A Policy–driven Trading Framework for Market–based Spectrum Assignment

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Abstract

We present a policy–driven trading framework for market–based spectrum assignment. Our work allows spectrum consumers to get exclusive access rights through payment of a fee, for a given period of time, and for a given frequency band and location. The key motivation behind our proposal stems from the increased complexity of new spectrum management strategies and the need for extracting the maximum benefit from the available spectrum. In this paper we demonstrate that a policy–driven solution is applicable for the management of spectrum markets, and we present a decentralised and lightweight framework for implementing such markets in networked environments.

1 Introduction

The field of *dynamic spectrum access* focuses on new and very dynamic methods for managing spectrum that move away from the traditional *command and control* means of regulation. Dynamic spectrum access promises greater spectral efficiency, wider access to spectrum and aims to promote more technologically innovative and economically efficient uses of the spectrum. There are many approaches to dynamic spectrum access varying from opportunistic usage regimes [9], [1] to commons models [13], to exclusive usage rights schemes [6], [8]. The U.S. Federal Communications Commission (FCC) has recently proposed the removal of regulatory barriers to facilitate the development of secondary markets in exclusive spectrum usage rights [7]. This allows broader access to spectrum resources through the use of leasing arrangements.

In this paper, we propose a novel policy–based trading framework to facilitate the assignment of exclusive spectrum usage rights through payments. Our work differs from previous proposals in that usage rights of specific spectrum blocks are assigned through payment of a fee by employing the well–established technology of electronic payments. Buyers are issued credentials that verify their purchases allowing the policing of spectrum use. The operation of the market is managed using policy mechanisms that take into consideration its economic and technical requirements. Since the framework aims to be deployed in environments with various performance requirements, it has to avoid unnecessary overhead and operate in a disconnected way with no reliance on global trusted entities.

The rest of this paper is structured as follows. Section 2 describes the complexities behind spectrum markets for exclusive usage rights. Section 3 presents the design of our policy–driven trading framework, its components and the participating entities. In section 4 we discuss our prototype implementation. Finally, we compare our work to previous related proposals in section 5, and we conclude in section 6 by summarising our contributions while presenting some details of ongoing work.

2 Spectrum Markets

The commodities that are traded on spectrum markets are exclusive usage rights. When we refer to the buying and selling of spectrum in the context of a market it is taken to mean the buying and selling of exclusive spectrum usage rights. The notion of usage rights is introduced to clarify that the spectrum *itself* is not bought and sold, but rather the right to its exclusive use.

Defining the rights associated with exclusive usage of spectrum is a challenging problem. There has been a range of interesting papers that have discussed this issue in the past number of years. Hatfield [8] does an excellent job of summarising many of the main contributions to this debate and traces the development of the definition of spectrum usage rights through from Coase [4], to De Vany [6] and to Matheson [14], before going on to further the discussion himself. In the main, in all these papers, the approach has been to attempt to define the parameters associated with some kind of *packet/bundle/block* of spectrum with the end aim of making the definition tight enough

1. so that the user of the packet/bundle/block has a clear set of entitlements,

2. and it becomes possible to trade a packet/bundle/block or multiples thereof in some kind of market system.

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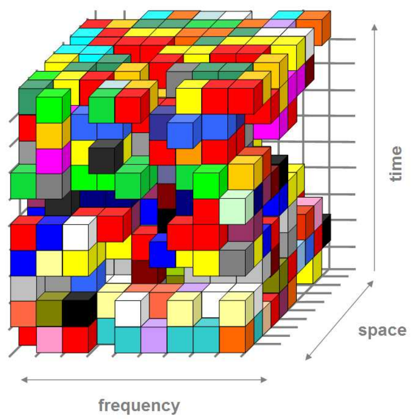

Figure 1. Completely disaggregated market–based assignments.

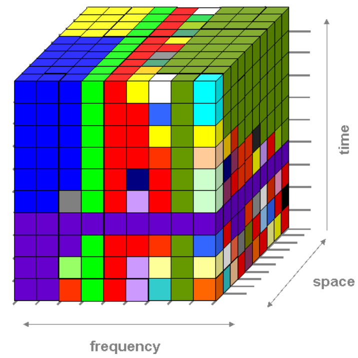

Figure 2. Aggregation of spectrum blocks.

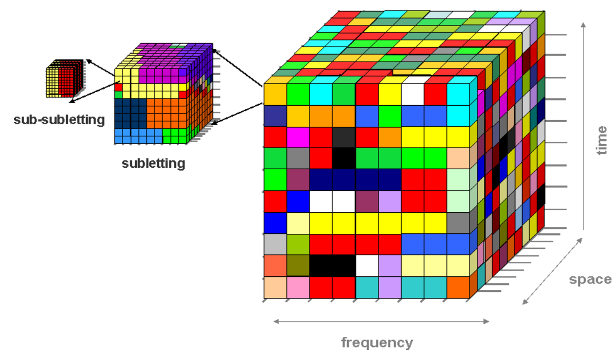

Figure 3. The subletting process.

Irrespective of how the block is defined the aim is to treat spectrum as a commodity. One means of visualising this is to use what we term the *radio spectrum rights continuum* as a three-dimensional model: space, time and frequency. We propose that such a continuum should be quantised into discrete packets/bundles/blocks. Each packet/bundle/block represents a unique assignment of spectrum rights at a particular place, for a particular frequency and at a fixed time.

At its most extreme, our proposal for a flexible market would facilitate a radical form of disaggregation of the RF spectrum, which could have a similar effect on the wireless telecommunications industry. This is illustrated in Figure 1. The Rubik's cube–like illustrations represent an area of the spectrum rights continuum in which there has been complete disaggregation of assignments over frequency, space and time.

Each block in the Rubik's cube–like figure represents a unique spectrum assignment and each colour represents a unique *spectrum consumer*. We have chosen the term spectrum consumer to convey the point that we do not wish to pre–empt the nature of future spectrum users or businesses built around fluid spectrum. Rather, we consider that some agent will want to acquire spectrum for some, possibly still unforeseen, use. We currently would understand such a market actor in terms of entities such as cellular network operators, TV companies and wireless broadband providers.

In a very fluid and flexible market spectrum consumers can freely buy and sell the exclusive rights to the cubes of spectrum that are illustrated in Figure 1. The services that owners of the usage rights deliver and the technologies used to deliver those are not proscribed, i.e. there is total liberalisation of the spectrum. There are no limits or rules as to what blocks can be neighbours and what services can be delivered by neighbouring blocks.

In such a very fluid system, the individual blocks of course may be aggregated to form larger assignments. This is depicted in Figure 2. Aggregations in this situation occur because of market drivers and not because of limitations due to the system for acquiring access to spectrum. Figures 1 and 2 therefore attempt to capture the fluidity of reaction to market forces that would characterise our framework.

Continuing along the lines of the technological influences on the block size, there are some communication system technological limits to realising each of the frequency/space/time dimensions. Any consumer of a block may deem to divide and sublet that block and undoubtedly technological barriers will be encountered at some stage of that division process. Figure 3 attempts to capture the subletting concept.

Additional usage terms and conditions may be attached to particular spectrum blocks as they are traded on different markets. Such terms and conditions may address economic issues (e.g. there may be spectrum aggregation caps that limit monopolistic entities and promote competition), social issues (e.g. spectrum may be traded subject to build–out clauses to meet universal service requirements) or technical issues. This notion tallies with the concept of grading the commodity to provide a resource suited to the general demands of a specific market; a WiFi hot–spot provider is unlikely to be looking for the same type (in terms of duration, spatial extent and bandwidth/frequency) of spectrum as a UMTS network operator. Furthermore, contextual data

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from the environment that affect the operation of the market must be taken into consideration when an entity has to reach a trade decision. For example, an offer for a particular spectrum block may not be as appealing if an emergency situation gives precedence to a different entity at the current time and location.

3 Policy–driven Spectrum Trading

3.1 Design Rationale

The main objective of our policy–driven trading solution is to tackle the complexities of spectrum markets as presented in the previous section. A rich and robust policy model such as the one defined by the Internet Engineering Task Force (IETF) [15] is able to describe the market requirements as well as the related socioeconomic and technical issues. Since the model allows us to assign roles to specific policies we are able to define different spectrum blocks for the needs of different markets. Conflict resolution is also handled by the IETF model by assigning priorities to policies.

3.2 Market Entities

The market entities that participate in our spectrum trading framework are the following:

Clearing house. This entity facilitates the selling and purchasing of spectrum rights through a range of offerings it hosts. Apart from the above, and some form of compensation it should receive for providing such hosting services, it is not involved in spectrum purchases. Although we refer to it as a single conceptual entity, it can also operate in a distributed way.

Spectrum consumer. A spectrum consumer makes offerings and purchases on the market; it plays the roles of buyer and seller in different transactions. Depending on the granularity of the traded spectrum blocks (see Figure 3), spectrum consumers may range from operators of wireless services to end users.

Bank. This entity is responsible for turning real–world money into tokens that can be exchanged over a networking protocol between spectrum consumers. It also handles the opposite operation, i.e. turning tokens into money deposited into accounts.

The clearing house and the spectrum consumers share monetary trust relationships with the bank. The former two also have one–to–one market trust relationships.

The spectrum consumers and the clearing house market entities run *market agents* that implement policy management functions; their components are shown in Figure 4. The *context manager* is responsible for gathering data regarding the demands of the specific market, technical/hardware issues, as well as environment conditions. These are interpreted and formatted; they are used to resolve possible conflicts by assigning priorities to existing policies and as input to the *policy decision point* (PDP). The PDP reaches market decisions by utilising existing policies, input market data (offers, bids) and context data.

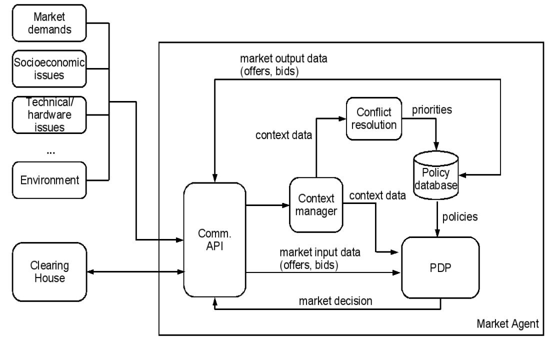

Figure 4. Components of the market agents running on the market entities.

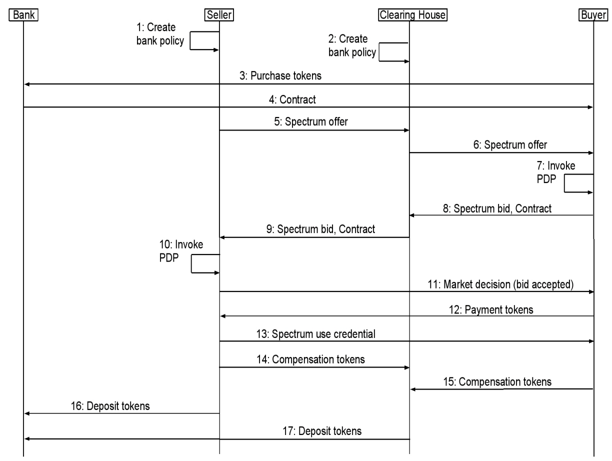

Figure 5. Sequence diagram for the open–cry spectrum auction model.

3.3 Auction Models

In our current design we support two different auction models; namely *open–cry* and *sealed bid*. In the open–cry model buyers openly submit bids for spectrum offers found at the clearing house. These bids are made public; each buyer has access to the bids submitted by a rival buyer and has a limited time to respond with a higher counter–bid [10]. The seller collects the bids, invokes their PDP and reaches a market decision (see Figure 5).

In a sealed bid spectrum auction a deadline is announced by the clearing house that collects and keeps secret all bids for a given seller's offer. The bids are evaluated against the offer at the clearing house's PDP and the winner is declared.

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In both auction models monetary compensations are handled by electronic payments.

4 Prototype Implementation

Our initial prototype addresses markets on which small spectrum sublet blocks are traded. Since frequent low–valued exchanges take place in such markets we rely on micropayments. Macropayments and money transfers can be used to facilitate the trading of larger spectrum blocks.

We use the KeyNote trust management system [2] to implement a subset of the IETF policy model and the real–time hash chain micropayment scheme proposed in [16] to handle monetary exchanges. Furthermore, we have extended the work presented in [3] to allow the management of the chosen hash chain micropayment scheme via KeyNote credentials. Our context manager component is responsible for creating the *action attribute set* that the KeyNote PDP utilises to describe the details of policy requests.

As an example of the operation of the market according to the open–cry auction model consider the following. Initially, a spectrum seller needs to define a policy statement that specifies which banks they trust to provide micropayment tokens and have an account with (public keys and signatures are truncated for readability):

```
comment: which banks does the seller trust?
authorizer: "POLICY"
 local-constants: seller = "rsa-hex:3048024100cc02..."
 bank_1 = "rsa-hex:3048024100bf78..."
 bank_2 = "rsa-hex:3048024100da71..."
 licensees: (bank_1 || bank_2) && seller
conditions: app_domain == "spectrum market" -> "true";
```

A spectrum buyer needs to have a contract with a bank that allows them to spend micropayment tokens. The buyer generates a random number that is then used to generate a hash chain by applying a hash function on it 100 times. This random number is the root element of the chain and is disclosed to the bank when the contract is issued. The following policy encodes a contract between `buyer` and `bank_1` for a hash chain of length 100 and a value of 0.1 monetary units for each element of the chain:

```
comment: buyer's contract with bank_1
local-constants: buyer = "rsa-hex:3048024100aa88..."
 bank_1 = "rsa-hex:3048024100bf78.."
authorizer: bank_1
licensees: buyer
conditions: app_domain == "spectrum market" &&
 @date <= 20070912 &&
 amount == "0.1" && @number <= 100 -> "true";
signature: "sig-rsa-sha1-hex:26d7da6725..."
```

The spectrum seller specifies in a signed policy statement an offer which is sent to the clearing house. The statement specifies the terms of the offer and the signature binds the seller to these terms. The following example encodes in a KeyNote credential the details of the offered spectrum usage rights, the expiration date of the offer, and that a bid should be greater or equal to 3.0 monetary units:

```
comment: seller's offer
local-constants: seller = "rsa-hex:3048024100cc02..."
authorizer: seller
conditions: app_domain == "spectrum market" &&
 &frequency <= 236.0 && &frequency >= 232.0 &&
 frequency_unit = "MHz" &&
 channel_bw == "1.75" && channel_bw_unit == "MHz" &&
 &transmit_power <= 1.0 && power_unit == "W" &&
 &latitude <= 51.15656 && &latitude >= 51.14949 &&
 &longitude >= 2.99228 && &longitude <= 3.01011 &&
 @date >= 20070417 && @date <= 20070418 &&
 @time >= 100000 && @time <= 220000 &&
 &amount * &number >= 3.0 -> "true";
signature: "sig-rsa-sha1-hex:81a0e2520f..."
```

When a buyer finds an offer at the clearing house they pass it to their PDP along with data from their context manager and local policies. If the PDP reaches a positive decision then a bid policy is created for the offer. The policy includes the anchor of the hash chain that the buyer commits to the bid:

```
comment: buyer's bid
local-constants: buyer = "rsa-hex:3048024100aa88..."
 seller = "rsa-hex:3048024100cc02..."
authorizer: buyer
licensees: seller
conditions: app_domain == "spectrum market" &&
 &frequency <= 236.0 && &frequency >= 232.0 &&
 frequency_unit = "MHz" &&
 channel_bw == "1.75" && channel_bw_unit == "MHz" &&
 &transmit_power <= 1.0 && power_unit == "W" &&
 &latitude <= 51.15656 && &latitude >= 51.14949 &&
 &longitude >= 2.99228 && &longitude <= 3.01011 &&
 @date >= 20070417 && @date <= 20070418 &&
 @time >= 100000 && @time <= 220000 &&
 commitment == "b80e336f22b733e4692e270" &&
 amount == "0.1" && number == "30" -> "true";
signature: "sig-rsa-sha1-hex:59295c356d..."
```

When a seller finds a bid they first need to verify that the buyer can indeed deliver the payment and that all market/context/technical terms are satisfied by the given bid. This is accomplished by passing the above credentials to the KeyNote PDP along with their local policies and the context data from their context manager. If the buyer has a valid contract with a bank that the seller trusts and the offer terms are met by the proposed bid then their PDP authorises the transaction. Therefore, the seller is sure that they are going to be paid for the provided spectrum usage rights. When the seller informs the buyer that they accept the bid, the latter releases the required number, in the above case 30, of tokens to the former. At that point, the seller issues a signed KeyNote policy statement to the buyer that includes the purchased spectrum usage rights as specified in the initial offer. We call this the *spectrum use credential*. It can be used by the buyer as a proof of the spectrum assignment facilitating the operation of policing schemes.

The seller collects tokens and periodically contacts the issuing bank to translate them into monetary units and deposit them to their account.

5 Related Work

In [6], [11] and [12], among others, the concepts behind spectrum markets are presented along with proposals for their operation. While these studies clearly demonstrate the complexity of the problem they do not provide any structured framework for solving it. To our knowledge we are the first to suggest a flexible policy–driven market for the assignment of spectrum, or indeed any other, access rights.

Kumar and Feldman propose a detailed software architecture for the operation of Internet–based auctions in [10]. A similar system is presented in [5]. These studies have been valuable to us in designing the protocols of our trading framework and identifying key differences between traditional and network–based spectrum auctions. We believe that policy mechanisms can be successfully applied to the problem of managing digital trading, especially when the target application environment is characterised by dynamic parameters.

The KeyNote trust management system is used in [3] to implement an offline micropayment protocol without the requirement of trusted hardware. In this paper we have extended this idea in two key aspects; instead of relying on digital cheques we use a lightweight hash chain micropayment scheme, and instead of buying and selling the resources themselves we trade access rights for using the resources (spectrum blocks in our case).

6 Conclusion and Ongoing Work

We have presented our ongoing work on a policy–driven trading framework for evolving market–based spectrum assignment regimes. Our system is able to address the social, economic and technical requirements of different spectrum markets while taking in consideration contextual information from the environment to support trade decisions. Such complexities prohibit the reliance on static assignment processes and make our policy–based solution an attractive choice. While our prototype implementation is far from complete it demonstrates the feasibility of our approach. Our ongoing work is focused on a complete implementation of the context manager component and the IETF policy model.

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