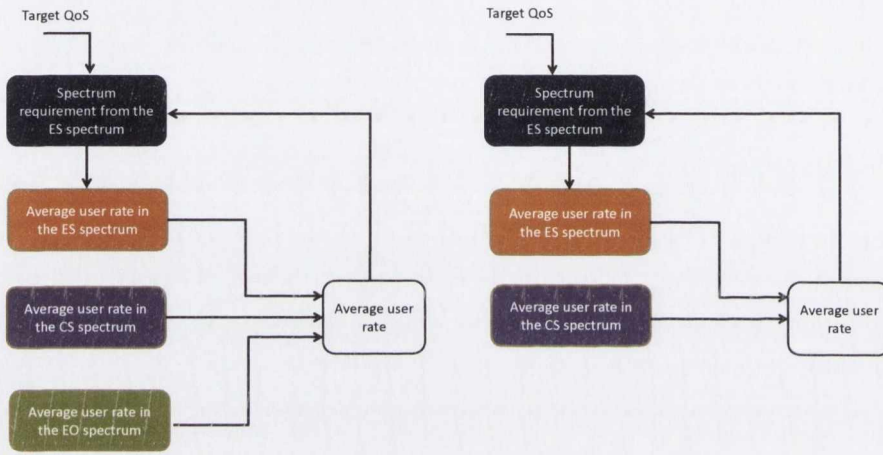


Fig. 7.2 Computation of spectrum requirement for CBB (left) and DBB architecture (right).

7.2.5 Mathematical formulation of the selection criteria

Mathematically, the criteria for the decision on spectrum requirement from the ES band can be written as:

$$\min w \quad (7.1)$$

In CBB, this is subject to:

$$1_\delta(\pi_c) \cdot E[R_1] + E[R_2] + E[R] \geq R_{th}, \quad (7.2)$$

whereas in DBB, Eq.(7.1) is subject to

$$1_\delta(\pi_c) \cdot E[R_1] + E[R_2] \geq R_{th}. \quad (7.3)$$

Here:

- $E[R_1]$ - mean throughput of a typical user in the CS band

- $E[R_2]$ - mean throughput of a typical user in the ES band
- $E[R]$ - mean throughput of a typical user in the EO band
- R_{th} - target throughput computed with respect to a desired gain of the mean user throughput in a macro cell with light load:

$$R_{th} = l \cdot E[R_{macro}] \quad (7.4)$$

- $E[R_{macro}]$ - mean user rate in a lightly loaded macro cell
- l - an integer multiplier denoting the required gain with respect to the mean user throughput in a macro cell
- $1_\delta(\pi_c)$ is an indicator function, where π_c is the probability of a typical user being able to access the CS band:

$$1_\delta(\pi_c) = \begin{cases} 1 & \text{if } \pi_c \geq \delta \\ 0 & \text{otherwise} \end{cases} \quad (7.5)$$

In line with the LTE standard, w is an integer decision variable, as spectrum can only be purchased in blocks of certain widths. As in the previous chapter, the nominal channel width is 5 MHz⁷. This is according to the LTE standard, including the fact that the greater channel widths in LTE i.e. 10, 15, 20 MHz are a multiple of the adopted nominal channel width. It is also the case with the channel width in the shared bands as stipulated by [61] (10 MHz). Furthermore, in this chapter, spectrum requirement from the ES band is capped at 20 MHz, i.e. $w \in \{0, 5, 10, 15, 20\}$. Namely, to consider the spectrum requirement from the ES band that is greater than 20 MHz would require considerations of the additional CCs i.e. channels, which would then have the implications for the throughput calculations, described in subsection 7.2.5.2, p. 116, and Table 7.4, p. 124. Hence, this chapter focuses on the analysis of the ES spectrum, with a single CC and a maximum bandwidth of 20 MHz.

Computing the average throughput of a typical user in each of the spectrum bands requires computation of *SINR*, normalised throughput and average bandwidth per a user. The remainder of this subsection (7.2.5) provides the details on each of these steps.

7.2.5.1 *SINR* computation

When computing *SINR*, each user is associated with the cell providing the strongest signal. Hence, the *SINR* of a random user u , associated with LPN (cell) i on the ES band is given

⁷As outlined in Chapter 6, p. 89, in LTE band 40 (2.3 – 2.4 GHz), only the channel widths that are multiple of 5 MHz are supported.

by:

$$SINR_{u,i} = \frac{P_{tx} \cdot L_{i,u}}{N_{th} + \sum_{\substack{j=1 \\ j \neq i}}^N P_{tx} \cdot L_{j,u}} \quad (7.6)$$

where

- P_{tx} - power of the LPN the user is associated with
- $L_{i,u}$ - path loss (including shadowing) and antenna gains on the link between serving LPN (cell) i and user u
- N_{th} - thermal noise
- $L_{j,u}$ - path loss (including log-normal shadowing) and antenna gains on the link between interfering (operator's own) LPN j and user u .

The $SINR$ on the macro tier is computed in the same way i.e. taking into account path loss and shadowing, and inter-cell interference, but for brevity is not shown.

The $SINR$ of random user u , associated with LPN (cell) m on the CS band is given by:

$$SINR_{u,m} = \frac{P_{tx} \cdot L_{m,u}}{N_{th} + \sum_{\substack{j=1 \\ j \neq m}}^N P_{tx} \cdot L_{j,u} + \sum_{z=1}^Z P_{tx} \cdot L_{z,u}} \quad (7.7)$$

where Z represents the total number of "foreign" interferers in the macro cell area, and $L_{z,u}$ incorporates path loss (including log-normal shadowing) and antenna gains on the link between "foreign" interferer z and user u . The $SINR$ distribution determines π_C , as π_C is a probability that the $SINR$ takes values that are greater to or equal to β .

7.2.5.2 Computation of a normalised throughput

In computing the normalised throughput, that is the spectral efficiency⁸ i.e. the $\log_2(1 + SINR)$ term in the Shannon formula, certain practical aspects of real (LTE and LTE-Advanced) systems are taken into account. They include maximum throughput that can be achieved using the highest order modulation and coding, as well as the loss of bandwidth efficiency.

Given this, for the calculation of normalised throughput - denoted by $SE(b/s/Hz)$ - modified

⁸Normalised throughput and spectral efficiency are interchangeably used in this chapter.

and truncated Shannon formula is used, according to [135]:

$$SE = \begin{cases} SYS_{eff} \cdot \log_2(1 + \frac{SINR_T}{SINR_{eff}}), & \text{if } SINR > SINR_T \\ SYS_{eff} \cdot \log_2(1 + \frac{SINR}{SINR_{eff}}), & \text{if } \beta \leq SINR \leq SINR_T \\ 0, & \text{otherwise} \end{cases} \quad (7.8)$$

where

- SYS_{eff} is a factor that incorporates the losses in bandwidth and system efficiency due to guard band, cyclic prefix, and system related aspects. Bandwidth efficiency losses relate to guard-band and cyclic-prefix. Namely, to suppress OFDM associated out-of-band emissions, LTE uses guard band in the frequency domain. In the time domain, cyclic prefix is a guard-time, introduced to preserve orthogonality between the subcarriers [71]. Within this analysis, system related aspects include CRS, synchronisation signals and downlink control channel signalling.
- $SINR_{eff}$ is a factor that adjusts for the implementation loss in $SINR$, compared to theoretical, AWGN channel (Shannon) capacity [134], which envisages error-correction codes of an infinite-length.
- $SINR_T$ is a value at which a maximum throughput is reached, using the highest order modulation and coding [135].

It should be noted that SYS_{eff} has a different value for the EO, ES and CS bands in the two baseband architectures within the framework. Firstly, in both architectures, in all spectrum classes, the overhead associated with guard band, cyclic prefix, and cell reference signals is considered. Namely, the guard band and cyclic prefix are inherent to LTE/OFDM systems. Furthermore, as discussed in subsection 7.2.2, p. 109, CRS is required for channel quality measurements and channel estimation for coherent demodulation. In the CBB architecture, the additional overhead due to synchronisation signals and control channel signalling is calculated only on the EO spectrum resources (macro tier). Hence, as per control channel signalling, the EO spectrum should carry all the information regarding scheduling on all carriers. It also should carry any UL transmission acknowledgements. In the DBB architecture, a small overhead associated with the additional synchronisation information should be included in the shared spectrum (the tier of LPNs)⁹. Also, the overhead associated with the control region of a radio subframe that should carry the scheduling information on the shared carriers is included. This control region (i.e. the overhead) should be smaller than is the case with the EO spectrum where spectrum resources carry the scheduling assignments and grants for all users in a macro cell.

⁹The additional synchronisation information is used for the alignment of discontinuous reception and identification of measurement gap [90].

7.2.5.3 Average bandwidth per a user

As outlined earlier, this chapter considers a throughput that a typical user will experience over several time-scales of the scheduling time interval, and the use of the round-robin scheduler. It is, therefore, envisaged that, on average, equal bandwidth b_u is allocated to each user. Here, b_u is the number of basic units of resource allocation Δ_{RB} , and depends on the number of users U , and the total amount of bandwidth, i.e. $b_u = \frac{W}{U \cdot \Delta_{RB}} \cdot 10$

7.2.5.4 Constraints computation finalised

Given all the above, for the CBB architecture, the expected rate of a typical user is the sum of expected rates from all tiers. The constraint in Eq.(7.2) can be written as:

$$1_\delta(\pi_c) \cdot \frac{W_1}{K_1} \cdot E[SE_1] + \frac{w}{K_2} \cdot E[SE_2] + \frac{W}{K} \cdot E[SE] \geq R_{th} \quad (7.9)$$

For the DBB architecture, the average user rate can only be provided either by the macro, or the tier of small cell. Hence, for a typical user within the coverage of small cells, the constraint in Eq.(7.3) can be written as:

$$1_\delta(\pi_c) \cdot \frac{W_1}{K_1} \cdot E[SE_1] + \frac{w}{K_2} \cdot E[SE_2] \geq R_{th} \quad (7.10)$$

where

- W - channel bandwidth in the EO spectrum
- W_1 - channel bandwidth in the CS spectrum
- K - number of users in a macro cell
- K_1 - number of users within the coverage of the CS band
- K_2 - number of users within coverage of the ES band
- $E[SE]$ - mean normalised throughput of a typical user in a macro cell, according to Eq.(7.8), computed over spatial domain
- $E[SE_1]$ - mean normalised throughput of a typical user in the CS band, according to Eq.(7.8), computed over spatial domain
- $E[SE_2]$ is a mean normalised throughput of a typical user in the ES band, according to Eq.(7.8), computed over spatial domain

¹⁰This is applicable to LTE/OFDMA systems.

- R_{th} is the minimum required average user rate defined in Eq.(7.4).

Spectrum decision aspects described in subsections 7.2.4, p. 112, and 7.2.5, p. 112, are represented in the flowchart - Fig. 7.3. It should be noted that when the required bandwidth from the ES spectrum class needs to be drawn from multiple carriers, the total number of carriers cannot exceed the maximum supported number of carriers as per the LTE standard¹¹. In the case of CBB architecture, this includes the EO carrier and the CS carrier, if it is available. For the case of DBB architecture, this includes the CS carrier if it is available.

¹¹The maximum number of carriers in Carrier Aggregation is up to Release 12 fixed to 5 with maximum transmission bandwidth of 100 MHz [89]. As mentioned in Chapter 6, in Release 13, this number is expected to be increased to 32, supporting also greater transmission bandwidth [143].

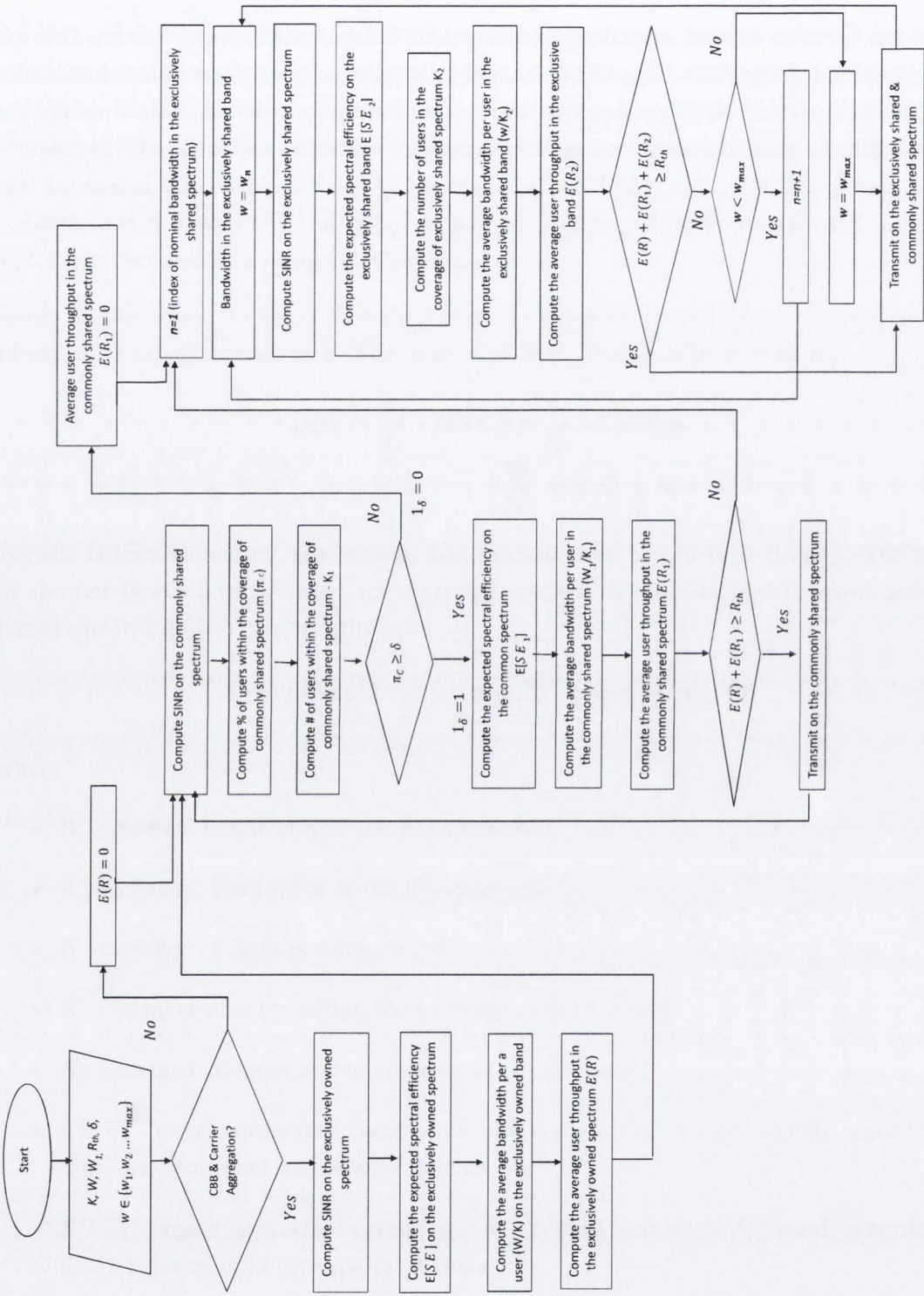


Fig. 7.3 Flowchart of the decision-making process to compute the spectrum requirement from the ES spectrum.

7.2.6 Modelling the framework

In the previous chapter, HetNet+ was used to compute the user rate and spectrum requirement from the ES band, using the PF scheduler. The scenario in this chapter features some additions. They include new channel model for urban microcell and the addition of "foreign" interferers. These would require further modifications to the simulator. Considering that the focus of the analysis in this chapter is on the mean user rate using the simplest form of scheduler, i.e. RR scheduler, the scenario in this chapter is modelled using separate Matlab-based modules that:

- simulate deployment of users and "foreign" and operator's LPNs within a macro cell. The users are deployed randomly using non-uniform distribution, adhering to the distance constraints to macro cell and LPNs, according to [77]. As outlined in subsection 7.2.1, p.108, a fixed number of users is clustered around operator's LPNs, whereas the remainder of users is deployed throughout the cell area. All LPNs are deployed randomly, with the distance constraints to the macro cell, and between the LPNs. Different density of "foreign" and operator's LPNs are considered.
- calculate SINR for all carriers on macro tier and tier of LPNs, based on the deployment and according to subsection 7.2.5.1, p. 115. The computed SINR distributions for the ES and CS spectrum for different LPN densities are used to compute:
 - coverage probabilities and corresponding (average) number of users on each shared carrier¹²
 - normalised throughput, according to subsection 7.2.5.2, p. 116
- calculate spectrum requirement for each of the baseband architectures, as described in subsection 7.2.5.4 and as per Fig. 7.3.

As in the previous chapters, the full-buffer traffic model is used.

7.3 System parameters

This section outlines the main parameters and their values used in the analysis. The placement of the LPNs and users, with respect to minimum distance is given in Table 7.1, according to Table A.2.1.1.2-3 in [77]. The placement of users is clustered and non-uniform, and broadly follows case 4a in [77]¹³. The low, medium and high density of LPNs are analysed - operator's as well as "foreign" interferers in the CS band, as outlined in Table 7.2. The main input parameters for the EO, ES and CS bands are given in Table 7.3.

¹²The analysis shows that macro cell provides full coverage.

¹³The number of users that are dropped within 40m of an LPN in configuration 4a in [77] is 4. In this analysis, 2 users are dropped within 40m of an LPN, however, a greater LPN density is considered.

Table 7.1 Distance between the nodes and UEs in this chapter

Minimum distance	(m)
Macro nodes - inter-site distance (urban environment)	500
Macro nodes - LPNs	≥ 75
Distance between LPNs	≥ 40
UE - macro nodes	≥ 35
UE - LPNs	> 10
UE distribution	2 UEs within 40m of an LPN remaining users over the entire macro cell area

Table 7.2 Density of the LPN nodes

# of operator's LPNs	2, 4, 10, 20
# of "foreign" LPNs in the CS band	0, 3, 10, 20, 30

Table 7.3 Input parameters for the EO, ES and CS bands

	EO Spectrum	ES Spectrum	CS Spectrum
Spectrum	50 resource blocks over 10 MHz @ 2 GHz	25 resource blocks over basic unit of bandwidth of 5 MHz @ 3.63 GHz	25 resource blocks over bandwidth of 5 MHz @ 3.55 GHz
TX power (dBm)	46	24	1, 6, 11, 16, 21, 26, 30
BS Antenna pattern/gain (dBi)	Omni-directional antenna / 14	Omni-directional antenna / 6	Omni-directional antenna / 0
Channel model	Urban macro cell (Model 2), according to [77]	Urban micro-cell, according to [77]	Urban micro-cell, according to [77]

Finally, Table 7.4 depicts the factors taken into account when calculating SYS_{eff} parameter in Eq. (7.8), where entry in each cell of the table is calculated based on the bandwidth of the relevant spectrum band and a radio frame duration (10 ms). Specifically:

- LTE uses the guard band of 10% of the total bandwidth [162]. In this thesis, the guard band is already taken into account with the size of resource block, as mentioned in Chapter 4, p.65.
- As per the cyclic prefix, normal length cycle prefix introduces overhead of approximately 6.7% [162].
- CRS introduces approximately 4.8% overhead by occupying 4 out of 84 resource elements in each resource block [162].
- Downlink common control channel occupies first few OFDM symbols in the subframe, with the maximum supported three (3) symbols per a subframe, and spans the whole bandwidth [163]¹⁴.
- Primary and secondary synchronisation signals, together with the broadcast channel in the radio frame occupy, in total, 488 resource elements [162]. These are included in the calculation of macro cell system efficiency. On the other hand, the information on synchronisation offset between Master and Secondary eNodeBs in the DBB architecture is envisaged to be carried on the broadcast channel, which requires 240 resource elements [162].

The SYS_{eff} is obtained by multiplying the corresponding factors and is given at the bottom of the table for all the bands, depending on the architecture - CBB, or DBB.

7.4 Results

This section describes the results, according to the considered scenario and selection criteria, explained in subsections 7.2, p. 108 and 7.3, p. 108. First, the access probability and mean spectral efficiency results are presented, followed by the spectrum requirement results in subsection 7.4.2, 127.

7.4.1 Access probability & mean normalised throughput

In the ES spectrum, access probability ranges from 0.98 in the case of 2 LPNs per macro cell to 1 in the case of 20 LPNs per macro cell, for the 5 MHz ES channel¹⁵. Fig. 7.4 and Fig. 7.5 illustrate the access probabilities, that is the average percentage of users within the

¹⁴Only for the LTE bandwidth of 1.4 MHz, 4 symbols are supported. It should also be noted that Release 11, in addition to the existing downlink control channel Physical Downlink Control Channel (PDCCH), introduces an enhanced version of this channel - ePDCCH to support an increase in control channel capacity in a flexible manner, using time and frequency domains [95].

¹⁵In cases of 2 LPNs and 10, 15 and 20 MHz channel, access probability is slightly reduced compared to the 5 MHz channel, but it is still greater than 0.86. This is due to the effects of noise i.e. - the wider the bandwidth, the greater is the noise in the receiver. This effect can also be seen for 4 LPNs, but then the access probability for 20 MHz channel is greater than 0.96%.

Table 7.4 System efficiency calculations for both architectures

Factor effecting the efficiency	EO spectrum (only for CBB)	Shared spectrum (CBB)	Shared spectrum (DBB)
Guard band	1	1	1
Cyclic prefix	0.93	0.93	0.93
Cell reference signal	0.95	0.95	0.95
Common control channels	0.79 (3 symbols)	1	0.93 (1 symbol)
Synchronisation signals & broadcast channel	0.99	1	0.99
Correction factor, according to [135]	0.9	0.9	0.9
SYS_{eff}	0.62	0.79	0.73

coverage of the CS band. Fig. 7.4 depicts the access probability for all considered number of "foreign" interferers, whereas Fig. 7.5 shows access probabilities for all power levels when there are no "foreign" interferers. The following trends can be observed:

- For the low and medium density of LPNs, and the case of 30 dBm and no interferers, 2 LPNs per macro cell already provide practically full coverage, Fig. 7.4. The access probability for different power levels is, however, very different, as depicted in Fig. 7.5. Cases with low power levels (1 dBm) have 34%, that is 57% percentage of users within the coverage, for 2 and 4 LPNs respectively, even when no "foreign" interferers are present. The number of "foreign" interferers, as expected, has a detrimental effect on the access probability. With the addition of 3 "foreign" interferers, for the case of 2 LPNs, Fig. 7.4, the access probability almost halves. This trend of sharp fall in the access probability with the presence of "foreign" interferers can be seen at all power levels. As the number of "foreign" interferers further increases to 20 and 30, their effect on the rate of reduction lessens, but the access probability is low, as Fig. 7.4 shows. Furthermore, the results indicate that in all cases where the number of "foreign" interferers is 10 or higher, the network enters interference-limited regime. In these cases, for a given number of LPNs, practically the same access probability can be observed regardless of the power levels.
- In dense LPN networks (10 and 20 LPNs), most cases with no "foreign" interferers provide the coverage to above 90% of users - the exception being the case with the

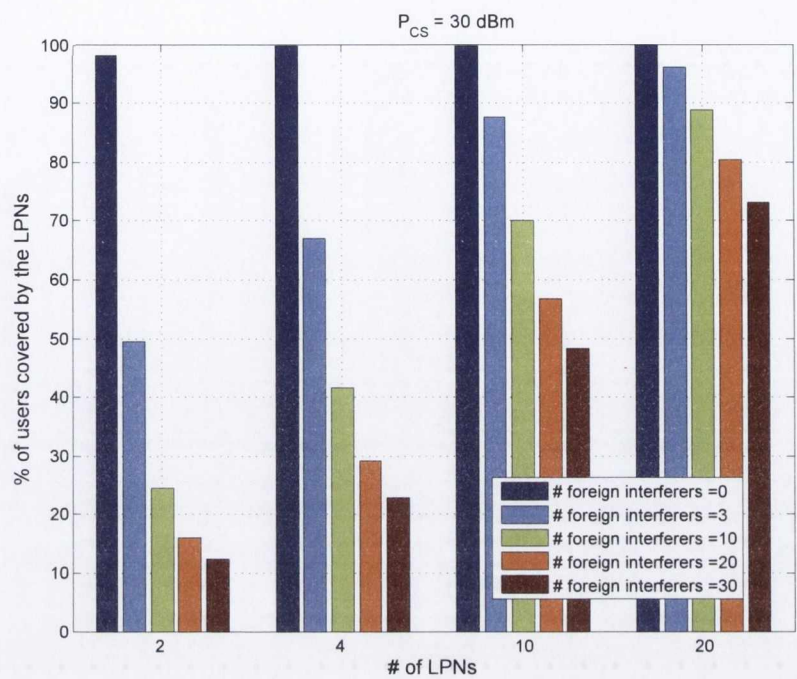


Fig. 7.4 Access probability for the CS band for all cases with different cell densities and a different number of "foreign" interferers. The power level is set to 30 dBm. For the case of 2 LPNs, the difference in coverage between 0 and 30 "foreign" interferers is pronounced and ranges from 98% to 12%. With 20 LPNs, the difference in coverage probability with a different number of "foreign" interferers subsides significantly. It falls from 100% with 0 to 73% with 30 "foreign" interferers.

power of 1 dBm and 10 LPNs. The effect of reduction in coverage with the increasing number of "foreign" interferers is reduced in all cases, as the received (useful) signal improves for a range of user's locations due to a denser network. This trend is particularly pronounced for 20 LPNs and any number of "foreign" interferers. For example, for 20 LPNs and 30 interferers, percentage of users that can avail of CS spectrum resources is, on average, 73%, for all power levels.

Mean normalised throughput As expected, the mean normalised throughput, that is the mean spectral efficiency in the ES band gradually increases with the increase in the number of LPNs per a macro cell. With 4 and 10 LPNs, the mean normalised throughput for the 5 MHz ES channel reaches just over 3 b/s/Hz¹⁶. By increasing the number of LPNs from 4 to 10, the access probability is increased, but the mean normalised throughput

¹⁶As with the access probability, the normalised throughput for the ES channel of 10, 15 and 20 MHz width is slightly reduced compared to the 5 MHz channel, in cases of 2 and 4 LPNs due to the effects of noise. With 10 or more LPNs, the dominating factor is interference and there is no difference in mean normalised throughput between different channel widths. The calculation of mean spectral efficiency takes into account the link-level losses, which include cyclic prefix, guard band and the correction factor according to Table 7.4.

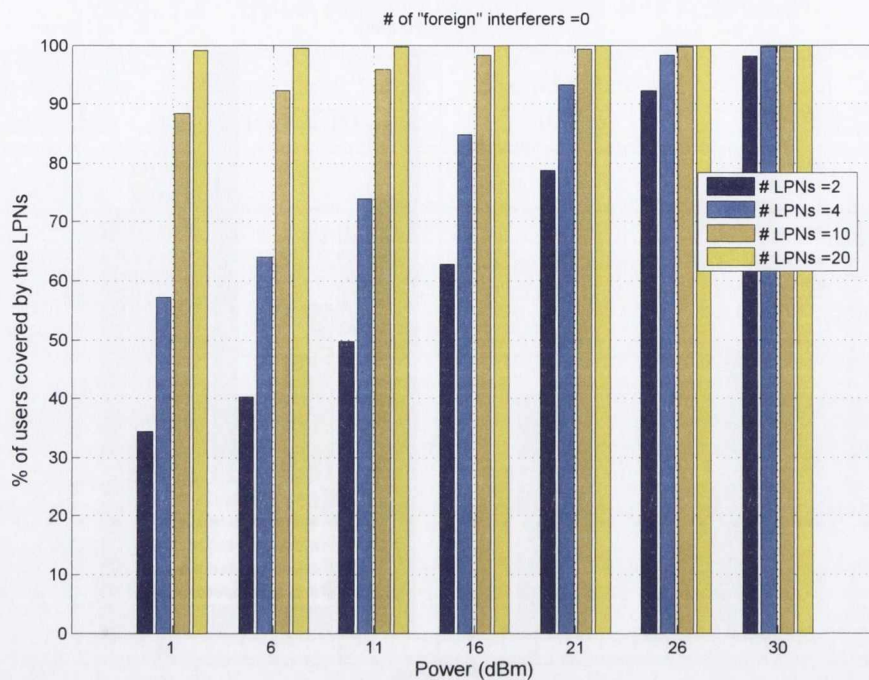


Fig. 7.5 Access probability for the CS band for all power levels, and no "foreign" interferers. The impact of power levels for the low and medium LPN density is pronounced.

remains the same. Eq. (7.8) gives an insight why this is the case. Namely, if $SINR$ is above a certain value of $SINR_T$, regardless of the further increase in $SINR$, the normalised throughput remains the same. With 20 LPNs, due to inter-cell interference, normalised throughput is reduced to below 2.5 b/s/Hz - a decrease of around 20% compared to 10 LPN¹⁷. In the CS band, in addition to the LPN density, different power levels, and number of interferers determine normalised throughput. Fig. 7.6 depicts the effects of a different LPN density and power levels, for the instances with no "foreign" interferers. The increase in normalised throughput with the rise in power is noticeable for low and medium LPN density (2 and 4 LPNs), up to 21 dBm. The effect of different number of interferers on the mean spectral efficiency is depicted in Fig. 7.7. Fig 7.7 shows that for a low density of operator's LPNs, the effect of "foreign" interferers is more pronounced. The best mean normalised throughput for 0 "foreign" interferers (for the power of 26 dBm) is achieved with 4 and 10 LPNs, as in the ES band. As the number of interferers increases to 3, 10 LPNs provide the best performance. However, with 10 or more "foreign" interferers, the best normalised throughput is achieved with 20 LPNs, which demonstrates the benefit of LPN densification.

¹⁷Clearly, a cellular operator can apply different methods to tackle inter-cell interference, such as ICIC, aimed to coordinate scheduling between the cells in e.g. time-domain [164]. The operator can also resort to a mechanism that enables smart activation/deactivation of small cells, based on the cell load, which also improves energy efficiency [165]. Furthermore, with the expected rise of dense networks, advanced UE-based interference suppression techniques should be considered together with network-based coordination schemes to tackle interference [164].

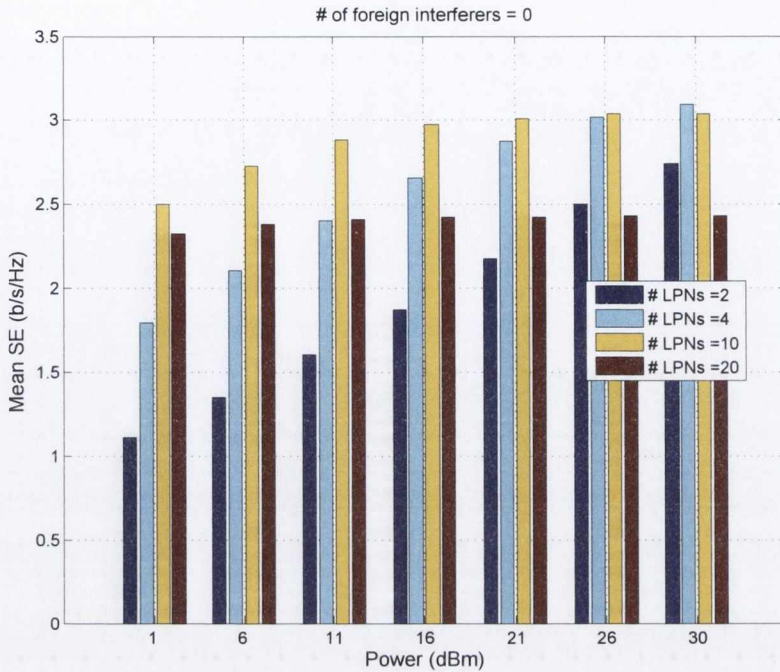


Fig. 7.6 Mean spectral efficiency in the CS band for the case of 0 "foreign" interferers. The highest mean spectral efficiency is achieved in the case of 10 LPNs (except for the power of 1 dBm). The effects of different transmit power are noticeable for power levels up to 21 dBm, and 4 LPNs.

7.4.2 Spectrum requirement - both baseband architectures

7.4.2.1 Impact of CS spectrum availability

Fig. 7.8 illustrates the spectrum requirement in the CBB architecture. The spectrum requirement is plotted versus the availability of the CS spectrum (x-axis) and the number of users in a macro cell (y-axis), for a given density of LPNs and target throughput gain. When the CS band is available, i.e. $Av_{cs} = 1$ - the power and number of "foreign" interferers are also fixed. The colour-bar on the right-hand side of the figure indicates the amount of spectrum required to meet the target throughput - from 0 MHz (cold blue) to maximum of 20 MHz (deep red). In all cases, there is a difference in the spectrum requirement for the two cases of CS channel availability - $Av_{cs} = 0$ and $Av_{cs} = 1$. This difference is always 5 MHz, which is the nominal CS channel width. When $Av_{cs} = 1$, no additional spectrum is required when macro cell is lightly-loaded ($K = 10$). As expected, the spectrum requirement increases with the rise in the number of users and reaches 10 MHz for a heavily-loaded macro cell. When $Av_{cs} = 0$, the spectrum requirement ranges from 5 MHz for $K = 10$ to 15 MHz for $K = 50$. With the same layout as in figure Fig. 7.8, Fig. 7.9 depicts the results of the additional spectrum requirement for both baseband architectures for the case of 2 LPNs. When CS channel is available ($Av_{cs} = 1$), there are no "foreign" interferers and the

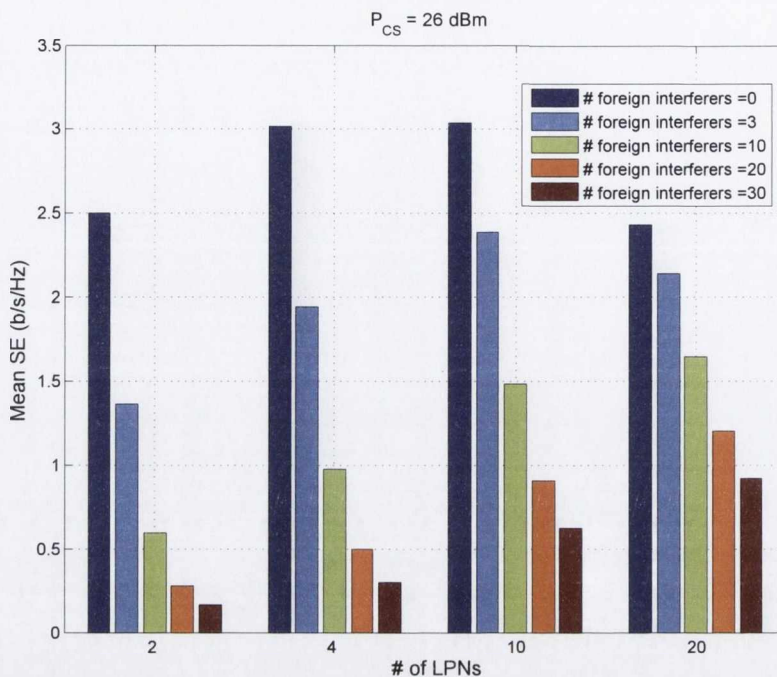


Fig. 7.7 Mean spectral efficiency in the CS band for the power of 26 dBm.

power is set at 30 dBm. Each image illustrates the additional spectrum requirement versus the availability of CS spectrum (x-axis) and the number of users (y-axis) for each of the architectures. Different rows represent different values for the indicated target throughput gain. For example, the image in position (1, 1) depicts the spectrum requirement in the CBB architecture, for the case of target throughput gain of $\times 2$. Position (1, 2) is the corresponding spectrum requirement in the DBB architecture. Comparing the two columns shows that even for the lowest target throughput gain of $\times 2$ and $K \geq 40$, the maximum spectrum requirement is reached in both architectures, regardless of the availability of the CS band. The reason for the high spectrum requirement is that practically all users can access both bands (see Fig. 7.4) and only 2 LPNs provide spectral resources for high number of users ($K \geq 40$). The difference between the requirement in the two architectures can be seen in the case of target throughput gain of $\times 2$, and $K \leq 30$, and for target throughput gain of $\times 4$ and $K = 10$. In these cases, the CS band reduces the amount of required spectrum by 5 MHz. Hence, by combining the CS spectrum and the CBB architecture, a reduction of 10 MHz in spectrum requirement can be achieved (Fig. 7.9, row 1, $K \leq 30$, CBB & $Av_{cs} = 1$ vs. DBB & $Av_{cs} = 0$). Fig. 7.10 depicts the results for a dense network with 10 LPNs per macro cell area. When $Av_{cs} = 1$, the power in the CS channel is 30 dBm. The case with 3 "foreign" interferers is shown. For low and medium target throughput gain (i.e. $\times 2$, that is $\times 4$), with $Av_{cs} = 1$ and medium, that is lightly loaded cells, both spectrum architectures can meet the required target throughput without resorting to the ES spectrum - see images

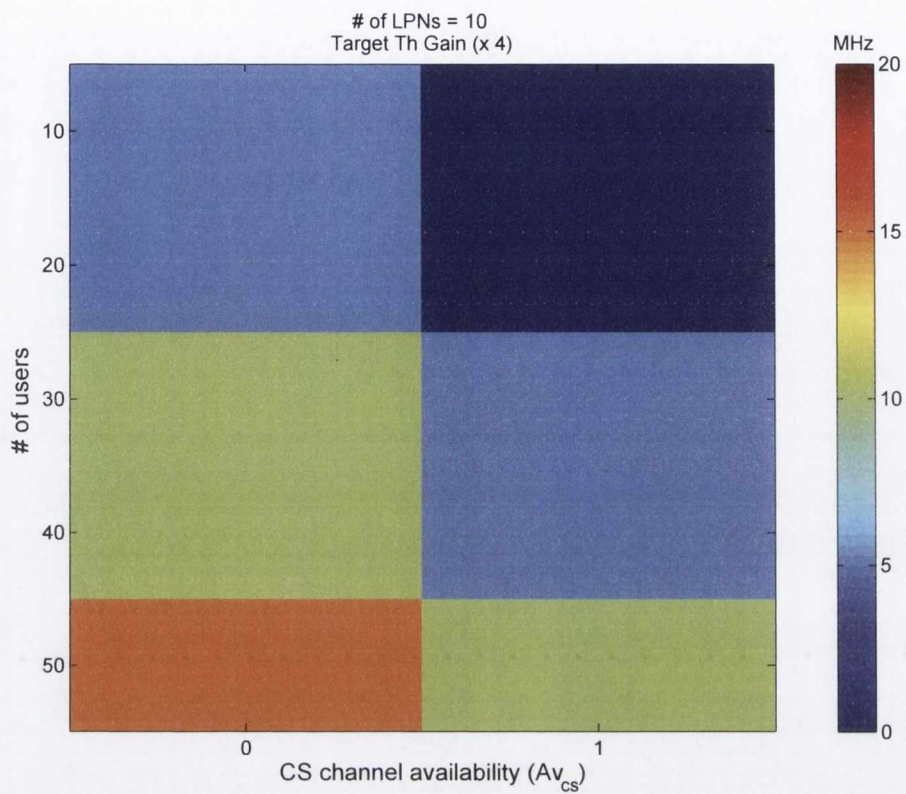


Fig. 7.8 Spectrum requirement for the CBB architecture for the case of 10 LPNs per macro cell. Power in the CS band, when available, is 1 dBm, and there are 3 "foreign" interferers. The x-axis represents the availability of the CS band, and the y-axis depicts the number of users in a macro cell.

in rows 1 and 2. Note that for target throughputs $\times 10$ and $\times 20$, and $K \geq 20$, spectrum requirement is the same for both architectures and both cases of CS channel availability. The case of an even denser network with 20 LPNs with 0 "foreign" interferers per a cell is depicted in Fig. 7.11. The images, amongst others, illustrate:

- There is no difference in spectrum requirement between the CBB and DBB architecture for low target throughput gain ($\times 2$), and any number of users, for a given availability of the CS channel. The same applies for high target throughput gain ($\times 20$), and the number of users $K \geq 40$, when maximum amount of spectrum is required.
- For target throughput gains of $\times 2$, and $\times 4$ with $A_{v_{cs}} = 1$, with the number of users $K \leq 30$, there is no requirement for the additional spectrum. This is also the case for target throughput $\times 10$, and lightly loaded cells - $K = 10$ ($A_{v_{cs}} = 1$).

The above results highlight the interaction and the impact of different parameters - primarily CS channel availability, target throughput gains and the number of users. It also bring out the difference between the CBB and DBB architectures. As per the impact of CS channel

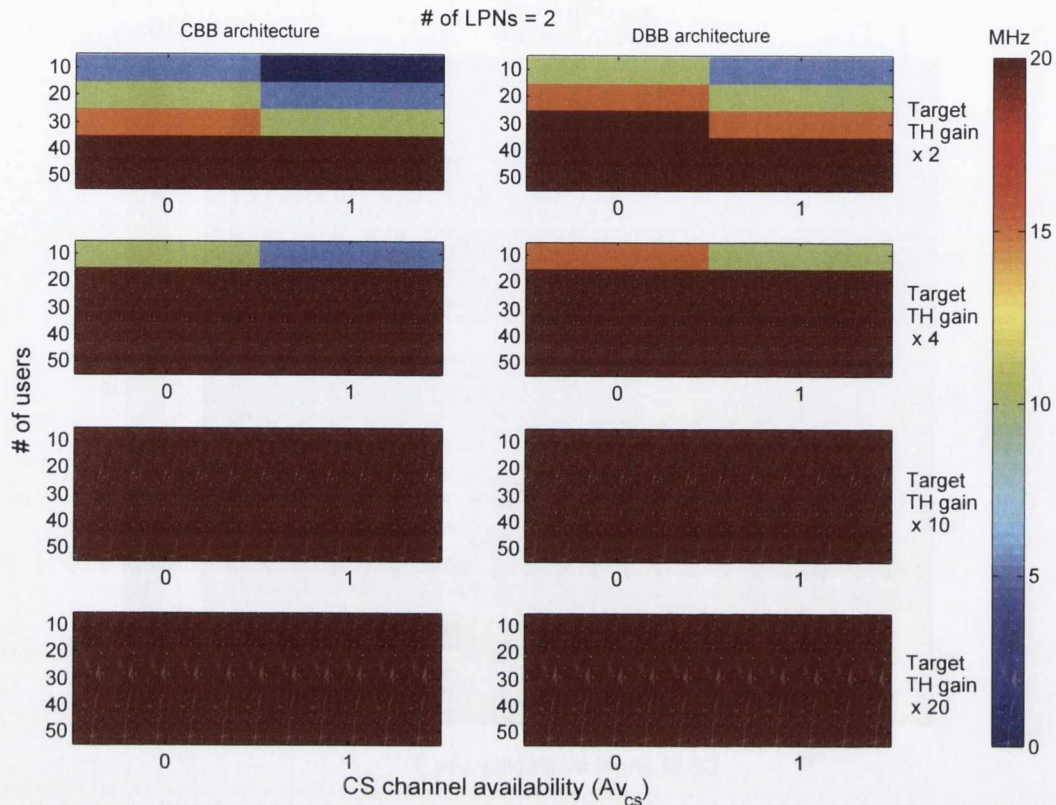


Fig. 7.9 Spectrum requirement for the CBB and DBB architectures for the case of 2 LPNs per macro cell. Power in the CS band, when available, is 30 dBm, and there are no "foreign" interferers. The x-axis represents the availability of the CS band and y-axis depicts the number of users in a macro cell. Each row represents spectrum requirement for the indicated target throughput gain.

availability (within the same architecture), as expected, the number of instances with a reduced spectrum requirement when $Av_{cs} = 1$ compared to when $Av_{cs} = 0$ increases with the LPN density. This effect occurs due to an increasing spatial spectrum reuse of the CS spectrum. The results show that for 2 and 4 LPNs, the reduced spectrum requirement occurs only for a dozen of cases and always when there are no "foreign" interferers in the CS band. Also, these instances can be mainly found for low-medium target throughput gains. With 10 and 20 LPNs, the reduction in spectrum requirement occurs in significantly more instances, even for a congested CS channel (with up to 10 and 30 "foreign" interferers, respectively), and for all considered target throughput gains and network loads. The difference is for majority of cases 5 MHz and only in a few instances reaches 10 MHz.

On the other hand, the difference between the architectures for the same channel availability is always 5 MHz and is more notable for a low and medium density of LPNs, and

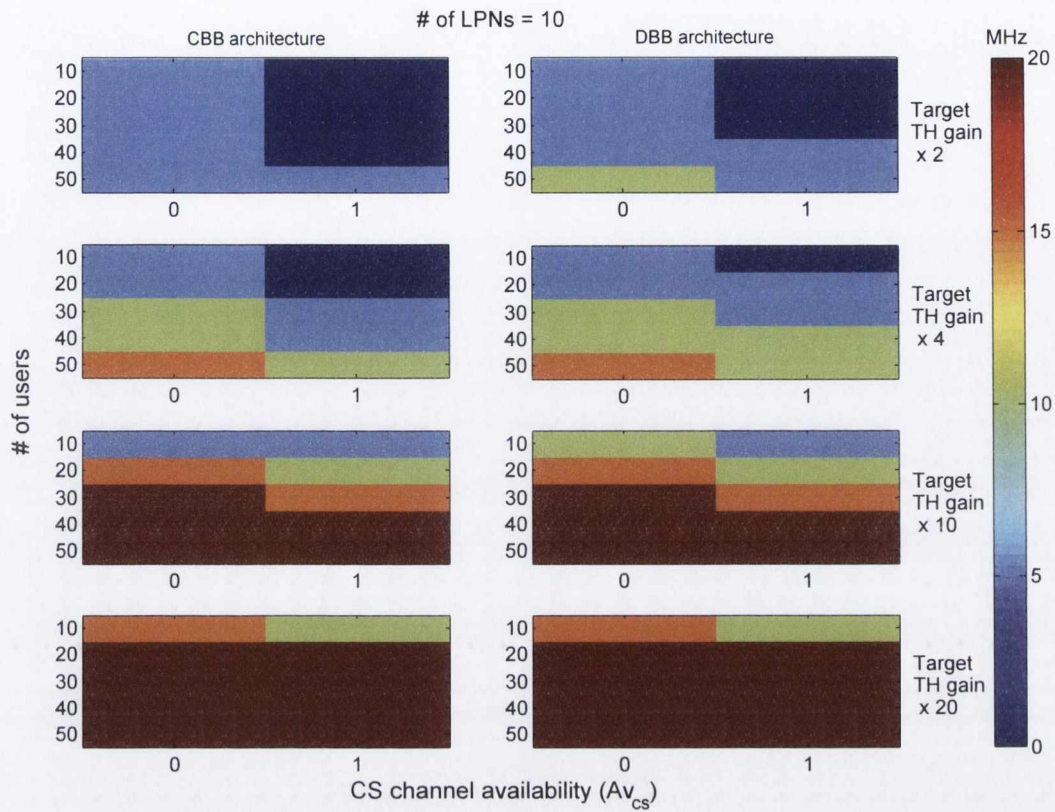


Fig. 7.10 Spectrum requirement for the case of 10 LPNs per macro cell. Power in the CS band, when available, is 30 dBm, and there are 3 "foreign" interferers.

low-medium target throughput gains, with a different number of users. This difference can also be interpreted such that the CBB architecture meets the target rate with the same spectrum requirement as the DBB architecture, but supporting higher number of users or a higher target throughput. Namely, in these cases, the EO spectrum resources provide enough gain for the CBB architecture to benefit from it.

Further analysis and discussion of the impact of target throughput and a number of users, but also other parameters and differences between the baseband architectures, is included in the sensitivity analysis - Section 7.5.

7.4.2.2 Impact of power scaling and "foreign" interferers in the CS band

The effects of spectrum sharing in the CS band are accounted for in two ways: by including "foreign" interferers and by scaling the power used by the LPNs. In this subsection, the results are depicted particularly with respect to these two parameters.

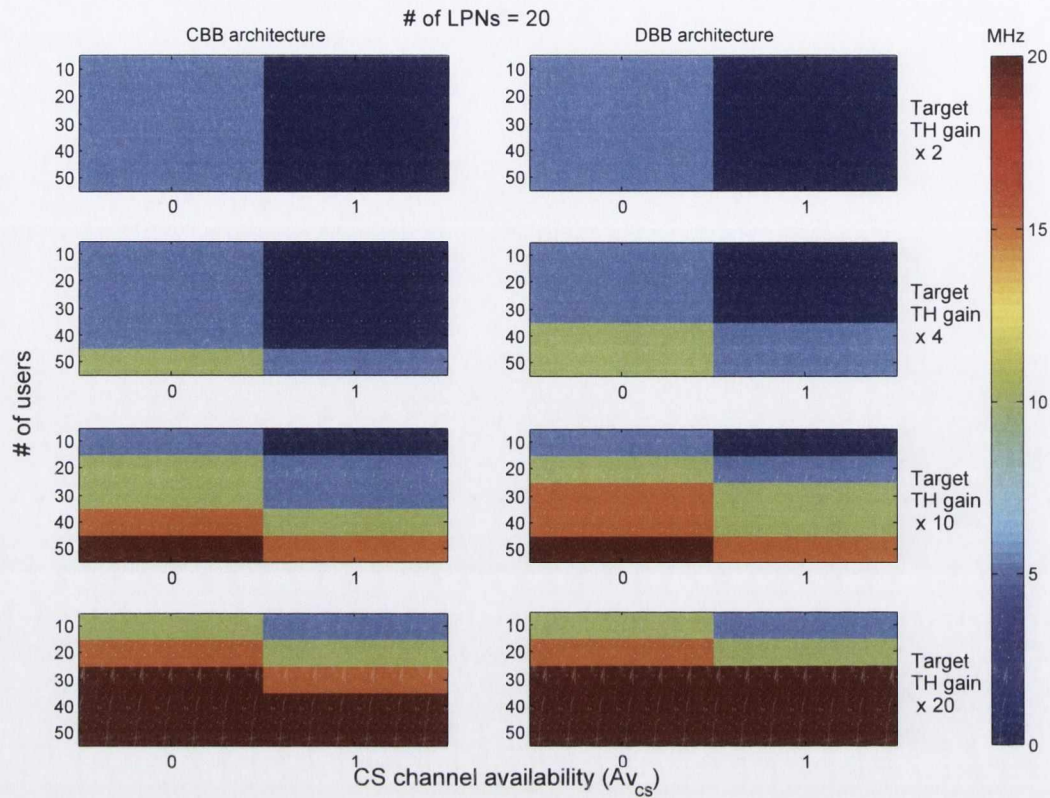


Fig. 7.11 Spectrum requirement for the case of 20 LPNs per macro cell. Power in the CS band, when available, is 30 dBm, and there no "foreign" interferers.

Fig. 7.12 depicts 4×4 images by using two power levels - the lowest and highest power considered for the CS channel i.e. 1 and 30 dBm. In the figure, the plots in columns 1 and 2 refer to the CBB architecture for the two power levels. The plots in columns 3 and 4 represent the corresponding spectrum requirements for the DBB architecture. The x-axis of each image depicts the number of "foreign" interferers while the y-axis shows the density of LPNs. The rows, again, represent the target throughput gain. Results in Fig. 7.12 refer to the case of a medium network load, i.e. $K = 20$. It can be observed that regardless of the baseband architecture, power level or a number of "foreign" interferers, for a particular LPN density and target throughput gain, the maximum amount of spectrum is required - see rows 2 – 4. The figure also illustrates the effects of increasing interference in the CS band and increasing power levels within the same architecture. Out of 16 combinations with different LPN density and target throughput, in half of them (Fig. 7.12), the influence of interferers can be seen (power level 30 dBm). The impact of power (Fig. 7.12) within the same architecture is only visible in about 8 – 9% of the cases in each architecture.

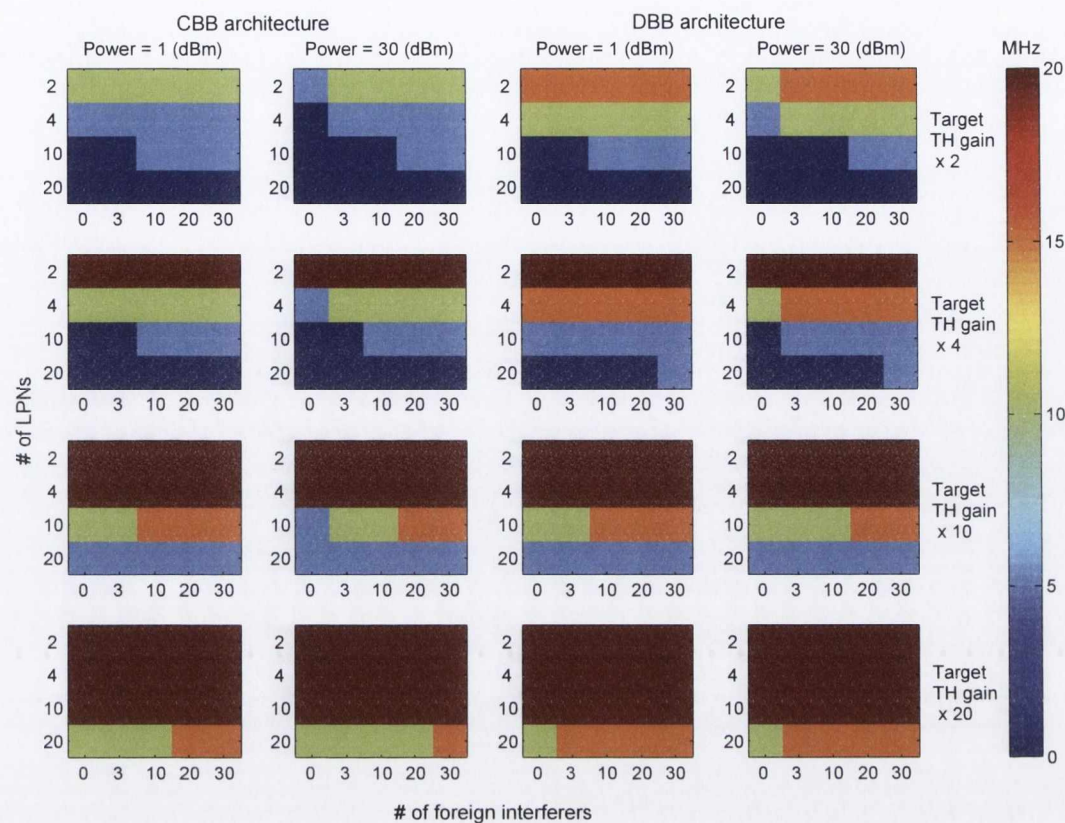


Fig. 7.12 Spectrum requirement for medium-loaded macro cell ($K = 20$), when the CS band is available. Power levels are 1 and 30 dBm.

The difference between the architectures, for the same power levels, occur in all cases for LPN density 2 and 4, and target throughput gain ($\times 2$), as well as for the LPN density (4) and target throughput gain ($\times 4$). The difference can also be observed in few other instances, for example, with 10 and 20 LPNs. In all these instances, the spectrum requirement differs by 5 MHz. In other words, in these cases, if the same amount of ES spectrum should be employed by the CBB and DBB architectures, the CBB architecture would allow for a greater number of "foreign" interferers, given all the other parameters. The role of the LPNs density is evident and expected. In each row, a lower spectrum requirement can be seen for a higher number of LPNs (colder colours at the bottom of each row). For example, in the CBB architecture, no additional spectrum is required, even with 4 LPNs and 0 interferers, with the power of 30 dBm (image (1, 2)).

As per the target throughput, the effects can be seen comparing row by row. Naturally, there is an increase in spectrum requirement with the higher target rates - warmer colours become more dominant when moving along the rows. With target throughput $\times 10$,

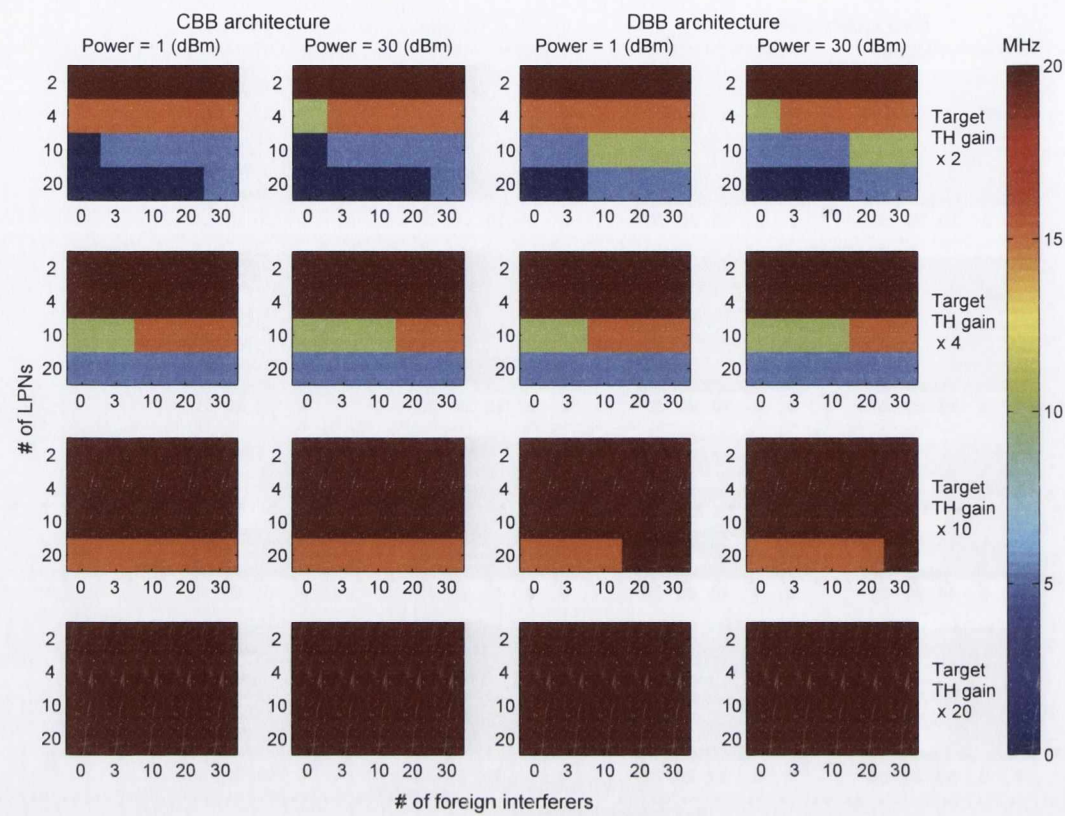


Fig. 7.13 Spectrum requirement for highly-loaded macro cell ($K = 50$), when the CS band is available. Power levels are 1 and 30 dBm.

for 2 and 4 LPNs, the maximum permitted amount of spectrum is required regardless of the power, and the baseband architecture. With target throughput $\times 20$, the maximum amount of spectrum is required even in the case of 10 LPNs. In the case of a high network load, with $K = 50$, Fig. 7.13, the maximum bandwidth is required in more than 63% of all the cases. Only for certain instances with 10 and 20 LPNs, and target throughput $\times 2$, the additional spectrum is not required. Also, the impact of "foreign" interferers is seen in a few combinations of target throughput and LPN density e.g rows 1 and 2 with LPN density 10 and target throughput gain $\times 2$ and $\times 4$.

The difference between the two architectures can be observed for different instances with 10 and 20 LPNs. Again, in these cases, it can be observed that the CBB architecture allows for a greater number of "foreign" interferers for the same amount of required spectrum, given all the other parameters. Also, Fig. 7.13 illustrates that power plays a role only in a small number of cases (approximately 1% in CBB and 3% in DBB architecture), where higher power levels result in a smaller spectrum requirement.

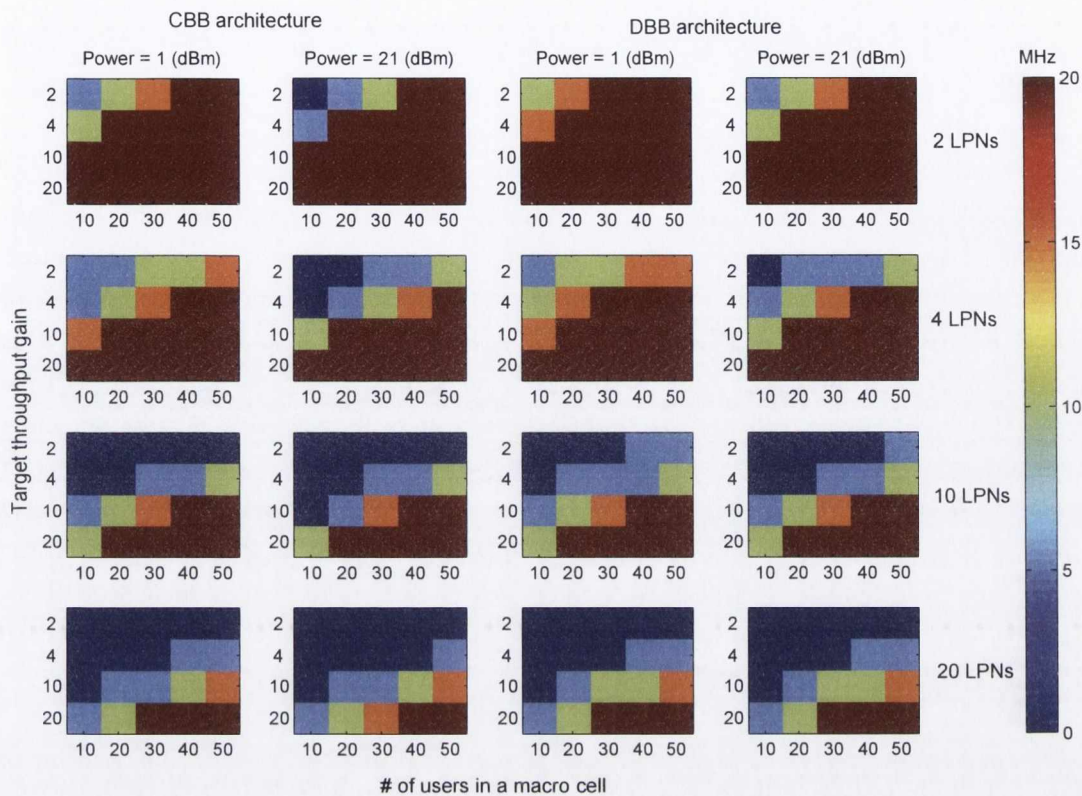


Fig. 7.14 Figure depicts bandwidth requirement when CS band is available, with power levels of 1 and 21 dBm, with 0 "foreign" interferers.

Finally, the spectrum requirement from the perspective of LPN density and number of users is depicted, given the availability of the CS channel and for zero "foreign" interferers. Two power levels are illustrated - 1 and 21 dBm, see Fig. 7.14. The images in columns represent the CBB, that is the DBB architecture for two power levels. The x-axis in each image depicts the number of macro cell users while the y-axis shows the target throughput gain. The rows in Fig. 7.14 represent different cell density. The heterogeneity of spectrum requirement suggests the significance of the parameters - the target throughput and the network load, for a given LPN density. Note how this effect moves from the left-hand corner of each image in the first row to the right-hand corner at the bottom row, following the increase in the number of LPNs. The impact of power (within the same architecture) is more significant in a network with a medium density of LPNs (the second row in the figure). Here, for low or medium throughput gain values, a higher power almost always corresponds to a reduced spectrum requirement.

7.5 Sensitivity Analysis

In the previous section, only a small subset of the overall results is presented. Namely, with all the parameters used in this analysis: the density of LPNs, the number of users in a macro cell, target throughput gains, the availability of CS spectrum, the number of "foreign" interferers and power scaling, in total 2880 possible combinations were considered ($4 \times 5 \times 4 \times 4 \times 5 \times 7 + 4 \times 5 \times 4$). The contribution of each of these parameters to the spectrum requirement is determined using sensitivity analysis. Before presenting the findings resulting from the sensitivity analysis, it should be noted that out of all the combinations, in 17 % of them, the CBB architecture performs better than the DBB architecture. That difference, as mentioned earlier, is always 5 MHz. Also, it is much more pronounced for 2 and 4 LPNs, corresponding with low to medium target throughput gain ($\times 2$) and ($\times 4$). Namely, the main factor affecting the difference in the user rate between the architectures is the capability of the CBB architecture to avail of the EO spectrum. However, the contribution of the EO spectrum to the user rate is reduced due to the signalling overhead and also depends on the network load in the macro cell. Hence, it is greater for low and medium density of LPNs, resulting in a difference in the spectrum requirement that does not exceed 5 MHz (due to the adopted nominal channel width).

Returning now to the sensitivity analysis, of particular interest is the contribution of different parameters, for a given density of LPNs. There are many ways in which the sensitivity analysis can be performed. One of the reviews of sensitivity analysis techniques is given in [166]. There, amongst other techniques, a simple sensitivity analysis that allows to determine sensitivity index (SI) and ranking based on the percentage difference in the output is outlined. To assess the SI, a single parameter is varied from its minimum to the maximum value, for the whole range of values, according to formula in 2.4. in [166]:

$$SI = \frac{D_{max} - D_{min}}{D_{max}} \quad (7.11)$$

where D_{min} and D_{man} are the function outputs for the minimum, that is the maximum considered value, whereas all other parameters are fixed. In this analysis, D_{min} and D_{max} can be written as:

$$D_{min} = w(p_{min}) \quad (7.12)$$

and

$$D_{max} = w(p_{max}) \quad (7.13)$$

where $w(p_{min})$ and $w(p_{max})$ are computed spectrum requirements that correspond to a minimum p_{min} , that is a maximum p_{max} value of the parameter in question.

Based on the above, the following sensitivity indices are computed: number of users

(SI_K), target throughput (SI_T), number of "foreign" interferers (SI_I), and power in CS band (SI_p). Each SI, therefore, signifies the contribution of a change of the parameter to the change in spectrum requirement. Two cases of CS channel availability are considered separately. When CS band is not available, only the impact of the target throughput gain and the number of users (for a given number of LPNs) can be analysed, as other parameters are not applicable. In the case of availability of CS band, all parameters are considered. In essence, the greater the absolute value of the index is, the greater is the contribution of the corresponding parameter. Negative sign indicates that as the parameter increases, the function value decreases. It should be noted that $-\infty$ appears when the spectrum requirement is 0 (Eq. 7.11), for the maximum considered value of the input parameter.

It should be noted that in the analysis, the SIs are computed for the whole range of values for each parameter. The interest here, however, is in understanding the impact when a parameter changes from its minimum to the maximum considered value. For that reason and brevity, the detailed analysis is presented when p_{max} takes the highest value from the values presented in Section 7.3, p. 121. The key observations when p_{max} takes other values from within the considered intervals are outlined in Section 7.6, p. 143.

7.5.1 CS band not available

The value of the sensitivity index for K, SI_K , for both architectures and all densities of LPNs, is presented in Table 7.5. Maximum and minimum values are highlighted. As can be seen, changing the number of users for cases when the target throughput gain is either ($\times 10$) or ($\times 20$), with 2 LPNs, does not result in a change in the spectrum requirement in either architecture - i.e. $SI_K = 0$ (see also Fig. 7.9). Here, the maximum bandwidth is required due to a high target throughput, regardless of the number of users. Similarly, with target throughput gain ($\times 2$) and 20 LPNs in both architectures (see Fig. 7.11 - row 1), the same amount of spectrum is required, regardless of the number of users or the baseband architecture i.e. $SI_K = 0$. On the other hand, in 25% of all cases that show sensitivity to the change in the number of users, the CBB architecture has a higher value of index. Namely, for lightly-loaded cells ($K = 10$), the EO spectrum contributes more significantly to the overall throughput and reduces the spectrum requirement. Hence, the difference in spectrum requirement between $K = 10$ and $K = 50$ is greater in the CBB architecture than in the DBB architecture in these cases. For 20 LPNs and target throughput gain ($\times 10$) both architectures see the same, highest value of index. The sensitivity of spectrum requirement to the change in target throughput can be seen in Table 7.6. It is clear that for higher density of LPNs, i.e. the cases with 10 and 20 LPNs, the spectrum requirement changes with the change in target throughput gains, for almost all the cases of network load (i.e. the number of users). Namely, with 20 LPNs and target throughput ($\times 2$), the minimum amount of spectrum is required in both architectures, regardless of the number of users. With target

Table 7.5 SI_K when the CS band is not available. The value is computed, based on the spectrum requirement for $K = 10$ and $K = 50$.

	2 LPNs		4 LPNs		10 LPNs		20 LPNs	
	CBB	DBB	CBB	DBB	CBB	DBB	CBB	DBB
Target TH gain ($\times 2$)	0.75	0.5	0.67	0.67	0	0.5	0	0
Target TH gain ($\times 4$)	0.5	0.25	0.75	0.5	0.67	0.67	0.5	0.5
Target TH gain ($\times 10$)	0	0	0.25	0.25	0.75	0.5	0.75	0.75
Target TH gain ($\times 20$)	0	0	0	0	0.25	0.25	0.5	0.5

throughput ($\times 20$), the required bandwidth reaches maximum value when $K \geq 30$ - see Fig. 7.11, p. 132. The change in the target throughput does not affect the spectrum requirement for the case of 2 LPNs and $K \geq 40$ in both architectures, as maximum bandwidth is needed in these cases, as illustrated by Fig. 7.9, p. 130. For the cases of 2 LPNs, when $K \leq 30$, the sensitivity in the CBB architecture is higher than in the DBB architecture due to a greater value of the numerator in (Eq.7.11), which is a result of a reduced spectrum requirement for the minimum (baseline) value of the target throughput.

Table 7.6 SI_T when the CS band is not available. The value is computed, based on spectrum requirement for target TH gain $\times 2$ and $\times 20$.

	2 LPNs		4 LPNs		10 LPNs		20 LPNs	
	CBB	DBB	CBB	DBB	CBB	DBB	CBB	DBB
$K = 10$	0.75	0.5	0.75	0.75	0.67	0.67	0.5	0.5
$K = 20$	0.5	0.25	0.75	0.5	0.75	0.75	0.67	0.67
$K = 30$	0.25	0	0.5	0.5	0.75	0.75	0.75	0.75
$K = 40$	0	0	0.5	0.25	0.75	0.75	0.75	0.75
$K = 50$	0	0	0.25	0.25	0.75	0.5	0.75	0.75

7.5.2 CS band available

Sensitivity indices for the case of CS band availability are given in the Appendix 1, where they are laid out per a number of LPNs. The trends in this subsection for each of the indices are described per a number of LPNs. The reader should note that the calculation of the SI_I index refers to the case when the baseline value for the number of "foreign" interferers is 3. Furthermore, the value of SI_I is 0 for 2 and 4 LPNs, which can be observed in Fig. 7.12, p. 133 and Fig. 7.13, p. 134.

7.5.2.1 2 LPNs

SI_K . $SI_K \in [0, 1]$. The maximum value is reached in the CBB architecture, for target throughput ($\times 2$), only in the case when there are no "foreign" interferers, and power levels are 21 – 30 dBm. In these cases, the spectrum requirement goes from 0 to 20 MHz, as illustrated by Fig. 7.9, p. 130 for 30 dBm. Also, the sensitivity index changes with different power levels in both architectures only when there are no "foreign" interferers. As discussed earlier (also see Fig. 7.9), with 2 LPNs and high target throughput gains ($\times 10$ and $\times 20$), maximum amount of spectrum is required, regardless of the number of users, the number of interferers, or the architecture. For that reason, half of all the cases have zero sensitivity in both architectures.

SI_T . $SI_T \in [0, 1]$. In the CBB architecture, the target levels have the highest contribution in the case of lightly loaded cell ($K = 10$), and when there are no "foreign" interferers, see Fig. 7.9, p.130, with power levels between 21 – 30 dBm. In the DBB architecture, the sensitivity index is slightly reduced as the DBB architecture does not benefit from the EO spectrum and hence requires more spectrum to meet the baseline target throughput gain ($\times 2$). In both architectures, the sensitivity index changes with power only for the case when there are no "foreign" interferers and $K \leq 30$.

SI_p . $SI_p \in (-\infty, 0]$. Changes in power affect spectrum requirement only in few cases when $K = 10$ and $K = 20$ and there no "foreign" interferers, with target throughput gain of $\times 2$. The value of index is negative, which is a result of a decrease in the required spectrum when power changes from the baseline to the maximum value. In the CBB, the index value $\rightarrow -\infty$ for $K = 10$, resulting from a decrease of spectrum requirement to 0 MHz. In the DBB architecture, the value of the index goes down to -1 .

7.5.2.2 4 LPNs

SI_K . $SI_K \in [0, 1]$, but now the sensitivity of the index when target throughput gain is ($\times 10$) can also be seen. This effect occurs due to a higher density of LPNs, which provides more spectral resources and better normalised throughput. In the CBB architecture, the

strongest influence of parameter K is for target throughputs ($\times 2$) and ($\times 4$), with no "foreign" interferers and powers 11 – 30 dBm in the CBB architecture. The DBB also sees the maximum value of the index, but only for target throughput gain ($\times 2$). Again, the sensitivity index changes with power only in the case when there are no "foreign" interferers. However, the number of cases that show sensitivity to the changes of parameter K has doubled compared to the case with 2 LPNs. Now, only the cases with high target throughput gains ($\times 20$) in both architectures result in $SI_K = 0$, as there is no change in the spectrum requirement.

SI_T . $SI_T \in [0.25, 1]$. This means that in all cases, the change in target throughput from the baseline to the maximum value results in a change in the spectrum requirement. Fig. 7.14, p. 135, row 2, illustrates these effects for two power levels and 0 interferers. The index reaches its maximum for power levels 11 – 30 dBm and $K = 10$, when there are no "foreign" interferers. This is the case for both architectures. In the CBB architecture, this is also the case for $K = 20$. With "foreign" interferers, there is no difference in the values of SI_T for different power levels.

SI_p . $SI_p \in (-\infty, 0]$. Non-zero values of the sensitivity index can be found for low-medium target throughput gains, corresponding to different number of users, in the instances when there are no "foreign" interferers. In the CBB architecture, index $\rightarrow -\infty$ in a few cases for target throughput gain $\times 2$ and target throughput $\times 4$ and $K = 20$. In the DBB architecture, index $\rightarrow -\infty$ only for target throughput gain $\times 2$ and $K = 10$.

7.5.2.3 10 LPNs

SI_K . $SI_K \in [0, 1]$. However, only in the CBB architecture, there are cases that show no sensitivity ($SI_K = 0$). These cases occur for different power levels, and number of interferers, but always for target throughput gain $\times 2$. The effect can be seen in Fig. 7.14, p. 135, row 3 for the case with 0 interferers and power levels 1 and 21 dBm. The highest value of the index also occurs when there are "foreign" interferers - 3 or 10 in both architectures.

SI_T . $SI_T \in [0.5, 1]$. Evidently, the minimum value of this index increases with the increase in the LPN density. For the case with no "foreign" interferers, for almost all power levels and number of users, the value of this index is 1 in the CBB architecture. It is a result of spectrum requirement increase from the minimum (baseline) value of 0 MHz - see Fig. 7.14, p. 135, row 3. With the increase in number of interferers, the impact of the target throughput is reducing in both architectures as the spectrum requirement for target throughput $\times 2$ increases. SI_T is lowest for $K = 50$ and cases with 20 and 30 foreign interferers in the DBB architecture.

SI_I . $SI_I \in [0, 1]$. A general trend in the CBB architecture is that for a low target rates and a low number of users, the change in the number of interferers from 3 to 30 has the highest possible impact. With the increase in number of users and target rates, the impact lessens, see Fig. 7.13, p. 134. For example, $SI_I = 0$ for target throughput $\times 2$ and $K = 50$ in the CBB architecture. Also, in the CBB architecture, the sensitivity to the changes in the number of interferers does not depend on the power levels. In the DBB architecture, 42% of all cases show no sensitivity to the change in number of interferers, as opposed to 40% in the CBB architecture.

SI_p . $SI_p \in (-\infty, 0]$. The non-zero values appear in 15% and 13.75% of the cases for the CBB and DBB architectures, respectively. They are observed in cases with 0 and 10 foreign interferers in both architectures, and appear for different target throughput gains and number of users.

7.5.2.4 20 LPNs

SI_K . $SI_K \in [0, 1]$. The spectrum requirement does not show sensitivity to the change in number of users for target throughput $\times 2$, and number of "foreign" interferers ranging from 0 to 20 in the CBB and 0 to 10 in the DBB architecture. Namely, with such a high number of LPNs that provide spectral resources, the impact of the number of users is eliminated for low target throughput rates and the above-mentioned number of interferers. Fig. 7.14, p. 135, row 4 illustrates this effect for the case with 0 interferers and two power levels. The number of cases with maximum sensitivity is also increased to 50% of all cases in each architecture as their spectrum requirement is reduced to 0 MHz when there are 10 users in a macro cell.

SI_T . $SI_T \in [0.75, 1]$. In the CBB architecture, 96% of all cases have a maximum value of the index. The exceptions are the cases with 30 "foreign" interferers and $K = 50$. In the DBB architecture, over 87% of cases take the maximum value of the index, for 0, 3 and 10 "foreign" interferers. The reduced value of 0.75 can, hence, be seen for higher number of users and "foreign" interferers in both architectures.

SI_I . $SI_I \in [0, 1]$. The number of cases where $SI_I = 0$ increases compared to the case with 10 LPNs, while the number of cases with the maximum value ($SI_I = 1$) decreases. There is no dependence on the power levels in either architecture, while the sensitivity index changes with the number of users and target rates.

SI_p . $SI_p \in (-\infty, 0]$. The non-zero values can only be found in 3 cases in each architecture.

7.5.3 Synopsis of the sensitivity analysis

This subsection gives a synopsis of the sensitivity analysis for each of the sensitivity indices.

- SI_K for all cases of LPN density lies in the interval $[0, 1]$. For 2 LPNs, the results show no sensitivity to a change in the number of users for high target throughput gains of $\times 10$, and $\times 20$ in both architectures, regardless of CS channel availability. There, for half of all the cases, the sensitivity index is zero for both architectures, as maximum spectrum is required regardless of the change in the number of users. As the LPN density increases, so does the sensitivity to this parameter in both architectures. With 20 LPNs, half of all the cases have a maximum sensitivity in both architectures when CS channel is available ($Av_{cs} = 1$). When CS channel is not available ($Av_{cs} = 0$), the maximum sensitivity ($SI_K = 1$) is not reached for any density of LPNs, as there is no benefit to the user rate from the CS spectrum and the difference in spectrum requirement for $K = 10$ and $K = 50$ is smaller compared to when $Av_{cs} = 1$.
- SI_T lies in $[\alpha, 1]$, and α increases with the number of LPNs from 0 to 0.75. In other words, the minimum impact of the target throughput increases with the number of LPNs. Interesting is the case with 20 LPNs, when the highest value of this index can be observed for 96% of all cases in the CBB architecture (when $Av_{cs} = 1$), regardless of power, the number of users and the number of "foreign" interferers. In the DBB architecture, this is valid for over 87% of cases when $Av_{cs} = 1$. Hence, for 20 LPNs, the change in the target throughput from the baseline ($\times 2$) to the maximum considered value ($\times 20$) has a maximum impact on the change in spectrum requirement in most cases, regardless of the power levels, interferers and number of users. Again, when CS channel is not available, the index does not reach the maximum value ($= 1$) due to the increased spectrum requirement for the baseline value of the target throughput gain ($\times 2$).
- SI_I In computing SI_I , 3 was the baseline for the number of foreign interferers. The change in their number has no impact on the change in spectrum requirement for the case of 2 and 4 LPNs. Namely, in these cases the user rate provided by the CS spectrum does not affect the spectrum-decision process, as the percentage of users that can access the band is below 70%, which is the adopted threshold value for access probability. For the cases of 10 and 20 LPNs, SI_I lies in the interval $[0, 1]$. The sensitivity to the change in the number of interferers shows a dependence on the power levels (given the number of users, and target throughput) only in a few cases of the DBB architecture for 10 LPNs. Both architectures see the maximum sensitivity of the index ($SI_I = 1$). For 10 LPNs, more cases show sensitivity in the CBB architecture, while the situation is reversed with 20 LPNs.

- The sensitivity index for power has the maximum absolute value of all indices - $-\infty$, as in these cases, with the increase in power, the spectrum requirement reduces to 0. The greatest number of cases showing sensitivity to the change in power levels can be observed for 4 and 10 LPNs in both architectures. For 2 and 4 LPNs, the CBB architecture has more cases with the maximum absolute value of the index due to the benefit of the EO spectrum, which reduces spectrum requirement to 0 MHz. In case of high LPN density (10 and 20 LPNs), non-zero sensitivity indices in two architectures are seen in a few cases, for different target throughput gains. With 20 LPNs, however, practically power change does not result in a change in spectrum requirement.

7.6 Key findings - Discussion & Summary

This chapter presented a comprehensive analysis of the proposed framework for both baseband architectures, relying on Carrier Aggregation and Dual Connectivity. The analysis was performed for the case when both shared carriers come from the same band - 3.5 GHz. As QoS metric, the average throughput of a typical user that can access shared spectrum is analysed. The objective is to determine the minimum spectrum requirement from the ES spectrum to meet the target rate for such a user. In this way, the cost to the cellular operator is minimised, while meeting the QoS requirements. System parameters and their values, different baseband architectures and the introduction of design parameters in the spectrum decision process, such as access probability threshold directly influence the obtained results. Below are the insights into the key findings of the analysis:

Access probability and access probability threshold As discussed in subsection 7.2.4, p. 112, coverage, that is the access probability, is one of the aspects taken into account in the spectrum decision process, as it determines the likelihood of a typical user being able to avail of the spectral resources. It can also be considered as an average percentage of users within the coverage of LPNs. The results show that even with 2 LPNs, a high portion of users avail of the ES band, as the deployment is considered for a small, urban macro cell. Clearly, the access probability in the CS band depends on the power and number of foreign interferers. Power levels play a significant role in the access probability when the number of LPNs is below 10. Namely, with 10 or more LPNs, the network enters interference-limited regime, and as the nodes operate using the same power level, signal-to-interference ratio only depends on the distances between the serving node and interferers. As per the "foreign" interferers, as expected, their number has a detrimental effect on the access probability - evident even with a small number, particularly for 2 and 4 LPNs. By deploying a denser network, the operator can significantly lessen the fall in the access probability due to a presence of "foreign" interferers. For example, for the case of 30 "foreign" interferers, by

increasing the number of LPNs from 10 to 20 increases the percentage of users that can access the band from 48% to 73% (power levels of 30 dBm).

Mean normalised throughput The mean normalised throughput in the ES band increases with the number of LPNs up to 4 LPNs when it reaches a plateau. Further increase in the density - from 10 to 20 LPNs reduces the mean spectral efficiency due to the inter-cell interference. The situation in the CS spectrum is more nuanced, as it depends on the power levels and the number of "foreign" interferers, in addition to the density of LPNs. The results show that there is no dependency on power in the CS band for 10 "foreign" interferers or more, due to the interference-limited regime. Furthermore, as is the situation in the ES spectrum, increasing the LPN density from 10 to 20 LPNs, results in a reduced spectral efficiency. This is valid for the cases of 0 and 3 foreign interferers due to inter-cell interference among operator's nodes. However, where the number of "foreign" interferers exceeds 3, mean spectral efficiency diverges from this trend. Then, an increase in the mean spectral efficiency is seen, resulting from network densification, which lessens the impact of "foreign" interferers that now dominate the interference. Hence, network densification helps not only in improving the coverage but also in increasing the mean spectral efficiency when CS band is highly congested.

Maximum amount of spectrum and channel width of 5 MHz The use of a cap on the maximum amount of bandwidth from the ES spectrum greatly affects the results and findings presented in this Chapter. As discussed earlier (p.115), the limit on the amount of the ES spectrum has been introduced to reflect the real LTE-Advanced system, with the focus on a single CC. Such a system setting also impacts QoS in cases with high target throughput rates and low density of LPNs, as with the imposed limit on the amount of bandwidth, the target rates cannot be met. Regardless of the actual limit that may be applied, considering bandwidth greater than 20 MHz requires aggregation of channels with an increased impact of system overhead on spectrum requirement.

Clearly the results are also affected by the adopted channel width. By using, for example, a smaller bandwidth - e.g. 3 or 1.4 MHz provides a better granularity of spectrum requirement and hence a more efficient use of spectrum resources. However, LTE does not provide channels that are multiples of e.g. 1.4 MHz.

Impact of CS channel availability Evidently, within each baseband architecture, the availability of CS reduces spectrum requirement and increases with the LPN density. This effect occurs due to an increasing spatial spectrum reuse of the CS spectrum. The results show that for 2 and 4 LPNs, the reduced spectrum requirement occurs when there are no "foreign" interferers in the CS band and for low-medium target throughput gains. With 10

and 20 LPNs, the reduction in spectrum requirement occurs in significantly more instances, even for a congested CS channel (with up to 10 and 30 "foreign" interferers, respectively), and for all considered target throughput gains and network loads. The difference is in a majority of instances 5 MHz and only in a few cases reaches 10 MHz.

Difference between the CBB and DBB architectures For the adopted system parameters, the results show that the CBB architecture performs better than the DBB architecture in 17% of all instances. The difference in spectrum requirement between the two architectures is always 5 MHz, and can be seen for all LPN densities. However, it is more pronounced for 2 and 4 LPNs, corresponding to low to medium target throughput gain ($\times 2$) and ($\times 4$). With a high density of LPNs, the difference between the architectures can be observed for all target throughput gains. The difference in spectrum requirement is a direct consequence of the fact that CBB architecture can exploit EO spectrum resources, in addition to the shared spectrum, contributing to the user rate. As outlined earlier however, the contribution of the EO spectrum to the user rate is reduced due to the signalling overhead and also depends on the network load in the macro cell. In case the maximum bandwidth from the ES spectrum is higher than the considered value of 20 MHz, it can be anticipated that a significantly larger percentage of instances would differ in the spectrum requirement between the two architectures. Namely, the spectrum requirement would have a greater range of values and there would also be overhead implications due to aggregation of channels. In case smaller channel widths are used, it could also be expected that the number of instances with different spectrum requirements between the architectures would increase due to a finer granularity of the computed bandwidth.

Sensitivity analysis An important tool for determining the importance of different parameters and their values on the spectrum decision process is a sensitivity analysis. The results of the sensitivity analysis conducted in this chapter highlight few interesting trends:

- For a low density of LPNs and high target throughput gains, the change in the number of users does not affect the result, as maximum bandwidth is needed even for a lightly loaded macro cell. The sensitivity to a change in the number of users grows with the density of LPNs, and with 20 LPNs half of all the cases in both architectures have the maximum value of the index as there is no requirement to resort to the ES spectrum for a lightly loaded macro cell.
- Similarly, the sensitivity to the changes in target throughput increases with the rise in the LPN density. With 10 and 20 LPNs, the change in target throughput gain always impacts the spectrum requirement, regardless of the number of users, the availability of the CS channel, its power and number of interferers. With 20 LPNs, when CS channel is available, most instances in both architectures see the maximum value of

the index as the spectrum requirement for the minimum target throughput is reduced to 0 MHz.

- Clearly, for an operator the best use of the CS band takes place when there are no "foreign" interferers. The results illustrate that there is no impact of having more than three (3) "foreign" interferers on the spectrum requirement for 2 and 4 LPNs. In these cases, the access probability goes below the adopted value of the access probability threshold of 0.7, even for 3 interferers and hence CS spectrum does not play a role in the decision-making process. Hence, for the low and medium density of LPNs with "foreign" interferers, the resources provided by the CS spectrum do not reduce the spectrum requirement in either architecture. For high LPN density, "foreign" interferers sensitivity index changes, in the main, with the number of users and the target throughput, but not with the power.
- The maximum absolute value of any of the index is found with power, as the increase in power results in a drop in spectrum requirement to 0 MHz. Sensitivity is seen for different target throughputs, the number of users and interferers, but mainly up to 10 LPNs. For 20 LPNs the change in power, practically, does not affect the change in spectrum requirement.
- Overall, there is a greater sensitivity to the CBB architecture as it requires less spectral resources for the baseline value of each of the parameter, benefiting from the EO band. The exceptions are the cases where for the CBB architecture the sensitivity indices are 0 due to the constant spectrum requirement when changing the parameter from the baseline to its maximum value.
- Finally, as mentioned earlier (p. 137), sensitivity indices are also computed for other ranges of parameters. A brief analysis shows that, in these cases, the sensitivity of spectrum requirement to the changes in target throughput and the number of users is reduced in value, but also in the number of instances. For example, the number of cases showing sensitivity when the maximum considered target throughput is $\times 4$ for 10 and 20 LPNs is significantly reduced. In terms of power, there is no sensitivity to the changes in power from 1 to 16 dBm for 2 LPNs and from 1 to 6 dBm for 4 LPNs. As per a change in the number of "foreign" interferers, with 10 LPNs, sensitivity is the same regardless whether the maximum number of interferers is 20 or 30. With 20 LPNs, the CBB architecture does not show sensitivity for the case when the maximum number of interferers is 10.

Chapter 8

Conclusion

8.1 What this thesis addresses

The objective of the framework was to provide a broad basis for spectrum sharing in different frequency bands and embrace different sharing models. The sharing models represent two distinct and wide-ranging classes of spectrum - one based on the fee-paying, exclusive transmission, and the other based on a free, open access regime. Furthermore, the framework was set within a heterogeneous network, which is of great importance in enabling spatial densification using low power nodes. The framework dealt with the two opposing baseband architectures - namely, the centralised one comprising RRHs and the distributed one using small cells. The central proposition of the framework was to extend two inherent features of LTE-Advanced - Carrier Aggregation and Dual Connectivity and systematically incorporate spectrum sharing of the two spectrum classes. To achieve this, the spectrum selection mechanism was put forward, addressing two typically competing objectives - providing QoS and minimising spectrum costs.

In summary, the thesis addressed:

- the need for wider bandwidths and use of spectrum resources from highly fragmented spectrum bands using Carrier Aggregation and Dual Connectivity
- the heterogeneity of shared spectrum resources from different frequency bands, with different sharing rules
- the network topologies featuring a tier of high-power equally spaced nodes, overlaid by randomly placed LPNs with both, centralised and the distributed baseband processing
- the balancing of QoS and cost for the cellular operator through spectrum selection mechanism, which minimises cost, while at the same time provides the required QoS

- the identification and the analysis of the main factors that affect spectrum selection decisions in both architectures, given different densities of low power nodes
- the formalising of the effect of each of the inputs into the spectrum selection process using sensitivity analysis.

In this, the literature review provided the context and aided the identification of the topics and the issues of relevance. Namely, the ISM bands, WiFi, Cognitive Radio and Dynamic Spectrum Access, together with the main spectrum sharing initiatives i.e. TV White Spaces, LSA and CBS, discussed in Chapter 1. Some of them were used as input in Chapters 4, 6 and 7. Carrier Aggregation and Dual Connectivity, discussed in Chapter 2, were used as input in Chapters 6 and 7. The topology and architecture aspects, also discussed in Chapter 2, were used as input in Chapters 6 and 7.

To evaluate the proposed solutions, the extended simulator HetNet+ was used in modelling the framework in Chapter 6. Additionally, few stand-alone Matlab-based modules were developed to model the scenarios addressed in Chapter 7.

8.1.1 The main findings

Some general findings that should be emphasised include:

- The systematic incorporation of spectrum sharing into LTE-Advanced seems promising. Companies, standards bodies and the research community are beginning to embrace this approach in different guises, which bodes well for the future deployment of the propositions made in the thesis.
- Of particular importance for the framework are the models for the ES and CS spectrum classes. The rules of each sharing band determine these, including the techniques for accessing the shared spectrum, the operating parameters and importantly, in the case of CS spectrum class, how the inter-system interference is modelled. In the main, the thesis considers a database-governed access to spectrum, according to a few major spectrum sharing initiatives, such as TV WS, LSA and CBS. They are also used as a basis to derive the main operating parameters for the simulations. Inter-system interference in the CS band is treated as additive noise.
- Clearly, the results show there is a significant benefit from spectrum sharing using LPNs, particularly in the network with medium & high density of LPNs due to the spatial spectrum reuse, and when CS band is available.
- Many parameters and their mutual interaction affect the proposed sharing framework. Nevertheless, the thesis identifies few critical parameters. For a given density of LPNs, these are the target throughput, number of users, and the availability and the

congestion in the CS band. These factors greatly impact the cost for the operator, as they are central to determining the spectrum requirement from the ES band.

- Network densification has multiple benefits in the proposed framework. In both bands, it significantly improves the end-user throughput due to the spatial spectrum reuse. Besides, in the CS band, when band is highly congested, it lessens the impact of "foreign" interferers by enabling a higher percentage of users to avail of the band, and by increasing the mean spectral efficiency.
- The nominal channel width and the maximum amount of bandwidth from the ES band also have a significant impact on the spectrum requirement and QoS. Namely, using a smaller nominal channel than 5 MHz would achieve a better granularity of spectrum requirement, and thus a more efficient use of spectrum resources. However, the nominal channel is determined not only by the channel width of the ES band but also by what the cellular systems (LTE-Advanced and future 5G systems) support. As per the maximum amount of spectrum that the ES spectrum can provide, the results have shown that the cap affects QoS, particularly in cases with a low density of LPNs and high target throughput rates, as the target rates cannot be met even with the maximum amount of spectrum.
- The results show that it matters whether sharing is implemented using CBB or DBB architecture. In other words, with LPNs, sharing cannot be abstracted from the underlying fronthaul/backhaul infrastructure. For example, in the 3.5 GHz band case study in Chapter 7, in 17% percent of all cases, the baseband architecture played a differentiating role. Namely, as the CBB architecture exploits EO spectrum resources, in addition to the shared spectrum, it benefits more from the use of the free CS band. These effects are most pronounced for the medium density of LPNs.
- Due to a multitude of parameters that need to be taken into account in the spectrum decision process, sensitivity analysis is an important tool, determining the relevance of a particular parameter in a considered scenario.
- The sensitivity analysis results show that that for the low & medium number of LPNs, the spectrum requirement, that is the cost to the operator, is not sensitive to the change in the network load, when target throughput is high, as maximum bandwidth is needed even for a lightly loaded macro cell. Also, in these cases, the CS band does not affect the spectrum requirement, as the access probability goes below the adopted threshold value.
- The sensitivity to the changes in target throughput affect the spectrum requirement in all instances with the high density of LPNs, regardless of the number of users, the availability of the CS band, its power and number of interferers.

- Overall, there is a greater sensitivity to the results in the case of the CBB architecture as it requires less spectral resources for the baseline value of each of the parameter since it can use spectral resources from the EO band.

There are also specific findings, relating to the details of the different studies in the thesis. They are listed below under separate headings.

Shared spectrum characterisation. Identifying the appropriate attributes of the shared spectrum and describing them is at the centre of the proposed framework as they directly impact the spectrum decisions. Two aspects deserve to be singled out - the availability and the inter-system interference modelling in the CS band. Regarding the availability, Chapter 4 considered the probability of availability based on a statistical characterisation. Taking into consideration that most of the current sharing initiatives stipulate the use of a geo-location database, where the database signals the availability of spectrum, in other chapters, the availability was analysed in binary terms. In Chapter 6, only the case when the CS channel is available was considered. In Chapter 7, both instances of channel availability were evaluated. Besides, in Chapter 7, the access probability threshold was defined as an input into the selection process, reflecting the conditions and the number of "foreign" interferers operating in the band. The availability of the CS channel and access probability could, therefore, be considered as the joint probability of availability, used as the operator's design parameter, controlling when spectrum from the CS band should be employed as an input into the spectrum decision. Another aspect of particular interest for the CS band is the inter-system interference modelling. The rules for spectrum access decide how the interference is modelled. This thesis treated interference as additive noise and did not consider other interference models, such as LBT. Using, for example, LBT or an LBT-based mechanism would require a different approach to the rate computation, which could have a potentially significant impact on the results.

Selection Criteria. In Chapter 4, the selection criteria unified two aspects - the probability of availability in the CS band and the qualitative measure of the quality of the two bands. Incorporating the probability of availability into selection criteria is important in spectrum bands where a central entity does not dictate the access to a band. Moreover, in bands where spectrum availability is signalled by the database, and the CS band is available, it is important to ensure that the spectrum decision is made based on a sufficiently large number of users that can avail of the band. Hence, as mentioned above, the CS spectrum availability and access probability may be viewed as the joint probability of availability and operator's design parameter for the selection criteria. In Chapters 6 and 7, QoS was evaluated through evaluation of user throughput. User throughput was a clear choice for the analysis, as it reflects the quality of spectrum and the network load, i.e. sharing the radio resources among a number of users. It was also shown that the range of target throughputs

had to be carefully selected, as target throughput was found to be one the main factors affecting spectrum requirement. Using target throughput relative to the throughput of a lightly loaded macro cell is an effective way of defining the selection criteria. Furthermore, considering that the spectrum decision is made on a significantly longer time-scale than the allocation of radio resources within a scheduling interval, the selection mechanism should avail of the simple allocation algorithms, such as round-robin. Finally, the cost model used throughout the thesis in the selection criteria was based on a linear function of bandwidth.

System level analysis. The thesis offered an extensive system level performance analysis as well as the analysis of the trade-off between the spectrum requirement (cost) and QoS. In Chapter 6, the analysis of the CBB architecture, with low to medium density of RRHs included shared carriers with very different propagation characteristics - at 620 MHz and 2.3 GHz. The CS band was modelled through power scaling, that is the chapter considered sharing in the power domain. The results highlighted the importance of the interaction between the density of RRHs and the power domain. The results demonstrated that for the medium density of RRHs, very similar performance could be obtained with the power levels reduced by a 10 dB from the maximum permitted power. A significant effect of the network load and target throughput on spectrum requirement was also illustrated. If the operator had the flexibility of lowering the target rate, the cost could be significantly reduced, particularly in cases of the medium and high load. Chapter 7 provided the system level analysis in the 3.5 GHz band for the entire framework. In addition to the parameters analysed in Chapter 6, Chapter 7 addressed the additional aspect - the inter-system interference in the CS band, modelled using spatially distributed "foreign" interferers (LPNs). This gave an interesting insight into the performance of the CS band in urban and dense urban areas. The results showed that the addition of "foreign interferers" had a significant detrimental effect on the number of users that could access the CS band evident even with a small number of "foreign" LPNs, particularly for the low and medium density of LPNs. However, by increasing the density of its network, the cellular operator could negate the effect of the interferers. The results also demonstrated that the mean spectral efficiency showed no dependency on the power levels with 10 "foreign" interferers or more. With the high density of LPNs (10 and 20) and a greater number of "foreign" interferers, network densification increases mean spectral efficiency, which is the opposite trend of what is seen in the ES band. Finally, as mentioned earlier, the results illustrated the importance of the baseband architecture in 17% of all cases, where the CBB architecture requires less of the ES spectrum. The difference in spectrum requirement is always 5 MHz. A significantly larger percentage of instances between the two architectures could be expected to differ in spectrum requirement if the maximum bandwidth from the ES spectrum is higher than the considered value of 20 MHz, or if smaller channels are used.

Sensitivity analysis Chapter 7 also presented the results of the sensitivity analysis, introduced to formalise the effect of each of the parameters on the spectrum requirement. Sensitivity analysis considered the change in spectrum requirement when an input parameter changed from its minimum to its maximum value while all other parameters were constant. The results showed that sensitivity to the change in the number of users and the target throughput increased with the rise in the number of LPNs. With high LPN density, the change in target throughput always impacts the results, regardless of the number of users, the availability of the CS channel, its power and number of interferers. The change in power levels, on the other hand, affects mainly low and medium density of LPNs, while the change in the number of foreign interferers from minimum to maximum value affects results only in deployments with 10 and 20 LPNs.

Key control plane & signalling aspect Chapter 7 also identified and included in the analysis some major aspects from a control plane and signalling perspective, relying on the existing mechanisms within LTE/LTE-Advanced systems. For example, the framework proposes utilising cell reference signals on all carriers for the purpose of channel estimation and coherent demodulation. In the CBB architecture, the cross-carrier scheduling was availed of, as the EO spectrum carried scheduling and other control information for the shared carriers. This, however, had an impact on the system overhead on the EO spectrum. In the DBB architecture, each carrier carried its signalling information.

Before concluding the thesis with the plans for future work, it is worthwhile to consider what has been done in the last 18 months regarding the standardisation and research to deploy LTE in the unlicensed (5 GHz) spectrum.

8.2 Developments with LTE in unlicensed 5 GHz spectrum

In November 2013, Qualcomm unveiled the initiative to enable operation of LTE in unlicensed spectrum in 5 GHz band [167]. Since then, few different flavours of the proposal have been developed and included as part of 3GPP standardisation - notably, LTE-Unlicensed (LTE-U) and License-Assisted Access (LAA), which both rely on the operation in the licenced spectrum. LTE-U and LAA use Carrier Aggregation in TDD mode or together with supplemental downlink. LTE-U targets deployments in the markets where LBT is not a requirement for the 5 GHz band, such as the US, Korea and China [168]. Although current LTE mechanisms and features up to Release 12 can be used to operate in the 5 GHz WiFi band, a number of works have shown that as-is LTE operation on the same channel significantly impairs the WiFi performance. In [169], the impact of coexistence between LTE and WiFi at 900 MHz on each system's performance is analysed. The authors show that while LTE suffers from a slight throughput degradation, the sharing severely

degrades WiFi performance, with WiFi station being in the listen-mode for more than 95% of the time. The impact of LTE operation and its effect on WiFi performance has been evaluated in [170], where authors consider the LTE operation in TDD and FDD mode. Analytical and numerical results show significant performance degradation for WiFi, even when considering the longest period when LTE system is silent. With the increase in the number of WiFi stations, this impact becomes even greater. Consequently, LTE-U Forum¹ has recognised the potential implications LTE-U may have on WiFi and issued technical report [171], which proposes three mechanisms to enable fair co-existence of LTE with WiFi. The first one includes an algorithm for channel selection, which entails choosing the best possible, uncongested channel, as well as monitoring the congestion and, if required, changing the channel. In case a clean channel cannot be found, the LTE operation would be muted for a period to allow the coexistence with WiFi. Besides, [171] proposes LTE cells operating at 5 GHz band to be dynamically switched on/off, depending on the traffic demand. In markets where LBT is a requirement, such as Europe and Japan, LAA will be implemented - it is now a part of 3GPP Release 13 [172]. Besides, the report also stipulates the use of WiFi channel frequencies only to reduce the search space for eNodeB and UE.

Clearly, the developments in standardisation have sparked significant interest in research in this domain. In addition to the works mentioned above, the system performance with WiFi coexisting with LTE is evaluated in [173], where LTE system is muted for a percentage of its transmission interval. Sharing between WiFi and LTE is proposed in [174], using LBT and RTS/CTS mechanism. The authors in [175] propose a design of MAC protocol for LTE-U to enable co-existence with Wifi, including asynchronous and synchronous LBT mechanism, medium reservation and modified link adaptation algorithm. As expected, LBT improves WiFi performance, therefore improving coexistence, which together with the appropriate selection of energy detection threshold for LTE-U system improves fairness and performance of both systems. In [176], proportional fair access is proposed to enable better coexistence between LTE-U and WiFi. The scheme does not require the exchange of messages between LTE and WiFi systems. Instead, the LTE system calculates the optimum probability of accessing the channel. LTE is only required to perform channel monitoring while WiFi does not need any changes to its protocol operation. To overcome unfairness with LTE-U, in [177] an etiquette whereby WiFi system is a primary user is proposed. For the proposed spectrum etiquette, LTE-802.11 fusion protocol stack for eNodeB is presented, comprising of the enhanced LTE and 802.11 protocols, which are modified to enable the exchange of signalling messages between the protocol stacks. Besides, the paper proposes interference coordination by eNodeBs to improve the performance of LTE in the unlicensed band. A distributed Q-learning mechanism on a cell level is proposed in [178], aimed at choosing a best possible channel in the WiFi band. The authors claim almost entirely optimal performance while also

¹<http://www.lteuforum.org>

pointing out the need to further evaluate the implications and performance of Q-learning channel selection and strategy design. Finally, a more detailed analysis of the implications for LTE systems for the operation in 5 GHz WiFi band is given in [179]. The article considers an enhanced mechanism for LBT, including a back-off defer period, as well as discontinuous transmission feature, both aimed to improve the coexistence. It then goes to discuss the impact and possible design of the shared/control channels, reference signals, feedback and retransmissions, as well as radio resource management aspects. The coexistence is analysed for a range of indoor and outdoor scenarios.

8.3 Future Work

The thesis has covered a wide range of work. However, like any thesis, more questions arise from the work. Evidently, analysing the framework proposed in this thesis in the context of the above-described advancements around LTE in the unlicensed spectrum would be one of the first avenues to explore. Namely, future work could entail addressing specific changes to the LTE-Advanced protocol to enable operation what is within the framework the CS band, using LBT mechanism. Furthermore, the use of a lean control plane with more advanced demodulation and reference signals, as hinted at in Chapter 7, and impact on scheduling and retransmissions in both shared bands also need further analysis. Some of these aspects are also pointed out in [179] in the context of 5 GHz band.

A design of scheduling algorithms that will take into account the attributes for particular shared spectrum bands is another important topic to be examined, also outlined in [180]. There, Carrier Aggregation across licenced, licenced-shared, and unlicensed bands is discussed. Although the authors do not consider different baseband architectures, they provide an interesting taxonomy of PHY and RRM challenges for future Carrier Aggregation-based systems. In [181], a dynamic activation of shared carriers, relying on Dual Connectivity is considered. There, a cellular operator owns spectrum used at macro layer and pico layer. An additional - shared carrier is considered at a pico layer only, using dynamic activation. More extensive considerations for a range of PHY and RRM challenges, as well system integration aspects can be found within the ongoing European project titled "Spectrum OverLay through aggregation of heterogeneous DispERsed Bands – SOLDER"². The project focus is on the aggregation of dispersed spectrum bands using licenced, licenced shared and unlicensed bands, with heterogeneous networks and radio access technologies. These examples illustrate that the topic considered in the thesis is not only of interest to the standardisation bodies and research community, but there are many aspects that warrant further investigation.

²<http://ict-solder.eu/>

Also, other QoS aspects besides user throughput should be investigated, particularly considering the requirements of 5G - the platform that will enable growth of diverse applications with massive broadband capabilities. 5G poses very low latency and ultra-high reliability requirements [182] to support existing and new delay-critical and vital applications. The questions, hence, arise about the suitability of each of the considered baseband architecture to support such applications, as well as about the scheduling aspects and spectrum selection mechanism. Also, the uplink communication in Carrier Aggregation and Dual Connectivity introduces different challenges, such as power-limited communication and UE complexity. Hence, the proposed framework may be worth exploring in the context of the uplink, including addressing various QoS aspects.

There are also many interesting, more general challenges that could be addressed by considering the sharing framework in the CBS band, which was indicated in Chapter 7. The sharing framework proposed here could map well to the ideas put forward by PCAST and rules that emerged from the FCC for the use of the 3.5 GHz band. Future work could consider how an LTE-Advanced network would access additional spectrum in the 3.5 GHz bands, under PA and GAA rules, using the proposed sharing framework, and on a much more dynamic basis than what is envisaged by the current regulations. There is also a broad scope to look at traffic demands of different cellular (LTE) operators and determine their correlation in time, as well as options for real-time auctioning of PA access and many more topics.

There are challenges that could be addressed through the implementation and testing of a real framework, with a number of software radio platforms that could be used as a basis. Clearly, extensive work would have to be carried out to extend those platforms to include Carrier Aggregation and Dual Connectivity capabilities. However, a real implementation would quantify the benefits more starkly.

The thesis analysed small cells but did not consider what is already a major trend, which is the use of millimetre wave (mmW) spectrum. Millimetre wave communication with frequencies between 30-300 GHz has been marked as one of "the big three technologies" of 5G [4], together with massive MIMO and ultra-dense networks. A number of challenges associated with such a radical move to these frequencies have already been identified, including an appropriate channel model, multiple access schemes, and resolving the limited coverage [183]. However, of particular interest would be to consider how the use of mmW spectrum would affect the framework. Besides mmW communication, massive MIMO and further densification of networks through the use of different LPNs are identified as cornerstones of 5G. Massive MIMO represents a large-scale antenna system, where a base station houses a much greater number of antennas than the number of active users in the time-frequency resource, which brings a huge increase in spectral efficiency [4]. On the other hand, the use of

much higher frequencies will also necessitate the deployments of single- and multi-hop relays. Hence, there is an extensive scope to consider LPN deployments featuring any combination of small cells, single- and multi-hop relays and massive MIMO and the effects such scenarios would have on the proposed framework. Clearly, they provide a rich environment for research of both - system level issues and PHY aspects.

Finally, there is room for work beyond the purely technical. There are options for exploring what, if indeed any, regulatory changes would need to be made to facilitate the framework, including competition issues that could arise. There is a plethora of cost modelling work that could be pursued to determine the trade-off between the costly CBB architectures, which benefit more from the CS spectrum, versus the cheaper DBB architectures.

In summary, the sharing framework proposed and explored in the thesis offers a clear way forward and opens up many new questions.

References

- [1] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014–2019," White Paper, Cisco, Feb. 2015.
- [2] Ofcom homepage. [Online]. Available: <http://www.ofcom.org.uk/>
- [3] Real Wireless, "Study on the Future UK Spectrum Demand for Terrestrial Mobile Broadband Applications," Report 3.1, Apr. 2014. [Online]. Available: http://stakeholders.ofcom.org.uk/binaries/consultations/cfi-mobile-bb/annexes/RW_report.pdf
- [4] J. Andrews *et al.*, "What Will 5G Be?" *Selected Areas in Communications, IEEE Journal on*, vol. 32, no. 6, pp. 1065–1082, June 2014.
- [5] A. Osseiran *et al.*, "Scenarios for 5G Mobile and Wireless Communications: the Vision of the METIS Project," *Communications Magazine, IEEE*, vol. 52, no. 5, pp. 26–35, May 2014.
- [6] S. Forge, R. Horwitz, and C. Blackman. (2012, February) Perspectives on the Value of Shared Spectrum Access. Final Report for the EC. [Online]. Available: https://ec.europa.eu/digital-single-market/sites/digital-agenda/files/scf_study_shared_spectrum_access_20120210.pdf
- [7] Presidents Council of Advisors on Science and Technology. (2012, July) Report to the President-Realizing the Full Potential of Government Held Spectrum to Spur Economic Growth. [Online]. Available: https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf
- [8] J. Peha, "Approaches to Spectrum Sharing," *Communications Magazine, IEEE*, vol. 43, no. 2, pp. 10–12, Feb 2005.
- [9] Implementing TV White Spaces. [Online]. Available: <http://stakeholders.ofcom.org.uk/consultations/white-space-coexistence/statement>
- [10] "The Impact of Licensed Shared Use of Spectrum," A Report For The GSM Association, Deloitte Prepared in Collaboration with Real Wireless, Jan. 2014. [Online]. Available: <http://www.gsma.com/spectrum/wp-content/uploads/2014/02/The-Impacts-of-Licensed-Shared-Use-of-Spectrum.-Deloitte.-Feb-20142.pdf>
- [11] ITU, "Frequency Ranges for Global or Regional Harmonization of Short-Range Devices," Recommendation SM.1896-0 (11/2011), Nov. 2011.
- [12] J. S. Lee, Y. W. Su, and C. C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE*, Nov 2007, pp. 46–51.

- [13] J. Kruys and L. Qian, *Sharing RF Spectrum with Commodity Wireless Technologies - Theory and Practice*. Springer, 2011.
- [14] IEEE, "802.11-2012 - IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE, Standard V 2012, 2012.
- [15] G. Hiertz *et al.*, "The IEEE 802.11 Universe," *Communications Magazine, IEEE*, vol. 48, no. 1, pp. 62–70, January 2010.
- [16] T. Li, "Improving Performance for CSMA/CA Based Wireless Networks," Ph.D. dissertation, Hamilton Institute National University of Ireland, Maynooth, Maynooth, Co. Kildare, Ireland, 2007.
- [17] A. Medeisis *et al.*, "ISM-Advanced: Improved Access Rules for Unlicensed Spectrum," in *Dynamic Spectrum Access Networks (DYSPAN), 2014 IEEE International Symposium on*, April 2014, pp. 194–205.
- [18] A. Zubow and R. Sombrutzki, "Adjacent Channel Interference in IEEE 802.11n," in *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, April 2012, pp. 1163–1168.
- [19] ECC, "The Current Status of DFS (Dynamic Frequency Selection) in the 5 GHz Frequency Range," ECC, Report 192, Feb. 2015.
- [20] CEPT, "To Study and Identify Harmonised Compatibility and Sharing Conditions for Wireless Access Systems Including Radio Local Area Networks in the Bands 5350-5470 MHz and 5725-5925 MHz for the Provision of Wireless Broadband Services," ECC, Report 57, Mar. 2015.
- [21] L. Verma, M. Fakharzadeh, and S. Choi, "Wifi on Steroids: 802.11ac and 802.11ad," *Wireless Communications, IEEE*, vol. 20, no. 6, pp. 30–35, December 2013.
- [22] A. Balasubramanian, R. Mahajan, and A. Venkataramani, "Augmenting Mobile 3G Using WiFi," *Proceedings of the 8th international conference on Mobile systems, applications, and services (MobiSys)*, p. 209, 2010.
- [23] S. Dimatteo, P. Hui, B. Han, and V. O. K. Li, "Cellular Traffic Offloading through WiFi Networks," *Proceedings - 8th IEEE International Conference on Mobile Ad-hoc and Sensor Systems, MASS 2011*, pp. 192–201, 2011.
- [24] "Integration of Cellular and WiFi Networks," White Paper, 4G Americas, Sep. 2013.
- [25] "Carrier-Wi-Fi: the Next Generation," Ericsson Review, Ericsson, Dec. 2013.
- [26] T. Zheng and D. Gu, "Traffic Offloading Improvements in Mobile Networks," in *The Tenth International Conference on Networking and Services, IARIA, ISBN: 978-1-61208-330-8*, April 2014, pp. 116–121.
- [27] C. Sankaran, "Data Offloading Techniques in 3GPP Rel-10 Networks: A Tutorial," *Communications Magazine, IEEE*, vol. 50, no. 6, pp. 46–53, June 2012.
- [28] "3G/Wi-Fi Seamless Offload," White Paper, Qualcomm, Mar. 2010.
- [29] J. M. III, "Cognitive Radio an Integrated Agent Architecture for Software Defined Radio," Ph.D. dissertation, Royal Institute of Technology (KTH), 2000.

- [30] S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications," *Selected Areas in Communications, IEEE Journal on*, vol. 23, no. 2, pp. 201–220, Feb 2005.
- [31] F. Paisana, N. Marchetti, and L. DaSilva, "Radar, TV and Cellular Bands: Which Spectrum Access Techniques for Which Bands?" *Communications Surveys Tutorials, IEEE*, vol. 16, no. 3, pp. 1193–1220, 2014.
- [32] I. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks," *Communications Magazine, IEEE*, vol. 46, no. 4, pp. 40–48, April 2008.
- [33] M. Mueck *et al.*, "ETSI Reconfigurable Radio Systems: Status and Future Directions on Software Defined Radio and Cognitive Radio Standards," *IEEE Communications Magazine*, vol. 48, no. 9, pp. 78–86, Sept 2010.
- [34] L. Lu, X. Zhou, U. Onunkwo, and G. Li, "Ten Years of Research in Spectrum Sensing and Sharing in Cognitive Radio," *EURASIP Journal on Wireless Communications and Networking*, vol. 28, no. 1, pp. 178–188, Jan 2012.
- [35] E. Axell, G. Leus, E. Larsson, and H. Poor, "Spectrum Sensing for Cognitive Radio: State-of-the-Art and Recent Advances," *Signal Processing Magazine, IEEE*, vol. 29, no. 3, pp. 101–116, May 2012.
- [36] S. Filin, H. Harada, H. Murakami, and K. Ishizu, "International Standardization of Cognitive Radio Systems," *Communications Magazine, IEEE*, vol. 49, no. 3, pp. 82–89, March 2011.
- [37] A. De Domenico, E. Strinati, and M. Di Benedetto, "A Survey on MAC Strategies for Cognitive Radio Networks," *Communications Surveys Tutorials, IEEE*, vol. 14, no. 1, pp. 21–44, 2012.
- [38] M. M. Buddhikot, "Understanding Dynamic Spectrum Access: Models, Taxonomy and Challenges," in *Proc. IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN 2007)*, Dublin, Ireland, 17–20 Nov. 2007, pp. 649–663.
- [39] R. Matheson, A.C. Morris, "The Technical Basis for Spectrum Rights: Policies to Enhance Market Efficiency," The Brookings Institution, Telecommunications Policy, Mar. 2011.
- [40] J. M. Peha, "Sharing Spectrum Through Spectrum Policy Reform and Cognitive Radio," *Proceedings of the IEEE*, vol. 97, 2009.
- [41] A. Medeisis, O. Holland, and L. De Nardis, "Taxonomy of Cognitive Radio Applications," in *Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on*, Oct 2012, pp. 166–170.
- [42] Q. Zhao and B. Sadler, "A Survey of Dynamic Spectrum Access," *Signal Processing Magazine, IEEE*, vol. 24, no. 3, pp. 79–89, May 2007.
- [43] K. Berg, H. Ehtamo, M. Uusitalo, and C. Wijting, "Priority-Based Classification of Spectrum Access Models [Accepted From Open Call]," *Communications Magazine, IEEE*, vol. 51, no. 8, pp. 162–167, August 2013.
- [44] T. Irnich, J. Kronander, Y. Selen, and G. Li, "Spectrum Sharing Scenarios and Resulting Technical Requirements for 5G Systems," in *Personal, Indoor and Mobile Radio Communications (PIMRC Workshops), 2013 IEEE 24th International Symposium on*, Sept 2013, pp. 127–132.

- [45] G. Salami *et al.*, "A Comparison Between the Centralized and Distributed Approaches for Spectrum Management," *Communications Surveys Tutorials, IEEE*, vol. 13, no. 2, pp. 274–290, Second 2011.
- [46] FCC, "Unlicensed Operation in the TV Broadcast Bands, Third Memorandum Opinion and Order," FCC, Report 12-36, Apr. 2012.
- [47] CEPT, "ECC Report 159: Technical and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the White Spaces of the Frequency Band 470-790 MHz," ECC, Report 159, Jan. 2011.
- [48] Ofcom, "TV White Spaces: Approach to Coexistence," Ofcom, Consultation, Sep. 2013. [Online]. Available: <http://stakeholders.ofcom.org.uk/binaries/consultations/white-space-coexistence/summary/white-spaces.pdf>
- [49] ITU, "Digital Divident - Insights for Spectrum Decisions," ITU, Report, August 2012. [Online]. Available: http://www.itu.int/ITU-D/tech/digital_broadcasting/Reports/DigitalDividend.pdf
- [50] D. Makris, G. Gardikis, and A. Kourtis, "Quantifying TV White Space Capacity," *Communications Magazine, IEEE*, vol. 50, no. 9, pp. 145–152, September 2012.
- [51] CEPT, "ECC Report 185: Further Definition of Technical and Operational Requirements for the Operation of White Space Devices in the Band 470-790 MHz," ECC, Report 185, Jan. 2013.
- [52] —, "ECC Report 186: Technical and Operational Requirements for the Operation of White Space Devices under Geo-location Approach," ECC, Report 186, Jan. 2013.
- [53] C. Stevenson, G. Chouinard, and Z. Lei, "IEEE 802.22: The First Cognitive Radio Wireless Regional Area Network Standard," *Magazine, IEEE*, no. January, pp. 130–138, 2009.
- [54] IEEE Computer Society, "IEEE Standard for Information technology - Local and metropolitan area networks - Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Television White Spaces (TVWS) Operation," IEEE, Standard, December 2013.
- [55] WeightlessSIG. [Online]. Available: <http://www.weightless.org/>
- [56] S. Filin *et al.*, "IEEE 1900.7 Standard for White Space Dynamic Spectrum Access Radio Systems," in *Standards for Communications and Networking (CSCN), 2015 IEEE Conference on*, Oct 2015, pp. 218–223.
- [57] ETSI, "TS 103 145 - Reconfigurable Radio Systems (RRS); System Architecture and High Level Procedures for Coordinated and Uncoordinated Use of TV White Spaces," ETSI, Technical Specification V1.1.1, Jan. 2015.
- [58] —, "TS 103 143 - Reconfigurable Radio Systems (RRS); System architecture for Information Exchange between Different Geo-location Databases (GLDBs) Enabling the Operation of White Space Devices (WSDs)," ETSI, Technical Specification V1.1.1, Jan. 2015.
- [59] —, "EN 301 598 - White Space Devices (WSD); Wireless Access Systems Operating in the 470 MHz to 790 MHz TV Broadcast Band," ETSI, European Standard V 1.1.1, Apr. 2014.

- [60] —, “Draft EN 303 387 - Reconfigurable Radio Systems (RRS); Signalling Protocols and information exchange for Coordinated use of TV White Spaces; Interface between Cognitive Radio System (CRS) and Spectrum Coordinator (SC) ,” ETSI, European Standard V1.0.1, Jul. 2015.
- [61] FCC, “Amendment of the Commission’s Rules with Regard to Commercial Operations in the 3550- 3650 MHz Band,” FCC, Report 15-47, Apr. 2015.
- [62] CEPT, “Licensed Shared Access (LSA),” ECC, Report 205, Feb. 2014.
- [63] M. Mustonen *et al.*, “Analysis of Requirements from Standardization for Licensed Shared Access (LSA) System Implementation,” in *Dynamic Spectrum Access Networks (DySPAN)*, 2015 IEEE International Symposium on, Sept 2015, pp. 71–81.
- [64] CEPT, “ECC Decision (14)02: Harmonised Technical and Regulatory Conditions for the Use of the Band 2300-2400 Mhz for Mobile/Fixed Communications Networks (MFCN),” ECC, Decision (14)02, Jun. 2014.
- [65] —, “Technological and Regulatory Options Facilitating Sharing Between Wireless Broadband Applications (WBB) and the Relevant Incumbent Services/Applications in the 2.3 GHz Band,” CEPT/ECC, Report 56, Mar. 2015.
- [66] ETSI, “ETSI SR 103 13 Electromagnetic Compatibility and Radio Spectrum Matters (ERM), System Reference Document (SRdoc); Mobile Broadband Services in 2300-2400 MHz Frequency Band Under the Licensed Shared Access Regime,” Special Report V1.1.1, Jul. 2013.
- [67] —, “ETSI TS 103 154: Reconfigurable Radio Systems (RRS); System Requirements for Operation of Mobile Broadband Systems in the 2 300 MHz - 2 400 MHz Band under Licensed Shared Access (LSA) ,” ETSI, Technical Specification V1.1.1, Oct. 2014.
- [68] —, “ETSI TS 103 235: Reconfigurable Radio Systems (RRS); System Architecture and High Level Procedures for Operation of Licensed Shared Access (LSA) in the 2 300 MHz - 2 400 MHz Band ,” ETSI, Technical Specification V1.1.1, Oct. 2015.
- [69] (2015) Policytracker. [Online]. Available: <http://www.policytracker.com/free-content/blogs/toby-youell/licensed-shared-access-still-stuck-on-the-runway>
- [70] “Mobile broadband enabled globally in the 694-790 MHz frequency band,” http://www.itu.int/net/pressoffice/press_releases/2015/55.aspx#.VuRD15yLR1s, accessed: 2016-03-12.
- [71] E. Dahlman, S. Parkvall, and J. Skold, *4G: LTE/LTE-Advanced for Mobile Broadband*, 1st ed. Academic Press, 2011.
- [72] S. Parkvall, A. Furuskar, and E. Dahlman, “Evolution of LTE toward IMT-advanced,” *Communications Magazine, IEEE*, vol. 49, no. 2, pp. 84–91, February 2011.
- [73] L. Doyle, J. McMenamy, and T. Forde, “Regulating for Carrier Aggregation & Getting Spectrum Management Right for the Longer Term,” in *Dynamic Spectrum Access Networks (DYSPAN)*, 2012 IEEE International Symposium on, Oct 2012, pp. 10–20.
- [74] A. Ghosh *et al.*, “Heterogeneous Cellular Networks: From Theory to Practice,” *Communications Magazine, IEEE*, vol. 50, no. 6, pp. 54–64, June 2012.

- [75] A. Khandekar, N. Bhushan, J. Tingfang, and V. Vanghi, "LTE-Advanced: Heterogeneous Networks," in *Wireless Conference (EW), 2010 European*, April 2010, pp. 978–982.
- [76] A. Damnjanovic *et al.*, "A Survey on 3GPP Heterogeneous Networks," *Wireless Communications, IEEE*, vol. 18, no. 3, pp. 10–21, June 2011.
- [77] 3GPP, "3GPP TR 36.814 Evolved Universal Terrestrial Radio Access (E-UTRA) Further Advancements for E-UTRA Physical Layer Aspects," Tech. Rep. V9.0.0, Mar. 2010.
- [78] J. Andrews, "Seven Ways That Hetnets are a Cellular Paradigm Shift," *Communications Magazine, IEEE*, vol. 51, no. 3, pp. 136–144, March 2013.
- [79] "Small Cell Definition," <http://www.smallcellforum.org/about/about-small-cells/small-cell-definition/>.
- [80] D. Bladsjo, M. Hogan, and S. Ruffini, "Synchronization Aspects in LTE Small Cells," *Communications Magazine, IEEE*, vol. 51, no. 9, pp. 70–77, September 2013.
- [81] A. Pizzinat, P. Chanclou, F. Saliou, and T. Diallo, "Things You Should Know About Fronthaul," *Lightwave Technology, Journal of*, vol. 33, no. 5, pp. 1077–1083, March 2015.
- [82] A. Checko *et al.*, "Cloud RAN for Mobile Networks: A Technology Overview," *Communications Surveys Tutorials, IEEE*, vol. 17, no. 1, pp. 405–426, 2015.
- [83] S. Kuwano, J. Terada, and N. Yoshimoto, "Operator perspective on next-generation optical access for future radio access," in *Communications Workshops (ICC), 2014 IEEE International Conference on*, June 2014, pp. 376–381.
- [84] ETSI/3GPP, "3GPP TR 36.932 E-UTRA Scenarios and Requirements for Small Cell Enhancements for E-UTRA and E-UTRAN, 3GPP Release 12," ETSI/3GPP, Tech. Rep. 12.1.0, Oct. 2014.
- [85] Next Generation Mobile Networks, "A Deliverable by the NGMN Alliance Further Study on Critical C-RAN Technologies," NGMN, Report v01, Mar. 2015.
- [86] T. Nakamura *et al.*, "Trends in Small Cell Enhancements in LTE Advanced," *Communications Magazine, IEEE*, vol. 51, no. 2, pp. 98–105, February 2013.
- [87] "Cloud RAN Architecture Framework," White Paper, Ericsson, Sep. 2015.
- [88] P. Chan *et al.*, "The Evolution Path of 4G Networks: FDD or TDD?" *Communications Magazine, IEEE*, vol. 44, no. 12, pp. 42–50, Dec 2006.
- [89] 3GPP, "Overview of 3GPP Release 10," 3GPP, Tech. Rep. V0.2.1, Jun. 2014.
- [90] ETSI/3GPP, "ETSI TS 136 300: Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2," ETSI/3GPP, Technical Specification V12.5.0, Apr. 2015.
- [91] ETSI/3GPP, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) Radio Transmission and Reception (TS 36.101)," ETSI/3GPP, Technical Specification V12.9, Oct. 2015.

- [92] K. I. Pedersen *et al.*, "Carrier Aggregation for LTE-Advanced: Functionality and Performance Aspects," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 89–95, 2011.
- [93] ETSI/3GPP, "ETSI TR 136 912 LTE; Feasibility Study for Further Advancements for E-UTRA (LTE-Advanced)," ETSI/3GPP, Tech. Rep. V10.0.0, Apr. 2011, release 10.
- [94] D. Bai *et al.*, "LTE-Advanced Modem Design: Challenges and Perspectives," *Communications Magazine, IEEE*, vol. 50, no. 2, pp. 178–186, February 2012.
- [95] "3GPP Release 11: Understanding the Standards for HSPA+ and LTE-Advanced Enhancements," White Paper, 4G Americas, Aug. 2013.
- [96] "3GPP Release 12: Understanding the Standards for HSPA+ and LTE-Advanced Enhancements," White Paper, 4G Americas, Feb. 2015.
- [97] Y. S. Wang, K. I. K. I. Pedersen, T. B. T. B. Sorensen, and P. E. Mogensen, "Carrier Load Balancing and Packet Scheduling for Multi-Carrier Systems," *IEEE Transactions On Wireless Communications*, vol. 9, no. 5, pp. 1780–1789, May 2010.
- [98] H. Lee, S. Vahid, and K. Moessner, "A Survey of Radio Resource Management for Spectrum Aggregation in LTE-Advanced," *Communications Surveys Tutorials, IEEE*, vol. 16, no. 2, pp. 745–760, Second 2014.
- [99] K. Yagyu *et al.*, "Investigation on Mobility Management for Carrier Aggregation in LTE-Advanced," in *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, Sept 2011, pp. 1–5.
- [100] F. Capozzi *et al.*, "Downlink Packet Scheduling in LTE Cellular Networks: Key Design Issues and a Survey," *IEEE Communications Surveys Tutorials*, vol. 15, no. 2, pp. 678–700, Second 2013.
- [101] L. Liu *et al.*, "Component Carrier Management for Carrier Aggregation in LTE-Advanced System," in *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, May 2011, pp. 1–6.
- [102] Y. Wang, K. I. Pedersen, T. B. Sorensen, and P. E. Mogensen, "Utility Maximization in LTE-Advanced Systems with Carrier Aggregation," in *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, May 2011, pp. 1–5.
- [103] 3GPP, "Carrier Aggregation; Base Station (BS) Radio Transmission and Reception (TR 36.808)," 3GPP, Tech. Rep. V10.1.0, Jul. 2013.
- [104] Z. Shen *et al.*, "Overview of 3GPP LTE-Advanced Carrier Aggregation for 4G Wireless Communications," *IEEE Communications Magazine*, vol. 50, no. 2, pp. 122–130, 2012.
- [105] H. Wang, C. Rosa, and K. Pedersen, "Uplink Component Carrier Selection for LTE-Advanced Systems with Carrier Aggregation," in *Communications (ICC), 2011 IEEE International Conference on*, June 2011, pp. 1–5.
- [106] H. Wang, C. Rosa, and K. I. Pedersen, "Dedicated Carrier Deployment in Heterogeneous Networks with Inter-Site Carrier Aggregation," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, April 2013, pp. 756–760.
- [107] 3GPP, "Overview of 3GPP Release 12," 3GPP, Tech. Rep. V0.1.4, Sep. 2014.

- [108] —, “3GPP TR 36.847 E-UTRA Study on LTE Time Division Duplex (TDD) - Frequency Division Duplex (FDD) Joint Operation including Carrier Aggregation (CA) (Release 12),” 3GPP, Tech. Rep. 1.0.0, Dec. 2013.
- [109] M. Alasti, B. Neekzad, J. Hui, and R. Vannithamby, “Quality of Service in WiMAX and LTE Networks [Topics in Wireless Communications],” *IEEE Communications Magazine*, vol. 48, no. 5, pp. 104–111, May 2010.
- [110] 3GPP, “3GPP TR 36.842 Study on Small Cell Enhancements for E-UTRA and E-UTRAN; Higher Layer Aspects,” 3GPP, Tech. Rep. 12.0.0, Jan. 2014.
- [111] A. Zakrzewska, D. Lopez-Perez, S. Kucera, and H. Claussen, “Dual Connectivity in LTE Hetnets with Split Control- and User-Plane,” in *Globecom Workshops (GC Wkshps)*, 2013 IEEE, Dec 2013, pp. 391–396.
- [112] M. Joud, M. Garcia-Lozano, and S. Ruiz, “Selective c-/u-plane split and comp to improve moderate speed users performance in small cell deployments,” in *Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2014 IEEE 10th International Conference on, Oct 2014, pp. 697–702.
- [113] A. Prasad and A. Maeder, “Energy Saving Enhancement for LTE-Advanced Heterogeneous Networks with Dual Connectivity,” in *Vehicular Technology Conference (VTC Fall)*, 2014 IEEE 80th, Sept 2014, pp. 1–6.
- [114] E. Ternon, P. Agyapong, L. Hu, and A. Dekorsy, “Database-aided Energy Savings in Next Generation Dual Connectivity Heterogeneous Networks,” in *Wireless Communications and Networking Conference (WCNC)*, 2014 IEEE, April 2014, pp. 2811–2816.
- [115] A. Mukherjee, “Optimal Flow Bifurcation in Networks with Dual Base Station Connectivity and Non-Ideal Backhaul,” in *Signals, Systems and Computers, 2014 48th Asilomar Conference on*, Nov 2014, pp. 521–524.
- [116] S. Jha, K. Sivanesan, R. Vannithamby, and A. Koc, “Dual Connectivity in LTE Small Cell Networks,” in *Globecom Workshops (GC Wkshps)*, 2014, Dec 2014, pp. 1205–1210.
- [117] Telecommunication Standardization Sector of ITU, “Quality of Telecommunication Services: Concepts, Models, Objectives and Dependability Planning – Terms and Definitions Related To The Quality Of Telecommunication Services,” ITU, Recommendation E800, Sep. 2008.
- [118] S. Gandhi, C. Buragohain, L. Cao, H. Zheng, and S. Suri, “A General Framework for Wireless Spectrum Auctions,” in *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, April 2007, pp. 22–33.
- [119] T. Kamakaris, M. Buddhikot, and R. Iyer, “A Case for Coordinated Dynamic Spectrum Access in Cellular Networks,” in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, Nov 2005, pp. 289–298.
- [120] W. Lehr and J. Crowcroft, “Managing Shared Access to a Spectrum Commons,” in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, Nov 2005, pp. 420–444.
- [121] M. Buddhikot et al., “DIMSUNet: 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*, June 2005, pp. 78–85.

- [122] S. Im and H. Lee, "Dynamic Spectrum Allocation Based on Binary Integer Programming Under Interference Graph," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on*, Sept 2012, pp. 226–231.
- [123] J. Deaton, M. Benonis, L. DaSilva, and R. Irwin, "Supporting Dynamic Spectrum Access in Heterogeneous LTE+ Networks," in *Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on*, Oct 2012, pp. 305–316.
- [124] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey," *COMPUTER NETWORKS JOURNAL (ELSEVIER)*, vol. 50, pp. 2127–2159, 2006.
- [125] E. Tragos, S. Zeadally, A. Fragkiadakis, and V. Siris, "Spectrum Assignment in Cognitive Radio Networks: A Comprehensive Survey," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 3, pp. 1108–1135, Third 2013.
- [126] W.-Y. Lee and I. Akyldiz, "A Spectrum Decision Framework for Cognitive Radio Networks," *Mobile Computing, IEEE Transactions on*, vol. 10, no. 2, pp. 161–174, Feb 2011.
- [127] C. Ghosh, S. Roy, and M. Rao, "Modeling and Validation of Channel Idleness and Spectrum Availability for Cognitive Networks," *Selected Areas in Communications, IEEE Journal on*, vol. 30, no. 10, pp. 2029–2039, November 2012.
- [128] M. Wellens and P. Mahonen, "Lessons Learned from an Extensive Spectrum Occupancy Measurement Campaign and a Stochastic Duty Cycle Model," in *Testbeds and Research Infrastructures for the Development of Networks Communities and Workshops, 2009. TridentCom 2009. 5th International Conference on*, April 2009, pp. 1–9.
- [129] M. Masonta, M. Mzyece, and N. Ntlatlapa, "Spectrum Decision in Cognitive Radio Networks: A Survey," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 3, pp. 1088–1107, 2013.
- [130] A. Sadek, W. Zhang, and S. Shellhammer, "Listen-Before-Talk Versus Treating Interference as Noise for Spectrum Sharing," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, Oct 2008, pp. 1–6.
- [131] B. Sklar, *Digital Communications*. Prentice-Hall PTR, 2001, 2001.
- [132] S. R. Saunders and A. A. Zavala, *Antennas and Propagation for Wireless Communication Systems*. Wiley, Second Edition, 2007.
- [133] E. Tragos, S. Zeadally, A. Fragkiadakis, and V. Siris, "Spectrum Assignment in Cognitive Radio Networks: A Comprehensive Survey," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 3, pp. 1108–1135, 2013.
- [134] C. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal, The*, vol. 27, no. 3, pp. 379–423, July 1948.
- [135] P. Mogensen *et al.*, "LTE Capacity Compared to the Shannon Bound," in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, April 2007, pp. 1234–1238.
- [136] T. Weiss and F. Jondral, "Spectrum Pooling: An Innovative Strategy for the Enhancement of Spectrum Efficiency," *Communications Magazine, IEEE*, vol. 42, no. 3, pp. S8–14, Mar 2004.

- [137] S. Mukherjee, *Analytical Modeling of Heterogeneous Cellular Networks*, 1st ed. Cambridge University Press, 2014.
- [138] F. Sallabi, A. Lakas, K. Shuaib, and M. Boulmalf, "WCDMA Downlink Simulator with Efficient Wrap-Around Technique," in *Wireless and Optical Communications Networks, 2005. WOCN 2005. Second IFIP International Conference on*, March 2005, pp. 472–476.
- [139] K. Brueninghaus *et al.*, "Link Performance Models for System Level Simulations of Broadband Radio Access Systems," in *Personal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005. IEEE 16th International Symposium on*, vol. 4, Sept 2005, pp. 2306–2311 Vol. 4.
- [140] Ofcom, "800 MHz and 2.6 GHz Combined Award - Technical Modelling for Competition Assessment - Annex 14," Ofcom, Statement, 2012. [Online]. Available: <http://stakeholders.ofcom.org.uk/binaries/consultations/award-800mhz/statement/Annexes7-12.pdf>
- [141] H. Sun *et al.*, "Introducing Heterogeneous Networks in HSPA," in *Communications (ICC), 2012 IEEE International Conference on*, June 2012, pp. 6045–6050.
- [142] V. Petrini and H. Karimi, "TV White Space Databases: Algorithms for the Calculation of Maximum Permitted Radiated Power Levels," in *Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on*, Oct 2012, pp. 552–560.
- [143] "LTE Carrier Aggregation Enhancement Beyond 5 Carriers (RP-141418)," http://www.3gpp.org/ftp/tsg_ran/tsg_ran/TSGR_65/Docs/.
- [144] K. Harrison, S. Mishra, and A. Sahai, "How Much White-Space Capacity is There?" in *New Frontiers in Dynamic Spectrum, 2010 IEEE Symposium on*, April 2010, pp. 1–10.
- [145] C. Ghosh, S. Roy, and D. Cavalcanti, "Coexistence Challenges for Heterogeneous Cognitive Wireless Networks in TV White Spaces," *Wireless Communications, IEEE*, vol. 18, no. 4, pp. 22–31, August 2011.
- [146] R. Jantti, J. Kerttula, K. Koufos, and K. Ruttik, "Aggregate Interference with FCC and ECC White Space Usage Rules: Case Study in Finland," in *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*, May 2011, pp. 599–602.
- [147] K. Koufos, K. Ruttik, and R. Jantti, "Controlling the Interference from Multiple Secondary Systems at the TV Cell Border," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*, Sept 2011, pp. 645–649.
- [148] L. Shi, K. W. Sung, and J. Zander, "Secondary Spectrum Access in TV-bands with Combined Co-channel and Adjacent Channel Interference Constraints," in *Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on*, Oct 2012, pp. 452–460.
- [149] T. Dudda and T. Irnich, "Capacity of Cellular networks Deployed in TV White Space," in *Dynamic Spectrum Access Networks (DYSPAN), 2012 IEEE International Symposium on*, Oct 2012, pp. 254–265.

- [150] S. Sen *et al.*, "A Dual Technology Femto Cell Architecture for Robust Communication Using Whitespaces," in *Dynamic Spectrum Access Networks (DYSPAN)*, 2012 IEEE International Symposium on, Oct 2012, pp. 242–253.
- [151] M. Mustonen *et al.*, "An Evolution Toward Cognitive Cellular Systems: Licensed Shared Access for Network Optimization," *Communications Magazine, IEEE*, vol. 53, no. 5, pp. 68–74, May 2015.
- [152] R. C. Dwarkanath, J. D. Naranjo, and A. Ravanshid, "Modeling of Interference Maps for Licensed Shared Access in LTE-Advanced Networks Supporting Carrier Aggregation," in *Wireless Days (WD)*, 2013 IFIP, Nov 2013, pp. 1–6.
- [153] T. Wirth *et al.*, "System Level Performance of Cellular Networks Utilizing ASA/LSA Mechanisms," in *Cognitive Cellular Systems (CCS)*, 2014 1st International Workshop on, Sept 2014, pp. 1–5.
- [154] V. Borodakiy *et al.*, "Modeling Unreliable LSA Operation in 3GPP LTE Cellular Networks," in *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, 2014 6th International Congress on, Oct 2014, pp. 390–396.
- [155] Y. He, E. Dutkiewicz, G. Fang, and M. Mueck, "Licensed shared access in distributed antenna systems enabling network virtualization," in *5G for Ubiquitous Connectivity (5GU)*, 2014 1st International Conference on, Nov 2014, pp. 76–80.
- [156] I. Gomez-Migueluez *et al.*, "Cloud-Ran Platform for LSA in 5G Networks 2014; Trade-off Within the Infrastructure," in *Communications, Control and Signal Processing (ISCCSP)*, 2014 6th International Symposium on, May 2014, pp. 522–525.
- [157] M. Mueck, V. Frascolla, and B. Badic, "Licensed Shared Access 2014; State-of-the-Art and Current Challenges," in *Cognitive Cellular Systems (CCS)*, 2014 1st International Workshop on, Sept 2014, pp. 1–5.
- [158] M. Mueck *et al.*, "Licensed Shared Access for Wave Cellular Broadband Communications," in *Cognitive Cellular Systems (CCS)*, 2014 1st International Workshop on, Sept 2014, pp. 1–5.
- [159] H. Ishii, Y. Kishiyama, and H. Takahashi, "A Novel Architecture for LTE-B: C-Plane/U-Plane Split and Phantom Cell Concept," in *Globecom Workshops (GC Wkshps)*, 2012 IEEE, Dec 2012, pp. 624–630.
- [160] C. Hoymann, D. Larsson, H. Koorapaty, and J.-F. Cheng, "A Lean Carrier for LTE," *Communications Magazine, IEEE*, vol. 51, no. 2, pp. 74–80, February 2013.
- [161] "A Comparison of LTE-Advanced HetNets and WiFi," White Paper, Qualcomm, Oct. 2011.
- [162] "3GPP Self-evaluation - Methodology and Results - Assumptions," ftp://www.3gpp.org/workshop/2009-12-17_ITU-R_IMT-Adv_eval/docs/pdf/REV-090007%20SelfEvaluation%20assumption.pdf.
- [163] ETSI/3GPP, "ETSI TS 136 211 Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation," ETSI/3GPP, Technical Specification V10.7, 2013, release 10.
- [164] B. Soret, K. Pedersen, N. K. Jørgensen, and V. Fernández-López, "Interference Coordination for Dense Wireless Networks," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 102–109, 2015.

- [165] Y.-n. R. Li and J. Li, "Energy Efficient Small Cell Operation under Ultra Dense Cloud Radio Access Networks," in *Globecom Workshops (GC Wkshps)*, 2014, Dec 2014, pp. 1120–1125.
- [166] D. M. Hamby, "A Review of Techniques for Parameter Sensitivity Analysis of Environmental Models," *Environmental Monitoring and Assessment*, Springer, vol. 32, no. 2, pp. 135–154, September 1994.
- [167] You Know LTE/LTE Advanced...But How About in Unlicensed Spectrum? [Online]. Available: <https://www.qualcomm.com/news/onq/2013/11/20/ltelte-advanced-unlicensed-spectrum>
- [168] "LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi," White Paper, Qualcomm, Jun. 2014.
- [169] A. Cavalcante *et al.*, "Performance Evaluation of LTE and Wi-Fi Coexistence in Unlicensed Bands," in *Vehicular Technology Conference (VTC Spring)*, 2013 IEEE 77th, June 2013, pp. 1–6.
- [170] A. Babaei, J. Andreoli-Fang, Y. Pang, and B. Hamzeh, "On the Impact of LTE-U on Wi-Fi Performance," *International Journal of Wireless Information Networks*, vol. 22, no. 4, pp. 336–344, 2015. [Online]. Available: "<http://dx.doi.org/10.1007/s10776-015-0288-6>
- [171] LTE-U Forum, "LTE-U Technical Report Coexistence, Coexistence Study for LTE-U SDL," LTE-U Forum, Tech. Rep. V1.0, Feb. 2015.
- [172] 3GPP, "3GPP TR 36.889; Study on License Assisted Access in Unlicensed Spectrum," 3GPP, Tech. Rep. V13.0, July 2015, Release 13.
- [173] T. Nihtila *et al.*, "System Performance of LTE and IEEE 802.11 Coexisting on a Shared Frequency Band," in *Wireless Communications and Networking Conference (WCNC)*, 2013 IEEE, April 2013, pp. 1038–1043.
- [174] R. Ratasuk *et al.*, "License-exempt LTE Deployment in Heterogeneous Network," in *Wireless Communication Systems (ISWCS)*, 2012 International Symposium on, Aug 2012, pp. 246–250.
- [175] A. Bhorkar, C. Ibars, A. Papathanassiou, and P. Zong, "Medium Access Design for LTE in Unlicensed Band," in *Wireless Communications and Networking Conference Workshops (WCNCW)*, 2015 IEEE, March 2015, pp. 369–373.
- [176] C. Cano and D. J. Leith, "Coexistence of WiFi and LTE in Unlicensed Bands: A Proportional Fair Allocation Scheme," in *Communication Workshop (ICCW)*, 2015 IEEE International Conference on, June 2015, pp. 2288–2293.
- [177] H. Song and X. Fang, "A Spectrum Etiquette Protocol and Interference Coordination for LTE in Unlicensed Bands (LTE-U)," in *Communication Workshop (ICCW)*, 2015 IEEE International Conference on, June 2015, pp. 2338–2343.
- [178] O. Sallent, J. Perez-Romero, R. Ferrus, and R. Agusti, "Learning-based Coexistence for LTE Operation in Unlicensed Bands," in *Communication Workshop (ICCW)*, 2015 IEEE International Conference on, June 2015, pp. 2307–2313.
- [179] A. Mukherjee *et al.*, "System Architecture and Coexistence Evaluation of Licensed-assisted Access LTE with IEEE 802.11," in *Communication Workshop (ICCW)*, 2015 IEEE International Conference on, June 2015, pp. 2350–2355.

- [180] Z. Khan *et al.*, "Carrier Aggregation/Channel Bonding in Next Generation Cellular Networks: Methods and Challenges," *Network, IEEE*, vol. 28, no. 6, pp. 34–40, Nov 2014.
- [181] J. D. Naranjo, G. Bauch, A. B. Saleh, I. Viering, and H. Ruediger, "A Dynamic Spectrum Access Scheme for an LTE-Advanced HetNet with Carrier Aggregation Systems," in *Proc. of 9th International ITG Conference on Systems, Communication and Coding (SCC)*, Munich, Germany, 21-24Jan. 2013, pp. 1–6.
- [182] E. Dahlman, S. Parkvall, and J. Peisa, "Special Section on 5G Radio Access Networks - Part 1: Radio Access Technologies and System Design," *IEICE Transactions on Communications*, vol. E98-B, no. 8, pp. 1407–141, August 2015.
- [183] S. Rangan, T. Rappaport, and E. Erkip, "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, March 2014.

Appendix A

Sensitivity analysis tables

The following tables depict the computed sensitivity indices for the analysis described in Chapter 7 when CS band is available. It should be noted that for each considered LPN density, the minimum and the maximum value of each index are highlighted, except for the power sensitivity index - SI_p . There, the non-zero cases are highlighted.

A.1 2 LPNs

A.1.1 SI_K

A.1.1.1 CBB architecture

Table A.1 Sensitivity Index (SI_K) for the case of 2 LPNs in the CBB architecture

0 'foreign' interferers		2 LPNs						
Power (dBm)		1	6	11	16	21	26	30
Target throughput gain (x 2)		0.75	0.75	0.75	0.75	1.0	1.0	1.0
Target throughput gain (x 4)		0.5	0.5	0.5	0.5	0.75	0.75	0.75
Target throughput gain (x 10 & x 20)		0	0	0	0	0	0	0

Target throughput gain (x 2)	0.5
Target throughput gain (x 4)	0.25
Target throughput gain (x 10 & x 20)	0

A.1.2 SI_T

A.1.2.1 CBB architecture

Table A.3 Sensitivity Index (SI_T) for the case of 2 LPNs in the CBB architecture

0 'foreign' interferers	2 LPNs						
Power (dBm)	1	6	11	16	21	26	30
K =10	0.75	0.75	0.75	0.75	1.0	1.0	1.0
K =20	0.5	0.5	0.5	0.5	0.75	0.75	0.75
K =30	0.25	0.25	0.25	0.25	0.5	0.5	0.5
K =40 & 50	0	0	0	0	0	0	0

3, 10, 20 & 30 'foreign' interferers	2 LPNs						
Power (dBm)	All power values						
K =10	0.75						
K =20	0.5						
K =30	0.25						
K=40 & 50	0						

A.1.2.2 DBB architecture

Table A.4 Sensitivity Index (SI_T) for the case of 2 LPNs in the DBB architecture

--

0 'foreign' interferers	2 LPNs						
Power (dBm)	1	6	11	16	21	26	30
K =10	0.5	0.5	0.5	0.5	0.75	0.75	0.75
K =20	0.25	0.25	0.25	0.25	0.5	0.5	0.5
K =30	0	0	0	0	0.25	0.25	0.25
K =40 & 50	0	0	0	0	0	0	0

3, 10, 20 & 30 'foreign' interferers	2 LPNs						
Power (dBm)	All power values						
K =10	0.5						
K =20	0.25						
K=30, 40 & 50	0						

A.1.3 SI_I

A.1.3.1 CBB & DBB architecture

Table A.5 Sensitivity Index (SI_I) for the case of 2 LPNs in both architectures

All target throughput gains	2 LPNs
Power (dBm)	All power levels

All values of K 0

A.1.4 SI_p

A.1.4.1 CBB architecture

Table A.6 (SI_p) for the case of 2 LPNs in the CBB architecture

0 'foreign' interferers	2 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2)	$-\infty$	-1.0	-0.5	0	0
Target throughput gain (x 4)	-1.0	0	0	0	0
Target throughput gain (x 10 & 20)	0	0	0	0	0

3, 10, 20 & 30 'foreign' interferers	2 LPNs
# of users (K)	All K values
Target throughput gain (all)	0

A.1.4.2 DBB architecture

Table A.7 (SI_p) for the case of 2 LPNs in the DBB architecture

0 'foreign' interferers	2 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2)	-1.0	-0.5	-0.33	0	0
Target throughput gain (x 4)	-0.5	0	0	0	0
Target throughput gain (x 10 & x 20)	0	0	0	0	0

3, 10, 20 & 30 'foreign' interferers	2 LPNs				
# of users (K)	All K values				
Target throughput gain (all)	0				

A.2 4 LPNs

A.2.1 SI_K

A.2.1.1 CBB architecture

Table A.8 Sensitivity Index (SI_K) for the case of 4 LPNs in the CBB architecture

0 'foreign' interferers	4 LPNs						
Power (dBm)	1	6	11	16	21	26	30
Target throughput gain (x 2)	0.67	0.67	1.0	1.0	1.0	1.0	1.0
Target throughput gain (x 4)	0.75	0.75	1.0	1.0	1.0	1.0	1.0
Target throughput gain (x 10)	0.25	0.25	0.5	0.5	0.5	0.5	0.5
Throughput gain - target (x 20)	0	0	0	0	0	0	0

3, 10, 20 & 30 'foreign' interferers	4 LPNs
Power (dBm)	All power levels
Target throughput gain (x 2)	0.67
Target throughput gain (x 4)	0.75
Target throughput gain (x 10)	0.25
Target throughput gain (x 20)	0

A.2.1.2 DBB architecture

Table A.9 Sensitivity Index (SI_K) for the case of 4 LPNs in the DBB architecture

0 'foreign' interferers	4 LPNs						
Power (dBm)	1	6	11	16	21	26	30
Target throughput gain (x 2)	0.67	0.67	1.0	1.0	1.0	1.0	1.0
Target throughput gain (x 4)	0.5	0.5	0.75	0.75	0.75	0.75	0.75
Target throughput gain (x 10)	0.25	0.25	0.5	0.5	0.5	0.5	0.5
Throughput gain - target (x 20)	0	0	0	0	0	0	0

3, 10, 20 & 30 'foreign' interferers	4 LPNs
Power (dBm)	All power levels
Target throughput gain (x 2)	0.67
Target throughput gain (x 4)	0.5
Target throughput gain (x 10)	0.25
Target throughput gain (x 20)	0

A.2.2 SI_T

A.2.2.1 CBB architecture

Table A.10 Sensitivity Index (SI_T) for the case of 4 LPNs in the CBB architecture

0 'foreign' interferers	4 LPNs						
Power (dBm)	1	6	11	16	21	26	30

K =10 & 20	0.75	0.75	1.0	1.0	1.0	1.0	1.0
K =30 & 40	0.5	0.5	0.75	0.75	0.75	0.75	0.75
K =50	0.25	0.25	0.5	0.5	0.5	0.5	0.5

3, 10, 20 & 30 'foreign' interferers	4 LPNs
--------------------------------------	--------

Power (dBm)	All power values
K =10 & 20	0.75
K =30 & 40	0.5
K =50	0.25

A.2.2.2 DBB architecture

Table A.11 Sensitivity Index (SI_T) for the case of 4 LPNs in the DBB architecture

0 'foreign' interferers	4 LPNs						
Power (dBm)	1	6	11	16	21	26	30
K =10	0.75	0.75	1.0	1.0	1.0	1.0	1.0
K =20 & 30	0.5	0.5	0.75	0.75	0.75	0.75	0.75
K =40	0.25	0.25	0.5	0.5	0.75	0.75	0.75
K =50	0.25	0.25	0.5	0.25	0.5	0.5	0.5

3, 10, 20 & 30 'foreign' interferers	4 LPNs						
Power (dBm)	All power values						
K =10	0.75						
K =20 & 30	0.5						
K =40 & 50	0.25						

A.2.3 SI_I

A.2.3.1 CBB & DBB architecture

Table A.12 Sensitivity Index (SI_I) for the case of 4 LPNs in both architectures

All target throughput gains	4 LPNs
-----------------------------	--------

Power (dBm)	All power levels
All values of K	0

A.2.4 SI_p

A.2.4.1 CBB architecture

Table A.13 (SI_p) for the case of 4 LPNs in the CBB architecture

0 'foreign' interferers	4 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2)	$-\infty$	$-\infty$	-1.0	-1.0	-0.5
Target throughput gain (x 4)	$-\infty$	-1.0	-0.5	-0.33	0
Target throughput gain (x 10)	-0.5	0	0	0	0
Target throughput gain (x 20)	0	0	0	0	0

3, 10, 20 & 30 'foreign' interferers	4 LPNs				
# of users (K)	All K values				
Target throughput gain (all)	0				

A.2.4.2 DBB architecture

Table A.14 (SI_p) for the case of 4 LPNs in the DBB architecture

0 'foreign' interferers	4 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2)	$-\infty$	-1.0	-1.0	-2.0	-0.5
Target throughput gain (x 4)	-1.0	-0.5	-0.33	0	0
Target throughput gain (x 10)	-0.5	0	0	0	0
Target throughput gain (x 20)	0	0	0	0	0

3, 10, 20 & 30 'foreign' interferers	4 LPNs
# of users (K)	All K values
Target throughput gain (all)	0

A.3 10 LPNs

A.3.1 SI_K

A.3.1.1 CBB architecture

Table A.15 Sensitivity Index (SI_K) for the case of 10 LPNs in the CBB architecture

0 'foreign' interferers		10 LPNs						
Power (dBm)		1	6	11	16	21	26	30
Target throughput gain (x 2)		0	1.0	1.0	0	0	0	0
Target throughput gain (x 4)		1.0	1.0	1.0	1.0	1.0	1.0	1.0
Target throughput gain (x 10)		0.75	1.0	0.75	1.0	1.0	1.0	1.0
Throughput gain - target (x 20)		0.5	0.5	0.5	0.5	0.5	0.5	0.5
3 'foreign' interferers		10 LPNs						
Power (dBm)		All power levels						
Target throughput gain (x 2 & x 4)		1.0						
Target throughput gain (x 10)		0.75						
Target throughput gain (x 20)		0.5						
10 'foreign' interferers		10 LPNs						
Power (dBm)		1	6	11	16	21	26	30

Target throughput gain (x 2)	0	0	0	1.0	0	1.0	1.0
Target throughput gain (x 4)	0.67	0.67	0.67	1.0	0.67	1.0	1.0
Target throughput gain (x 10)	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Throughput gain - target (x 20)	0.25	0.25	0.25	0.5	0.25	0.5	0.5

20 & 30 'foreign' interferers	10 LPNs
Power (dBm)	All power levels
Target throughput gain (x 2)	0
Target throughput gain (x 4)	0.67
Target throughput gain (x 10)	0.75
Target throughput gain (x 20)	0.25

A.3.1.2 DBB architecture

Table A.16 (SI_K) for the case of 10 LPNs in the DBB architecture

0 & 3 'foreign' interferers	10 LPNs						
Power (dBm)	All power levels						
Target throughput gain (x 2 & x 4)	1						
Target throughput gain (x 10)	0.75						
Target throughput gain (x 20)	0.5						

10 'foreign' interferers	10 LPNs						
Power (dBm)	1	6	11	16	21	26	30
Target throughput gain (x 2)	0.5	0.5	0.5	1.0	0.5	1.0	1.0

Target throughput gain (x 4)	0.67	0.67	0.67	1.0	0.67	1.0	1.0
Target throughput gain (x 10)	0.5	0.5	0.5	0.75	0.5	0.75	0.75
Throughput gain - target (x 20)	0.25	0.25	0.25	0.5	0.25	0.5	0.5

Power (dBm)	All power values
K = 10, 20, 30 & 40	1.0
K = 50	0.75

10 'foreign' interferers	10 LPNs						
Power (dBm)	1	6	11	16	21	26	30
K = 10	0.67	0.67	0.67	1.0	0.67	1.0	1.0
K = 20 & 30	0.75	0.75	0.75	1.0	0.75	1.0	1.0
K = 40 & 50	0.75	0.75	0.75	0.75	0.75	0.75	0.75

20 & 30 'foreign' interferers	10 LPNs
Power (dBm)	All power values
K = 10	0.67
K = 20, 30, 40 & 50	0.75

A.3.2.2 DBB architecture

Table A.18 Sensitivity Index (SI_T) for the case of 10 LPNs in the DBB architecture

0 'foreign' interferers	10 LPNs						
Power (dBm)	1	6	11	16	21	26	30
K = 10, 20 & 30	1.0	1.0	1.0	1.0	1.0	1.0	1.0
K = 40	0.75	1.0	1.0	1.0	1.0	1.0	1.0

K =10	0.67
K =20, 30 & 40	0.75
K =50	0.5

A.3.3 SI_I

A.3.3.1 CBB architecture

Table A.19 Sensitivity Index (SI_I) for the case of 10 LPNs in the CBB architecture

Target throughput gain (x 2)	10 LPNs
Power (dBm)	All power levels
K = 10, 20, 30 & 40	1.0
K = 50	0
Target throughput gain (x 4)	10 LPNs
Power (dBm)	All power levels
K = 10 & 20	1.0

K = 30 & 40	0.5
K = 50	0.33
Target throughput gain (x 10)	10 LPNs
Power (dBm)	All power levels
K = 10, 40 & 50	0
K = 20	0.33
K = 30	0.25
Target throughput gain (x 20)	10 LPNs
Power (dBm)	All power levels
K = 10	0.33
K = 20, 30, 40 & 50	0

A.3.3.2 DBB architecture

Table A.20 Sensitivity Index (SI_I) for the case of 10 LPNs in the DBB architecture

Target throughput gain (x 2)	10 LPNs						
Power (dBm)	1	6	11	16	21	26	30

K = 10, 20 & 30	1.0	1.0	1.0	1.0	1.0	1.0	1.0
K = 40	0	1.0	0	0	0	0	0
K = 50	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Target throughput gain (x 4)	10 LPNs						
Power (dBm)	1	6	11	16	21	26	30
K = 10	1.0	1.0	1.0	1.0	1.0	1.0	1.0

K = 20	0	0	0	0	1.0	1.0	0
K = 30	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K = 40	0	0.5	0	0	0	0	0
K = 50	0.33	0.33	0.33	0.33	0.33	0.33	0.33

Target throughput gain (x 10)	10 LPNs
Power (dBm)	All power levels
K = 10	0.5
K = 20	0.33
K = 30	0.25
K = 40 & 50	0

Target throughput gain (x 20)	10 LPNs
Power (dBm)	All power levels
K = 10	0.33
K = 20, 30, 40 & 50	0

A.3.4 SI_p

A.3.4.1 CBB architecture

Table A.21 (SI_p) for the case of 10 LPNs in the CBB architecture

0 'foreign' interferers	10 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2 & x 4 & x 20)	0	0	0	0	0
Target throughput gain (x 10)	$-\infty$	-1.0	0	0	0

10 'foreign' interferers	10 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2)	$-\infty$	$-\infty$	$-\infty$	0	0
Target throughput gain (x 4)	$-\infty$	0	-1.0	-1.0	-0.5
Target throughput gain (x 10)	0	-0.5	-0.33	0	0
Target throughput gain (x 20)	-0.5	0	0	0	0

3, 20 & 30 'foreign' interferers	10 LPNs				
# of users (K)	All K values				
Target throughput gain (all)	0				

A.3.4.2 DBB architecture

Table A.22 (SI_p) for the case of 10 LPNs in the DBB architecture

0 'foreign' interferers	10 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2)	0	0	0	$-\infty$	0
Target throughput gain (x 4)	0	$-\infty$	0	0	0
Target throughput gain (x 10 & x 20)	0	0	0	0	0

10 'foreign' interferers	10 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2)	$-\infty$	$-\infty$	0	0	-1.0
Target throughput gain (x 4)	$-\infty$	0	-1.0	0	-0.5
Target throughput gain (x 10)	-1.0	-0.5	-0.33	0	0
Target throughput gain (x 20)	-0.5	0	0	0	0

3, 20 & 30 'foreign' interferers	10 LPNs				
# of users (K)	All K values				

Target throughput gain (all)	0
------------------------------	---

A.4 20 LPNs

A.4.1 SI_K

A.4.1.1 CBB architecture

Table A.23 (SI_K) for the case of 20 LPNs in the CBB architecture

0, 3, 10 & 20 'foreign' interferers	20 LPNs
Power (dBm)	All power levels
Target throughput gain (x 2)	0
Target throughput gain (x 4 & x 10)	1.0
Target throughput gain (x 20)	0.75

30 'foreign' interferers	20 LPNs
Power (dBm)	All power levels
Target throughput gain (x 2 & x 4)	1.0
Target throughput gain (x 10)	0.67
Target throughput gain (x 20)	0.75

A.4.1.2 DBB architecture

Table A.24 (SI_K) for the case of 20 LPNs in the DBB architecture

0 & 3 'foreign' interferers	20 LPNs						
Power (dBm)	All power levels						
Target throughput gain (x 2)						0	
Target throughput gain (x 4 & x 10)						1.0	
Target throughput gain (x 20)						0.75	
10 'foreign' interferers	20 LPNs						
Power (dBm)	1	6	11	16	21	26	30
Target throughput gain (x 2)	1.0	0	0	0	0	0	0

Target throughput gain (x 4 & 10)	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Throughput gain - target (x 20)	0.75	0.75	0.75	0.75	0.75	0.75	0.75

20 'foreign' interferers	20 LPNs						
Power (dBm)	1	6	11	16	21	26	30
Target throughput gain (x 2 & 4)	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Target throughput gain (x 10)	0.75	0.75	0.75	0.75	0.75	0.75	0.67
Throughput gain - target (x 20)	0.75	0.75	0.75	0.75	0.75	0.75	0.75

30 'foreign' interferers	20 LPNs						
Power (dBm)	All power levels						
Target throughput gain (x 2 & x 4)	1.0						
Target throughput gain (x 10 & x 20)	0.75						

A.4.2 SI_T

A.4.2.1 CBB architecture

Table A.25 Sensitivity Index (SI_T) for the case of 20 LPNs in the CBB architecture

0, 3, 10 & 20 'foreign' interferers	20 LPNs
-------------------------------------	---------

Power (dBm)	All power levels
All values of K	1.0
30 'foreign' interferers	20 LPNs
Power (dBm)	All power levels
K = 10, 20, 30 & 40	1.0
K = 50	0.75

A.4.2.2 DBB architecture

Table A.26 Sensitivity Index (SI_T) for the case of 20 LPNs in the DBB architecture

0 & 3 'foreign' interferers	20 LPNs							
Power (dBm)	All power levels							
All values of K	1.0							
10 'foreign' interferers	20 LPNs							
Power (dBm)	1	6	11	16	21	26	30	
K = 10, 20, 30 & 40	1.0	1.0	1.0	1.0	1.0	1.0	1.0	

K = 50	0.75	1.0	1.0	1.0	1.0	1.0	1.0
20 'foreign' interferers	20 LPNs						
Power (dBm)	All power levels						
K = 10, 20, 30 & 40	1.0						
K = 50	0.75						
30 'foreign' interferers	20 LPNs						
Power (dBm)	All power levels						
K = 10,20 & 30	1.0						
K = 40 & 50	0.75						

A.4.3 SI_I

A.4.3.1 CBB architecture

Table A.27 Sensitivity Index (SI_I) for the case of 20 LPNs in the CBB architecture

Target throughput gain (x 2)	20 LPNs
Power (dBm)	All power levels
K = 10, 20, 30 & 40	0

K = 50

1.0

Target throughput gain (x 4)	20 LPNs
Power (dBm)	All power levels
K = 10, 20, 40 & 50	0
K = 30	1.0
Target throughput gain (x 10)	20 LPNs
Power (dBm)	All power levels
K = 10	1.0
K = 20, 30 & 50	0
K = 40	0.33
Target throughput gain (x 20)	20 LPNs
Power (dBm)	All power levels
K = 20	0.33
K = 10,30,40 & 50	0

A.4.3.2 DBB architecture

Table A.28 Sensitivity Index (SI_I) for the case of 20 LPNs in the DBB architecture

Target throughput gain (x 2)	20 LPNs
Power (dBm)	All power levels
K = 10, 20 & 30	0
K = 40 & 50	1.0

Target throughput gain (x 4)	20 LPNs						
Power (dBm)	1	6	11	16	21	26	30
K = 10, 40 & 50	0	0	0	0	0	0	0
K = 20	1.0	1.0	1.0	1.0	1.0	1.0	1.0
K = 30	0	1.0	1.0	1.0	1.0	1.0	1.0

Target throughput gain (x 10)	20 LPNs						
Power (dBm)	All power levels						
K = 10	1.00						
K = 20, 30 & 40	0						
K = 50	0.25						

Target throughput gain (x 20)	20 LPNs						
Power (dBm)	All power levels						
All values of K	0						

A.4.4 SI_p

A.4.4.1 CBB Architecture

Table A.29 (SI_p) for the case of 20 LPNs in the CBB architecture

0 'foreign' interferers	20 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2 & x 10)	0	0	0	0	0
Target throughput gain (x 4)	0	0	0	$-\infty$	0
Target throughput gain (x 20)	0	0	-0.33	0	0

3, 10 & 30 'foreign' interferers	20 LPNs				
# of users (K)	All K values				
Target throughput gain (all)	0				
20 'foreign' interferers	20 LPNs				
# of users (K)	10	20	30	40	50
Target throughput gain (x 2, x 4 & x 10)	0	0	0	0	0
Target throughput gain (x 20)	0	-0.5	0	0	0

A.4.4.2 DBB Architecture

Table A.30 (SI_p) for the case of 20 LPNs in the DBB architecture

0 & 30 'foreign' interferers	20 LPNs				
# of users (K)	All K values				
Target throughput gain (all)	0				
3 'foreign' interferers	20 LPNs				
# of users (K)	10	20	30	40	50

Target throughput gain (x 2, x 10 & x 20)	0	0	0	0	0
Target throughput gain (x 4)	0	0	$-\infty$	0	0

10 'foreign' interferers		20 LPNs				
# of users (K)		10	20	30	40	50
Target throughput gain (x 2)		0	0	0	0	$-\infty$
Target throughput gain (x 4, x 10 & x 20)		0	0	0	0	0

20 'foreign' interferers		20 LPNs				
# of users (K)		10	20	30	40	50
Target throughput gain (x 2, x 4 & x 20)		0	0	0	0	0
Target throughput gain (x 10)		0	0	0	0	-0.33