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DYNAMIC RESOURCE MANAGEMENT IN RADIO NETWORKS

László Kovács

Ph.D Dissertation

Supervised by

Dr. Attila Vidács
High Speed Networks Laboratory
Dept. of Telecommunications and Media Informatics
Budapest University of Technology and Economics

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László Kovács

High Speed Networks Laboratory

Dept. of Telecommunications and Media Informatics

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Dr. Vidács Attila
Nagysebességű Hálózatok Laboratóriuma
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To my family

Table of Contents

List of Tables

List of Figures

Abstract

The radio spectrum is a scarce, valuable and thus expensive resource. An efficient use of frequencies is primordial, but existing management systems fail to achieve this. On one hand, a substantial amount of spectrum is wasted at a given time and place with today's rigid frequency usage policies. On the other hand, spectrum usage rights are not always given to those who have the greatest need and would benefit from it the best, eventuating in lower overall social welfare. The possibility of on-demand spectrum allocation with Dynamic Spectrum Access (DSA) methods, together with the pressure of a liberalised spectrum market would lead to a much more efficient spectrum usage.

The objective of this dissertation is twofold. In the first part the goal is to establish a dynamic spectrum allocation framework that provides the possibility to replace today's rigid spectrum allocation method by a dynamic solution that is able to follow temporal and spatial variations of spectrum demands. The aim of the second part is to propose an adequate, real time auction- and pricing method for DSA systems. Since tolerance in a DSA scenario is much rewarded, the proposed pricing scheme charges providers who do not tolerate others and interfere to a larger extent than necessary.

Kivonat

A rádiós spektrum egy véges, értékes és ezért drága erőforrás. Elsődleges fontosságú lenne a frekvenciasávok hatékony kihasználása, ám a jelenlegi menedzsment rendszerrel ez nem megvalósítható. Egyrészről jelentős mennyiségű spektrum vész el adott időben és helyen a merev frekvencia kiosztás miatt. Másrészről, a spektrum-használati joggal nem mindig azok rendelkeznek, akiknek arra a legnagyobb szükségük lenne és a legtöbbet profitálnák belőle, ezáltal csökkentve a "közjót". Az igény szerinti, dinamikus spektrumhozzáférési (DSA) módszerek, a liberalizált spektrum piac hatásával együtt jelentős kihasználtság javulást eredményezhetnének.

A disszertáció célja kettős. Az első részben javaslatot teszek egy dinamikus spectrum allokációs keretrendszerre, mellyel lehetővé válik a jelenlegi merev spektrum kiosztási rendszer lecserélése olyan dinamikus megoldásra, ami képes az igények tér- és időbeli változásának követésére. A második részben bemutatok egy a DSA rendszerekben alkalmazható, valós idejű aukciós- és árazási módszert. Mivel a DSA rendszerben a tolerancia nagyon fontos tényező, a javasolt árazási módszerrel többet kell fizetniük azoknak a szolgáltatóknak, amelyek nem tolerálják a többieket, vagy a szükségesnél nagyobb interferenciát okoznak a környezetüknek.

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Budapest, László Kovács
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Introduction

The radio spectrum is one of the key attributes for the success of the future of radio communications. The radio spectrum is a valuable commodity, and a unique natural resource shared by various types of services. It can be repeatedly reused, provided certain technical conditions are met, but in practice, it is finite, can only accommodate a limited number of simultaneous users, and requires careful planning and management to maximise its value for all services. This is especially true as the demand for communication spectrum is rapidly increasing worldwide.

With the rapid growth in the society's demand for wireless applications, traditional spectrum management approaches are increasingly yielding inefficient spectrum utilisation and artificially restricting innovation and competition. Traditional ways to assess the merits of new technical solutions and to allocate as well as to tax use of frequencies appear to be less and less well adapted [15]. Consequently, efficient use of the spectrum (i.e., ensuring that new spectrum is only assigned when really needed) is a major challenge.

The current spectrum regulation framework is based on the allocation of the spectrum to radio services. This is reflected in the Radio Regulations (RR) published by the International Telecommunication Union (ITU), that contains definitions of these services, and a table defining their allocations for each of the ITU Regions. This rigid, static spectrum allocation does not provide enough flexibility and it becomes more and more difficult to ensure sufficient spectrum for new technologies.

The general trend towards more flexible spectrum management is driven by the growing market pressure for more commercialised spectrum, and the continuous appearance of new technologies offering a wide range of applications [46].

In addition, several measurements [34, 41, 7] show that a substantial fraction of the spectrum is wasted at a given time and place. First, the spatial distribution of spectrum usage is uneven. In today's allocations frequency usage rights are given for large areas, typically for the area of a whole country. By scaling down the size of the region we are looking at, high spatial spectrum utilisation variations are revealed. Second, radio communication networks are designed for "busy hours" but the spectrum is not fully utilised in the rest of the time. Furthermore, "old-fashioned" legacy services tend to take a back seat while still possessing a large slice from the spectrum, and at the same time new services emerge and try to get access to a fair slice of the spectrum.

These are the motivations for a more spectrum efficient technique, called Dynamic Spectrum Allocation (DSA), where the spectrum usage rights may vary in time and space in a finer scale.

The new spectrum allocation policies should ensure technology and service neutrality in order to allow new technologies to be deployed in the currently strictly conditioned spectrum. Note, that one recent example of a serviceneutral approach to spectrum regulation is the proposed Wireless Access Policy for Electronic Communications Services (WAPECS) initiative in Europe, which aims to identify a basket of frequency bands that can be allocated on a technology and serviceneutral basis, whilst satisfying all technical requirements against interference [6].

Combining on-demand dynamic spectrum access with the pressure of a liberalised "market for frequencies" would lead to a much more efficient spectrum usage and thus higher social-economic welfare. There are two distinct policies that could be introduced separately or in combination: *trading* – the transfer of spectrum usage rights between parties in a secondary market, and *liberalization* – the relaxation of restrictions on services and technologies associated with spectrum usage rights. While trading alone allows the market to determine *who* has access to spectrum, liberalization lets the users decide *how* spectrum is used. Without liberalization, secondary market activity will be limited to transfers of existing usage rights. Without trading, liberalization will only enable existing users to switch services and technologies; alternative users would not be able to access spectrum. Introduction of both trading and liberalization could lead to more efficient use of spectrum [4]. This process is supported by the European Commission. According to the Communication from the Commission to the Council [5]: "Reforming spectrum management in the EU to introduce a market-based approach to spectrum distribution constitutes a major challenge. But it is worth accepting since an effective introduction of spectrum markets would be:

- beneficial in terms of the gains to Europe in competitiveness, in innovation potential and in strengthening the internal market as well as in increasing the variety of services offered to the consumer, along with the positive effects on the creation of jobs and external trade;

- timely and necessary because spectrum management as practised so far has reached its limits due to technological progress, increasing demand on spectrum resources and the speed of changing business cases and markets;

- feasible in the proposed time frame."

In a DSA environment spectrum usage rights are associated with a set of *rights* (which enable the user to use spectrum in certain ways) and *obligations* (which specify conditions that users must fulfil in order to maintain their rights). Usage rights can be defined in relation to four basic parameters [4]: *geographical area* (e.g., a country, a region or a defined area around a base station), *duration and time of access* (e.g., unlimited or defined length, access to spectrum throughout the entire day, or at a specific time of day only), *spectrum block* (i.e., the frequency range to which access is granted), and *protection from interference* (i.e., the right to receive signals without harmful interference from other spectrum users and the obligation not to cause such interference). Holders of spectrum usage rights should be free to supply any type of electronic communication service (*service neutrality*) while ensuring that interference is appropriately dealt with, and to use any technology, abiding by common conditions (*technology neutrality*) [4].

The greater the flexibility in spectrum licensing conditions, the higher the risk of *interference*. Spectrum users in the liberalised environment will need to be confident that neighboring users will meet their obligations, especially in regard to interference, and that their own rights will be upheld. This requirement puts the additional burden on regulators and spectrum users of coordinating new and less predictable interference relationships. As a result, more flexible approaches to interference management would be necessary. Where possible new technology-neutral parameters for interference management will be required for adjacent frequencies and geographical areas.

To summarise spectrum is an important factor for new business development. It is a limited, valuable and thus expensive resource and must be managed efficiently. The major challenge is to develop a spectrum management framework that is commonly applicable independently of technologies and services. Such a framework is needed not only to satisfy the engineering, economic and policy challenges of future spectrum usage, but also to satisfy increasing enduser demands. Dynamic spectrum allocation is a promising approach to fully utilise the scarce spectrum resources.

Outline of the dissertation

The objective of the dissertation is twofold.

In the first part the goal was to establish a dynamic spectrum allocation framework that provides the possibility to replace today‘s rigid spectrum allocation method by a market based dynamic solution.

At first Chapter 1 gives an overview on Dynamic Spectrum Access (DSA) networks focusing mainly on spectrum allocation, auction and pricing solutions.

Chapter 2 introduces a dynamic spectrum allocation framework that models the interaction between different service providers operating in different parts of the area of a dynamic spectrum access network. Furthermore, spectrum quality descriptors are also defined as well as several metrics for comparison of fixed and dynamic spectrum allocation systems. I note that this dissertation -as well as the research on dynamic spectrum allocation- focuses on frequency allocation; resource distribution techniques lower in the hierarchy such as, CDMA, TDMA, OFDMA, etc. are out of the scope of this work. These techniques usually can be used for re-distribution of the resources among the users. I also note, that realisation of dynamic spectrum allocation on this hierarchy level would contradict the main requirement on DSA solution, i.e. technology neutrality.

Chapter 3 proposes two different models for spectrum allocation in DSA networks. For both models I give the feasibility conditions and also propose methods to determine the optimal allocations.

The aim of the second part is to establish an adequate, real time auction- and pricing DSA management framework.

Chapter 4 describes an allocation model that takes the specialities of dynamic spectrum allocation into account and gives the allocation and pricing rules that yield an optimal solution that maximises the social welfare. In order to find the optimal allocation several feasibility checks have to be carried out within one bidding period. The quick feasibility check is essential for real-time operation. In this chapter I also propose two methods to realise fast feasibility estimation and a rule-based algorithm for searching the most efficient allocation.

Chapter 5 unveils the connection between the framework and the allocation method proposed in the first part of the dissertation and the auction and pricing methods described in the second part; it also gives an overview on the allocation process and reveals some fundamental properties of the proposed system.

Finally, Chapter 6 summarises the main findings of this work, and gives an insight on the applicability of the results.

Chapter 1

Dynamic Spectrum Access Networks

The concept of Dynamic Spectrum Access Networks first came up in the neXt Generation Communications (XG) program [1], funded by the Department of Defense‘s (DoD) Defense Advanced Research Projects Agency (DARPA) and managed by the Air Force Research Laboratory (AFRL) in the USA. The XG Program is developing technology and system concepts for military radios to dynamically access spectrum in order to establish and maintain communications. In Phase I and II the goals were to develop, integrate and evaluate the technology in order to enable equipment that automatically selects spectrum and operating modes to both minimize disruption of existing users, and to ensure operation of U.S. systems. In 2006 they demonstrated the fundamental building blocks of a dynamic spectrum system and innovative technologies that enable dynamic access to the radio frequency spectrum. The live demonstration, held at Fort A.P. Hill, Virginia, was carried out as part of Phase III of the XG program. The demonstration used six mobile 802.16-based XG radios that operated in the same spectrum as a suite of fixed, instrumented military and commercial legacy radios. A wide-area instrumentation system was used to record the XG radio connectivity and the performance of the legacy radios. The field exercises demonstrated the operational utility of XG: that XG causes no harm to existing military radios in compliance with emission/regulatory rules; XG will allow additional radio networks or communication capacity then currently possible using existing procedures; and that XG can operate in the presence of electromagnetic interference (i.e., jamming) [13].

Due to the military application in the XG proposals there is no central entity, it requires complex spectrum sensing at individual radio nodes and distributed coordination protocols. In commercial applications, because of the existing architecture, the aggregation of regional demands and the centralization of spectrum management decisions is easily realizable and leads to a simpler solution.

The IST-DRiVE (Dynamic Radio for IP-Services in Vehicular Environments) [2] project dealt with the coordinated DSA problem. The goal was to develop methods for dynamic frequency allocation and for co-existence of different radio technologies in one frequency band in order to increase the total spectrum efficiency. They investigated only the co-existence of UMTS and DVB-T technologies [28] [29].

The IST-OverDRiVE project [3] dealt with the problem in more details. They defined 'DSA areas' in which the traffic demands of different RANs are rather constant in space (yet they may be time variant). In the proposed model providers have to allocate continuous spectrum blocks because they insert unused spectrum blocks (extra guard bands) at the border areas in order to avoid interference. They considered regions as "isolated islands" and did not deal with the interference arising between them.

In the IST-WINNER project (Wireless World Initiative New Radio) [24], mechanisms for cooperation between the radio segments of different RANs will be proposed. This cooperation is expected to enhance the functionality, performance, flexibility and radio coverage with respect to the single-RAN case. One of the goals of this project is the development and deployment of flexible, optimised mobile radio networks which will be able to adapt to the spatial and temporal variations in capacity demands in order to increase the overall spectral efficiency of the joint set of radio networks. This project focuses mainly on the technological aspect of the Dynamic Spectrum Access Networks and does not deal with spectrum allocation and pricing issues.

In the field of research on dynamic spectrum access networks there are several topics that investigate different aspects of enabling a new, more flexible spectrum management.

- **Technology aspects:** The key enabling technology of DSA networks are the software-defined and cognitive radios. Cognitivity refers to the ability of the radio technology to sense the information from its radio environment, and enables the radio to be dynamically programmed to transmit and receive on a variety of frequencies, and to use different transmission technologies supported by its hardware design [22]. More specifically, the cognitive radio technology has to enable the users to [7]:
    - determine which portions of the spectrum are available and detect the presence of licensed users when a user operates in a licensed band;
    - select the best available channel;
    - coordinate access to this channel with other users;
    - vacate the channel when a licensed user is detected in case of priority access solutions.

  For a detailed survey on technology aspects of dynamic spectrum access and cognitive radio networks, please refer to [7] and references therein.

- **Architectural aspects:** Architectural questions come up only in centralised solutions, where usually one or more centralised entities (called Spectrum Brokers) coordinate the spectrum allocation. Buddhikot *et al.* [10] gave a detailed description of an implementation architecture (called DIMSUMnet) for coordinated DSA. The "Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile network" (DIMSUMnet) implements statistically multiplexed access to spectrum in the coordinated access band (CAB). CAB is a contiguous chunk of spectrum reserved by regulating authorities. A spectrum broker permanently owns the CAB and leases it according to requests. DIMSUMnet uses a centralised, regional network level brokering mechanism that aims to significantly improve spectrum utilisation while reducing the complexity and the agility requirements of the deployed system. The base-station registers with its designated radio access network manager (RANMAN), which negotiates a lease with a spectrum information and management broker for an appropriate portion of the spectrum. If the lease is successfully obtained, the RANMAN configures the leased spectrum in the base-station. The base-station sends the spectrum information received from the RANMAN to its users for the configuration of clients. The auction and pricing model I proposed in Chapter 4 assumes a similar architecture as the DIMSUMnet.

- **Dynamic Spectrum Allocation aspects:** These proposals focus on spectrum sharing and allocation techniques. Spectrum allocation techniques have been investigated through two major theoretical approaches. While some work uses optimisation methods to find the optimal strategies for spectrum sharing, game theoretical analysis has also been used in this area. Whilst Chapter 2 and Chapter 3 focus on spectrum allocation in dynamic spectrum access networks, Section 1.1 gives a detailed overview on this topic.

- **Market aspects:** The main question in this area is how to organise a real-time dynamic auction and pricing mechanism that ensures optimal allocation from a specific point of view, e.g., maximises social welfare. A proper mechanism has to take the specialities of spectrum allocation into consideration, i.e., it charges providers who do not tolerate others and interfere to larger extent than necessary with other regions. Centralised and distributed iterative solutions can also be found in this field. Since Chapter 4 focuses on this aspect Section 1.2 contains a detailed overview of the scientific results within this topic.

1.1 Dynamic Spectrum Allocation

Dynamic spectrum allocation proposals face a problem that the resource to be distributed is the radio spectrum and dividing spectrum is very different from dividing, for example, bandwidth or other resources. The main difference lies in the fact, that spectrum usage can have considerable effect on other allocations in different regions, as well, because of interference. Hence, as not all spectrum slices are useable in all regions, the sum of allocated spectrum blocks is not necessarily equal to the size of the coordinated access band.

Due to this fact proposals in this field usually first define a more or less detailed model on interference then give an optimisation or game theory-based method to determine an optimal allocation from a specific point of view.

From architectural point of view the proposed solutions can be grouped according to access and coordination. By coordination we can distinguish:

- centralised solutions, where a spectrum broker controls and provides a time-bound access to a band of spectrum to service providers and determines the prices of the allocated spectrum blocks,

- and distributed solutions, where end users search for available spectrum holes then select an appropriate spectrum band for data transmission.

By the access we can distinguish:

- priority access solutions, where spectrum is dedicated to the primary system (usually the license owner) and the secondary system may only access the same spectrum as long as it does not cause significant interference to the primary system,

- and equal-right access solutions, where each provider has the same priority to access spectrum; allocation decision is made by the requests and offered prices.

All solutions have advantages and disadvantages summarised in Table 1.1.

In case of priority access solutions there is no possibility to provide exclusive licenses even for a short time period since secondary users may only have access to the spectrum as long as no primary request arrives. In equal right access solutions, when the spectrum is allocated in a distributed manner, it is also difficult to ensure exclusive licenses due to the synchronization problems. In case of centralised equal right access solutions exclusive licenses can be easily granted.

Independently of the access, there is a trade-off between the complexity of the system and the necessity of a high resource capacity central entity. In distributed spectrum allocation systems end user terminals have to be capable to search for spectrum holes, characterise

Table 1.1: Comparison of Dynamic Spectrum Allocation solutions

		COORDINATION	
		DISTRIBUTED	CENTRALISED
ACCESS	PRIORITY	– no exclusive licenses ø may converge to the optimal solution + no central entity needed – complex solution (spectrum sensing, characterising, etc., in the terminals)	– no exclusive licenses + provides optimal solution – high resource capacity central entity + simpler solution due to the central entity
	EQ RIGHT	– difficult to provide exclusive licences ø may converge to the optimal solution + no central entity needed – complex solution (spectrum sensing, characterising, etc. in the terminals)	+ exclusive licenses + provides optimal solution – high resource capacity central entity + simpler solution due to the central entity

them, and select an appropriate spectrum band for data transmission. However, a central entity is not required and allocations may lead to a near optimal solution in a few iterations.

In priority access solutions research focuses on the following topics [7]:

- Spectrum sensing: an important requirement is to detect the spectrum holes. The most efficient way to detect spectrum holes is to detect the primary users that are receiving data within the communication range. However, in practice it is difficult for a cognitive radio to have a direct measurement of a channel between a primary receiver and a transmitter. Thus, the most recent work focuses on primary transmitter detection based on local observations of the user. The spectrum sensing techniques can be classified as transmitter detection [16][17], cooperative detection [49][50], and interference-based detection [48].

- Spectrum analysis: the available spectrum holes show different characteristics which vary over time. Spectrum analysis enables the characterization of different spectrum bands, which can be exploited to get the spectrum band appropriate to the user requirements [43].

- Spectrum decision: Once all available spectrum bands are characterized appropriate operating spectrum band should be selected for the transmission [26][49].

In equal-right access solutions, usually a central entity grants short time exclusive licenses for the service providers. Buddhikot *et al.* gave a detailed description of an implementation architecture for coordinated DSA [10]. In their model a spectrum broker controls and provides a time-bound access to a band of spectrum to service providers. They also investigated algorithms for spectrum allocation in homogeneous CDMA networks [11] and executed spectrum measurements in order to study the achievable spectrum gain [23]. They investigated two different spectrum request models. In the online model each request is processed as it received independent of the future requests. If a request is admitted it is configured in the appropriate base stations immediately. In the batched model requests received in a time window are batched and processed together. They found that the batched model has several advantages; it guarantees a fixed, maximum latency for spectrum demands, it allows correlating and aggregating temporally and spatially clustered requests to optimise spectrum allocation, allocation and deallocation of spectrum is done at fixed intervals allowing network and end user devices to predict transitions and adapt to possible connectivity disruptions.

They proposed algorithms to determine spectrum allocation in homogeneous CDMA networks, and they do not allow two different providers to use the same spectrum block if there is any interference between them. They also proved that in this simple case the spectrum allocation problem relates to a well known NP-hard graph colouring problem [42]. Since fast spectrum allocation algorithms are crucial to the design of scalable spectrum brokers they designed efficient algorithms to solve the spectrum allocation problem. Specifically, they formulated the spectrum allocation problem as two optimisation problems: first with the objective of maximising the overall demand satisfied among the various base stations, and the second with the objective of minimising the overall interference in the network (Min-Interference) when all the demands of the base stations are satisfied. Then they used heuristic methods to determine the optimal allocation.

P. Leaves *et al.* dealt with the coordinated DSA problem, as well. They investigated only the co-existence of UMTS and DVB-T technologies [28] [29] and had some interesting results [19] [30] within the frameworks of the IST Drive and Overdrive projects. They defined DSA areas in which the traffic demands of different RANs are rather constant in space (yet they may be time variant). Only one gain, called “Grade of Service” (GoS), was defined, which is the fraction of the maximum traffic that can be carried by the allocated spectrum and the traffic demand. In their model providers have to allocate continuous spectrum blocks and they insert unused spectrum blocks (extra guard bands) at the border areas in order to avoid interference.

The authors of [38] focuses mainly on auction and pricing but also introduced a simple spectrum allocation model. While earlier works only concentrated on CDMA providers, in [39] the situation is further extended with the presence of a DVB-T network provider. The focus was on the simplest non-trivial model capturing the following issue: a 'two island' geography, in which each CDMA network has one cell per island but a single DVB-T cell covers both adjacent cells. This implies inter-cell interference issues and inter related auctions, where license to use a spectrum band over one island has no value to the DVB-T operator unless it comes with a license to use the same band over the adjacent island.

In my dissertation I also focus on batched dynamic spectrum allocation due to the advantages summarised by Buddhikot *et al.* in [23]. The main difference is that in the framework I proposed interference is taken into account in a flexible way. There is no need to use guard bands between adjacent spectrum blocks unlike in [30], as well as the technologies used by the providers are not limited to a restricted set unlike in [11] and [39]. In the interference tolerant model (see Section 3.2) interference is partially allowed but must be kept under pre-defined thresholds resulted in a more flexible and detailed model for dynamic spectrum allocation. This model is general in the sense, that, with the model parameters properly set, the model incorporates those ones proposed in [2],[39] and [11] as a special case.

I also examined the achievable gains in more details both from the regulator's and provider's point of view, and proposed several metrics for the comparison of DSA and rigid allocation systems.

1.2 Auction and Pricing

Proposals within this area aim at finding solution for the question: how to organise a real-time dynamic auction and pricing mechanism ensuring an allocation that is optimal from a specific point of view. One such point can be for example the maximisation of social welfare. This mechanism is required to take the special characteristics of dynamic spectrum allocation into account. E.g., providers who do not tolerate others and interfere with other regions to a larger extent than necessary are charged more as well as those providers that do not tolerate interference well enough.

Recall, that different solutions proposing dynamic spectrum allocation can be grouped according to access and coordination. From access's point of view equal right and priority access systems can be distinguished. As for coordination centralised and distributed systems can be found.

Auction and pricing methods were proposed for both centralised and distributed architectures. In centralised networks the pricing that leads to the optimal allocation can be unambiguously determined, in case of distributed architectures iterations converging to the optimum are constructed.

1.2.1 Auction and Pricing in Priority Access Networks

For pricing in priority access networks only centralised proposals can be found.

In [36] the authors considered a centralised Spectrum Server to coordinate the transmissions of a group of links within common spectrum. The Spectrum Server aims at finding an optimal schedule that maximises the average sum rate subject to a minimum average rate constraint for each link. The authors used a graph theoretic model for the network and a linear programming formulation to achieve a transmission pattern similar to spatial reuse in cellular networks.

The authors of [20] developed a framework for providers operating in a mixed commons / property-rights regime under the regulation of a spectrum policy server (SPS). The operators dynamically compete for portions of available spectrum. The competition is considered to be a noncooperative game and an SPS-based iterative bidding scheme is proposed that results in a Nash equilibrium of the game.

1.2.2 Auction and Pricing in Equal Right Access Networks

Within the proposals allowing the providers equal-right access to the spectrum resource both distributed and centralised solutions can be found.

An equal-right access distributed approach to dynamic spectrum management is presented in [44]. In this paper the authors present a dynamic spectrum sharing management scheme in which spectrum allocation and pricing is performed in a distributed manner. Within the framework they assumed that the participants are non-cooperative, the frequency leasers act for their own benefit. The goal is to assure an allocation that maximises spectrum utilisation. This is targeted to be achieved by maximising the spectrum owner's income. In this system the authors propose a game theory based iterative algorithm that converges to the optimal allocation.

In centralised systems there usually exists a central entity called Spectrum Broker that leads an supervises the auctions. The issue for centralised systems has recently been discussed in several works.

The authors of [12] examined the technical and economic issues of markets for DSA networks, described a number of wireless communication service market developments that are linked to dynamic spectrum access (both required enablers or potential effects) and can occur within existing regulatory frameworks. The paper also proposes technical and policy recommendations that facilitate the success of DSA.

The authors of [21] proposed a distributed competition-based architecture of spectrum management based on multi-agent model, called Market Competition Dynamic Spectrum Management (MCDSM). The authors used game theory, to make the MCDSM scheme able to utilise the spectrum efficiently, to maximise the operator's profits, and to improve the fairness among different RANs. They introduced two new concepts, namely 'spectrum trading unit' (i.e., the spectrum block is divided into small tradeable slices in a size of the smallest channel in a fixed service channel raster) and 'spectrum occupied state', to propel and simplify the operation of spectrum market. To fulfil the spectrum transactions each RAN is supposed to have an intelligent Trading Proxy Agent. In the spectrum market, if some RAN can deal with its own service requirements and have some spare spectrum it can sell the extra spectrum.

The authors of [38] introduced a DSA scheme in which a spectrum manager periodically auctions short-term spectrum licenses. They considered CDMA-based radio access technology and delay-tolerant data applications. In the proposed framework the central spectrum manager offers spectrum rights for sale on a very short-term basis and at a unit price. The paper focuses on the problem of the network operator, selecting a "proper" pricing mechanism is not within the scope. Such a solution may be plausible in certain scenarios, e.g., when there is a large number of spectrum buyers and none has enough power to influence the market clearing price.

In their related work [37] the authors investigate the question of pricing in the same framework. Price is determined through auctions. To overcome the situation when the above assumptions of the spectrum leasers are violated, here the spectrum manager uses second price (or Vickrey) auctions instead, i.e., the highest bidder wins but pays an amount that equals the highest losing bid. This method encourages the participants to submit a bid that is equal to their true valuation of the requested resource.

In [39] the situation is further extended with the presence of a DVB-T network provider operating in a single DVB-T cell that covers two adjacent CDMA cells. This implies inter-cell interference issues and inter related auctions, where license to use a spectrum band over one CDMA cell has no value to the DVB-T operator unless it comes with a license to use the same band over the adjacent CDMA cell.

Somewhat similar questions arise in wired communication networking environment as well. Lazar and Semret introduce the Progressive Second Price (PSP) Mechanism, an iterative auction scheme that allocates bandwidth on a single communication link among users [27] (see also the extensions in [45], [32]). The allocations and prices to pay are computed based on the bids submitted by all the players. Users can modify their bids by knowing the bids submitted by the others, until an equilibrium is reached. The main drawback of this scheme is that the convergence phase can be quite long. The mechanism was modified by Delenda, who proposed in [14] a one-shot scheme: players are asked to submit their demand functions, and the auctioneer directly computes the allocations and prices to pay without any convergence phase.

Also for wired networks Maill and Tuffin in [33] proposed a scheme based on second-price auctions that leads to an efficient allocation of resources in the sense that it maximizes social welfare. They suggested an intermediate mechanism, which is still one-shot, but which does not suppose any knowledge about the demand functions. They considered quasi-linear utility functions, just like in [40], but here they allowed players to submit several bids like in [47], and used an allocation and pricing scheme that is close to the one described in [14]. Unlike in the PSP mechanism, they did not suppose that players know the bids submitted by the others before bidding.

For dynamic spectrum access networks Rodriguez *et al.* [38, 39, 37] investigated the problem of choosing the right pricing mechanism for trading short-term spectrum licenses. They also proposed an iterative progressive second-price solution, with the restrictions that interference is not allowed at all, and only exclusive spectrum usage rights are given to the players.

In Chapter 4 I propose a one-shot (similar to [14]), multi-bid (like [33] and [47]) auction method with second-price pricing scheme, similar to that of [27]. However, in this case the resource to be distributed is the radio spectrum, that makes the allocation problem fundamentally different from the wired solutions. The allocation rule takes into account the special properties of the underlying DSA model, namely, that dividing spectrum is not the same as dividing, for example, bandwidth. The main difference lies in the fact, that spectrum usage can have considerable effect on other allocations in different regions as well because of interference. Thus not all spectrum slices are useable in all regions, the sum of allocated spectrum blocks is not necessarily equal to the size of the coordinated access band.

Chapter 2

Spatio-Temporal Dynamic Spectrum Allocation Framework

The goal of this Chapter is to propose a general framework to model the interaction between different service providers operating in different parts of the area of a dynamic spectrum access network. Section 2.1 describes the modelling assumptions, then the following sections answer the questions arising within the framework:

- How to model the interaction between regions and different technologies, i.e., the interference caused by service providers? (Sections 2.1 and 2.2)
- What metrics can be defined in the model for measuring the efficiency of dynamic spectrum allocation? (Section 2.3)
- What shall be the principle of spectrum distribution? How to handle interaction of different service providers in different regions? How to model the sensitivity of service providers to interference? Interference in neighbouring regions may be compensated (Section 3.1) or we may introduce a "tolerance" threshold for each provider (Section 3.2).
- What is the optimal allocation (in the afore-mentioned two models) that imposes – assuming fix available spectrum amount– minimum disturbance on the providers? Is the allocation feasible at all, with the available spectrum band? What is the minimum necessary spectrum amount to serve all demands? (Sections 3.1 and 3.2)

2.1 Modelling Assumptions

In the framework I propose dynamic spectrum allocation is interpreted as follows. The available area is divided into smaller regions; such a region can be for example a certain part of a city (business quarter, downtown, residential area, etc.). It is important to note, that our DSA method does not aim at dynamic allocation at the cell level in cellular networks. Instead, regions are larger areas covering fixed infrastructure wireless networks with more base stations. The system handles temporal demands in each region.

Time is divided into allocation periods; one allocation period is in the order of hours, the framework does not aim at dynamic allocation at the call level, the goal is to capture the daily variations. In each reallocation period service providers can bid for spectrum blocks with different sizes according to the user demands.

Within a region we assume that the spatial distribution of the spectrum demand is homogeneous, only temporal changes are allowed. The spectrum is owned by a central entity, called the Spectrum Broker (SB), that grants short-term licences for the service providers. Inside the regions, besides given conditions, service providers can use the allocated spectrum for whatever they want, which ensures the service and technology neutrality requirement.

Within each region temporal DSA (TDSA) is realised. Service providers operating in that region send their requests for spectrum periodically, and the SB allocates continuous spectrum blocks to satisfy the demands, if it is possible. The size of the blocks may vary in time, depending on the provider's requests and the availability of the spectrum. Besides TDSA, spatial DSA (SDSA) handles spectrum demands arising at the *same* time in *different* regions. The aim of the SDSA is to attune the different demands within different regions the most efficient way, that the least interference arises between regions.

The framework aims at modelling disturbance (interference) between the regions and ensuring only such spectrum allocations in which services provided for users are not ruined by interference.

Formally, let the available spectrum block (Coordinated Access Band) be $S_{CAB} = (\check{s}, \hat{s})$. The available area is divided into K regions. Within one region M service providers compete for the available resources. The spectrum block assigned to the m-th provider in the k-th region at time t:

$$S_{m,k}(t) = (\check{s}_{m,k}(t), \hat{s}_{m,k}(t)), \qquad (2.1)$$

where $\check{s}_{m,k}(t)$ *and* $\hat{s}_{m,k}(t)$ *denote the lower and upper bounds of the spectrum block.* Let us denote the size of the allocated spectrum by $|S_{m,k}(t)|$, i.e.

$$|S_{m,k}(t)| = \hat{s}_{m,k}(t) - \check{s}_{m,k}(t). \qquad (2.2)$$

The notations emphasise that the spectrum allocation is highly dynamic, each provider can be given different spectrum blocks in different regions and at different time instants. (To ease the notations, the dependence on time t is not written explicitly in the followings.)

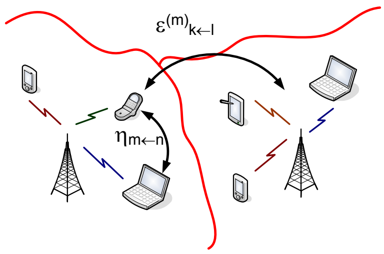


Figure 2.1: Coupling parameters

In the framework interference causes the *degradation of spectrum quality*. The extent of interference depends on the geographical location and the parameters of the used technology. Disturbance caused by interference can be split into two independent components (see Figure 2.1) as follows. Spectrum utilisation is decreased if the same frequency is used by different service providers in nearby regions. The level of interference depends on the geographic location and the size of the regions, as well as on the radio access technique used, the transmission power, and the positions and types of radio transmitters. The ε *geographical coupling* parameter describes the grade of disturbance caused by a provider operating in the same frequency range in the neighbouring (or further) region. Let $\varepsilon^{(m)}_{l\leftarrow k}$ denote the disturbance the m-th provider operating in the k-th region causes in the l-th region.

From the Network Service Providers' (NSPs') point of view, the level of interference is the measure of how much their radio technology is affected by competing technologies. The level of disturbance (or jamming) between different NSP radio technologies is captured by the $\eta_{m\leftarrow n}$ technology coupling parameter, that characterises the coupling between the technologies used by the m-th and n-th providers. This parameter describes how much of this disturbance can be "filtered out" depending on the used technology.

Practically, e.g., the value of the $\varepsilon^{(m)}_{l\leftarrow k}$ geographical coupling parameter can be expressed as the product of the $s^{max}_{k,m}$ allowed maximal power spectral density at the region borders and the $\varepsilon_{l\leftarrow k}$ signal attenuation between regions R_l and R_k.

$$\varepsilon^{(m)}_{l\leftarrow k} = s^{max}_{k,m} \cdot \varepsilon_{l\leftarrow k} \tag{2.3}$$

For example according to the Okumura-Hata propagation model for urban (medium city) environment [35] $\varepsilon_{k\leftarrow l}$ can be calculated as:

$$\varepsilon^{[dB]}_{k\leftarrow l} = -A^{[dB]}\left(d^{[km]}_{k,l}\right) = -130.52 - 10 \cdot \lg\left(d^{[km]}_{k,l}\right) \tag{2.4}$$

where attenuation A depends on the distance $d_{k,l}^{[km]}$ between regions R_k and R_l. For neighbouring sectors $\varepsilon_{k\leftarrow l}$ is approximately one.

The value of the radio technology coupling parameter $0 \leq \eta \leq 1$ can be determined by detailed simulations for different radio technology pairs. This parameter aims at describing the "extent of coexistence"of different radio technologies. Its value is influenced by a number of characteristics of the used technology (e.g., signal processing technology, synchronisation, advance knowledge, etc.). The smaller of the value of this parameter the better the technology is able to filter other technologies causing interference.

2.2 Spectrum Quality Metrics

Recall, that ε and η are two general parameters I propose to describe the disturbance caused by different providers in case of spatio-temporal DSA. $\varepsilon_{l\leftarrow k}^{(m)}$ is the geographic coupling parameter, which describes the disturbance the m-th provider operating in the k-th region causes in the l-th region; whereas the $\eta_{m\leftarrow n}$ technology coupling parameter characterises the coupling between the technologies used by the m-th and n-th providers.

The next step is to define appropriate spectrum quality metrics in this framework. Some spectrum bands are more crowded compared to others. Hence, the usage of a spectrum band determines the interference characteristics of the transmission channel. Channel capacity, that can be derived from the interference, is the most important factor for spectrum characterisation. So the spectrum quality depends on the strength of the interfering signals (described by the $\varepsilon_{l\leftarrow k}^{(m)}$ parameter) and the capability of the technology to filter out as much interference as possible (described by the $\eta_{m\leftarrow n}$ parameter).

According to the definition of these parameters the cumulative disturbance is the product of the geographical and technology coupling parameters. It means that the disturbance imposed by the m-th provider operating in the k-th region on the n-th provider operating in the l-th region is the interference signal of the disturbing provider ($\varepsilon_{l\leftarrow k}^{(m)}$) decreased by the amount of interference that can be filtered out due to the used technology ($\eta_{m\leftarrow n}$).

By using these general parameters I proposed the following metrics to describe the quality of an allocated spectrum block in the DSA framework. To determine the disturbance imposed on the B spectrum block offered to one provider let us denote the disturbance on the spectrum block by $\Xi_{m,k}(B, \varepsilon, \eta)$ from the point of view of the m-th provider operating in the k-th region.

$$\Xi_{m,k}(B, \varepsilon, \eta) = \frac{1}{|B|} \int_B \xi_{m,k}(\lambda, \varepsilon, \eta)\, d\lambda, \tag{2.5}$$

where

$$\xi_{m,k}(\lambda,\varepsilon,\eta) = \sum_{\forall i,j:(i,j)\neq(m,k)} \varepsilon^{(i)}_{k\leftarrow j} \cdot \eta_{m\leftarrow i} \cdot I_{\{\lambda\in S_{i,j}\}}. \tag{2.6}$$

The $\xi_{m,k}(\lambda,\varepsilon,\eta)$ needed for this calculation in (2.5) is the disturbance imposed on λ frequency from the point of view of the m-th provider in the k-th region; i.e., according to (2.6) we have to sum up the disturbances on band B, as in (2.6) $I_{\{\lambda\in S_{i,j}\}}$ indicates whether the λ frequency is assigned to the i-th provider in the j-th region.

After the integration we get the following formula for the average quality of an allocated spectrum block from the n-th provider's (operating in the k-th region) point of view:

$$\Xi_{m,k}(B,\varepsilon,\eta) = |B|^{-1} \sum_{\forall i,j:(i,j)\neq(m,k)} \varepsilon^{(i)}_{k\leftarrow j} \cdot \eta_{m\leftarrow i} \cdot |B \cap S_{i,j}|; \tag{2.7}$$

2.3 Achievable Gains

In case of the currently used static spectrum allocation the frequency usage rights are granted for large areas (usually the whole area of a country) and long terms (for years). This means that following today's rigid allocation policy a provider has to allocate (using the notations of the framework I proposed)

$$S^f_m = \max_{\tau,\kappa} |S_{m,\kappa}(\tau)| \tag{2.8}$$

amount of spectrum in order to be able to fulfil the demands of one provider all the time in all areas. Furthermore, to serve the demands of all providers

$$S^f = \sum_{m=1}^{M} S^f_m \tag{2.9}$$

amount of spectrum is necessary.

It is worth investigating, what gains we can achieve with the introduction of dynamic spectrum allocation both from the provider's and also from the regulator's point of view.

The provider's gain results from the fact that in case of dynamic spectrum allocation it has to allocate the amount of resource sufficient to fulfil the demands within one region and for one time period. Unlike in case of the rigid scheme when the allocation has to be done according to the highest demand of all regions over the whole time of the license. This allows the provider to fine-tune its spectrum requests according to the real user demands.

The "disengaged" spectrum amount is the basis of the regulator's gain. Due to the more efficient spectrum allocation more providers can be served within the given spectrum band than compared to rigid spectrum allocation techniques. The "surplus" spectrum blocks allow the regulator to utilise for other purposes (e.g inviting other participants to the market thus encouraging new technologies to appear). This nevertheless contributes to market regulations. An appropriate pricing mechanism described later in Chapter 4 ensures that the price paid by the providers corresponds to their real evaluation of the spectrum. This, altogether ensures that the unit value of the spectrum will increase. This can be considered as the regulator's gain.

2.3.1 Achievable Provider Gains

As a first step let us investigate how much gain would a provider (the m-th provider) acquire if only temporal dynamic spectrum allocation was introduced. In this case the provider has to request the highest amount of spectrum ($|S_m(t)|$) demanded in that time period over the whole service area from the spectrum broker. The gain resulting from comparing this spectrum amount with the S^f spectrum need of a rigid allocation is referred to as *temporary provider gain resulted from temporal DSA*. It can be calculated according to the following formula:

$$PG^t_m(t) = 1 - \frac{|S_m(t)|}{S^f_m}. \tag{2.10}$$

If we introduced only spatial dynamic spectrum allocation (i.e., providers could request spectrum for smaller regions but for long term), then the m-th provider operating in the k-th region would have to request the highest demand in the whole time period in the region ($S_{m,k}$) from the spectrum broker. In this case the *gain of the provider resulted from spatial dynamic spectrum allocation* can be determined by:

$$PG^s_{m,k} = 1 - \frac{S_{m,k}}{S^f_m}. \tag{2.11}$$

In case spatio-temporal dynamic spectrum allocation is introduced, the provider has to request only the highest demand in the given region within the given time period ($|S_{m,k}(t)|$) from the spectrum broker. The achievable gain is the highest in this case. The *temporary provider gain resulted from spatial- and temporal DSA* can be calculated by the following equation:

$$PG^{st}_{m,k}(t) = 1 - \frac{|S_{m,k}(t)|}{S^f_m}. \tag{2.12}$$

Gains can be averaged in time, and so the *average provider gain* resulted from temporal dynamic spectrum allocation for a given time period can be determined as:

$$PG_m^{avg} = \int_T PG_m^t(t)dt. \tag{2.13}$$

Extending this equation and integrating the temporary gain from spatio-temporal DSA instead of the temporary gain from temporal DSA the provider gain can be also determined for a given region.

Spatial averaging is also possible, but in this case further parameters are needed that describe the relation of the regions (e.g., area proportions, average spectrum price rate within one region, etc.).

2.3.2 Achievable Regulator Gain

Recall, that from the regulator's point of view gain results from the size of the spectrum that serves all demands in all regions, in other words the size of the "disengaged" spectrum compared to rigid spectrum allocation.

The most important characteristic is the spectrum size which serves all demands in one time period, i.e., the distance between the lowest value of the starting points and the highest value of the end points of the allocation, and its relation to rigid spectrum allocation. This is the *guaranteed temporary regulator gain* whose value can be calculated according to:

$$RG(t) = 1 - \frac{\max\limits_{m,k}(\hat{s}_{m,k}(t)) - \min\limits_{m,k}(\check{s}_{m,k}(t))}{S^f}. \tag{2.14}$$

From the time variance of this metric we can determine how much of the previously used spectrum can be disengaged for other purposes by introducing dynamic spectrum allocation. In the simplest case the minimum of the gain over a longer time period can be considered as the amount of spectrum that can "permanently" be allocated for other purposes, e.g., it can be supplied to new arrivals (new technologies) on the market. A more sophisticated estimation for this unnecessary spectrum amount can be given by using probabilistic methods, statistical calculations and other advanced analytical tools. The detailed investigation of these methods is out of the scope of this work.

The *average regulator gain* expresses the cumulative gain of the regulator over a defined time period. Accordingly, it can be determined by integrating the guaranteed temporary regulator gain over time, as described by the following formula:

$$RG^{avg} = \int_T RG(t)dt. \tag{2.15}$$

2.4 Conclusion

Although there are several spectrum allocation models they have limitations in handling interference issues arising between different providers operating in different regions, or the technologies they model are restricted to a limited set. In this Chapter I introduced a general modelling framework that is able to model the interaction between different service providers operating in different parts of the area of a dynamic spectrum access network.

The main assumptions of the proposed framework are the following:

- equal-right, centralised DSA;
- the available area is divided into smaller regions, inside a region the spatial distribution of the demands is homogeneous;
- time is divided into allocation periods; one allocation period is in the order of hours (batched request processing);
- service providers can have different demands in different regions and demands may vary in time;
- inside the regions, besides given conditions, service providers can use the allocated spectrum for whatever they want (service and technology neutrality requirement).

I also introduced two general coupling parameters (geographical coupling and radio technology coupling) to describe the interference arising in the system in a flexible and general way. Furthermore, based on these parameters I proposed metrics characterising the quality of the spectrum band B available for the m-th provider in the k-th region.

The proposed framework can incorporate other proposals as well, and form a basis of new spectrum allocation models that are able to describe the DSA systems in a more detailed way.

In Section 2.3 I investigated the gains we can achieve with the introduction of dynamic spectrum allocation both from the provider's and also from the regulator's point of view, and I have proposed several metrics to use for the comparison of DSA and rigid allocation systems.

Chapter 3

Spectrum Allocation Models

Having defined the arising interference and after establishing metrics to characterise spectrum quality the next task is to allocate sufficient amount and quality of spectrum to fulfil the providers' needs. Therefore an appropriate spectrum allocation model has to characterise the providers' relation to interference and it also has to determine the conditions that ensure the feasibility of the allocation.

A great advantage of the framework I proposed comes from its flexibility and modularity. Within this framework different allocation models may be used. One can suggest a description with different modelling parameters for the same purpose. The task is simply to replace the relevant assumptions and give a new definition of feasibility but the same spatio-temporal DSA framework can be used. In addition, a method has also to be given to determine the optimal allocation from a certain point of view.

In the following sections I propose two different models for spectrum allocation in DSA networks. Section 3.1 describes the so-called *compensation model*. The main idea of this model is that the service degradation caused by interference is compensated with additional spectrum blocks. This model can be realised in the future when technical advances allowing its realisation are available. The *interference tolerant model* described in Section 3.2 is based on the idea that interference arising between the providers is tolerated until it is below a pre-defined threshold. Recent advances in technology allow this model to be realised in the near future.

For both models I give the feasibility conditions and also propose methods to determine the optimal allocations from the following two points of view:

- The first interesting question is what is the allocation that results the highest guaranteed regulator gain. That is, what is the smallest amount of spectrum that is enough to serve the given demand set and which spectrum block has to be allocated to which provider in order to respect the feasibility conditions.

- The second question to answer is: having a determined amount of spectrum (S_{CAB}) is the given demand set feasible, i.e., is there an allocation that respects the feasibility conditions? Furthermore, which of the feasible allocations (which spectrum block has to be allocated to which provider) has minimal interference?

3.1 Compensation Model

As introduced in the previous section the compensation model aims at compensating the degradation of service due to arising interference. The basic idea of this model is that providers do not request spectrum directly, but a transmission channel with specified capacity. It is the task of the spectrum-estimators to determine the sufficient spectrum block size to the requested transmission capacities. This is a complex problem as it depends on the environment (interference imposed on the block). Here the interference arising in the noisy environment is compensated with additional spectrum blocks. Since capacity depends not only on bandwidth but the transmission power, as well the providers are required to submit their transmission powers together with their capacity.

The model uses the set of spectrum demands, the available bandwidth and a so-called "compensation parameter" to determine the degradation in service capacity; and so the amount of spectrum to compensate.

Section 3.1.1 describes the feasibility conditions of a given spectrum allocation in the compensation model. The method proposed in Section 3.1.2 determines the smallest spectrum size sufficient to serve all demands (that is the maximal guaranteed regulator gain); furthermore, it determines the starting and end points of the corresponding spectrum allocation. Section 3.1.3 proposes a method to check the feasibility of the allocation for the given demands in case of a fixed amount of available spectrum and determines the minimal interference allocation. The allocation mechanism using this model is illustrated through an example in Section 3.1.4.

3.1.1 Feasibility Conditions

In this model feasibility is interpreted as follows.

Let us denote by $b_{m,k}$ the bandwidth needed for the requested digital transmission channel with given technology in case there is no interference. Within one region disjoint spectrum blocks have to be distributed among the providers due to the high interference arising inside the region. Since interference arises also from the neighbouring regions additional spectrum blocks need to be allocated for the providers in order to compensate the interference and ensure the digital transmission channel capacity. The level of compensation depends on the accumulated interference; we call an allocation feasible, if the spectrum blocks of the providers enlarged by the interference compensation can be distributed within the available spectrum band. The complexity of this problem lies in the fact that the additional spectrum block provided as compensation is also affected by interference, therefore the additional capacity is smaller than in case of a "clear" spectrum block.

In other words, in the compensation model an $\mathbf{S} = (\mathbf{S}_1, \ldots, \mathbf{S}_M)$ allocation (where $\mathbf{S}_m = (S_{m,1}, \ldots, S_{m,K})$) is feasible if the spectrum blocks used by the providers ($\{S_{m,k}\}$) fulfil the following two conditions:

$$S_{m,k} \cap S_{n,k} = \emptyset, \quad \forall m, n, k, \tag{3.1}$$

$$|S_{m,k}|(1 - \delta \Xi_{m,k}(S_{m,k}, \varepsilon, \eta)) \geq b_{m,k}, \quad \forall m, k\,, \tag{3.2}$$

where $\Xi_{m,k}(S_{m,k}, \varepsilon, \eta)$ characterises the allocated spectrum block from the interference's point of view, and can be calculated according to (2.7).

The first condition, (3.1) ensures that two providers within one region never get the same spectrum slice. The (3.2) condition means that a provider needs as much more allocated spectrum block as compensates the decrease in capacity due to interference. Parameter δ in this condition is the afore-mentioned "compensation constant" that gives the amount of spectrum block needed to compensate a unit measure of disturbance.

In the special case when $\delta \Xi_{m,k}(S_{m,k}, \varepsilon, \eta) \geq 1$, i.e. the providers totally disturb each other, the problem corresponds to the one described by Buddhikot *et al.* in [42]. They proved that this case relates to the well-known NP-hard graph colouring problem.

3.1.2 Allocation with Maximal Regulator Gain

The next step is to find the allocation that maximises the regulator gain. Certainly, the starting and end points of the spectrum blocks (i.e., "which spectrum block should be allocated to which provider") has to be found, too.

Let us model this problem with an undirected graph. Within this graph let a vertex represent one provider operating in one region, and let us represent the decrease in spectrum quality (which is the interference between the two vertices) by the cost of the edges connecting two vertices, $c_{(\{m,k\},\{n,l\})}$. It is important to note here, that –considering that one provider can have different demands in different regions– one vertex of the graph represents one provider-region pair. Accordingly, $c_{(\{m,k\},\{n,l\})}$ means the interference (that is spectrum quality degradation) between provider m in region k and provider n in region l.

The task is to find for each vertex within this graph the corresponding $S_i = (\check{s}_i, \hat{s}_i)$ optimal spectrum block. Let us define for each edge a variable $z(i,j)$ that represents overlapping.

Now let us determine a set of conditions that have to be satisfied by an allocation in order for that allocation to ensure the smallest spectrum size that is sufficient to fulfil all demands.

Now let

$$c_{(\{m,k\},\{n,l\})} = \begin{cases} 1, & \text{if } k = l \\ \delta \eta_{m,n} \varepsilon_{k,l}, & \text{otherwise} \end{cases} \tag{3.3}$$

Equation (3.3) describes the decrease of spectrum quality that has to be compensated. If two providers operate in the same region within the same frequency band (i.e., $k = l$), then to compensate one spectrum unit loss due to interference one additional unit of spectrum is needed (which is not a beneficial situation). In the case when the two providers are in different regions the service degradation can be described by the ε geographical and η technology coupling constants. The δ parameter is the "compensation constant" introduced in the previous section. This parameter describes the amount of spectrum block needed to compensate a unit measure of disturbance.

Furthermore, let

$$z_{(i,j)} = |S_i \cap S_j| = \max\{0, \min\{\hat{s}_i, \hat{s}_j\} - \max\{\check{s}_i, \check{s}_j\}\}. \tag{3.4}$$

The $z_{i,j}$ overlapping in (3.4) shows the size of the intersection of spectrum blocks S_i and S_j.

Now let us introduce two working variables $\check{y}_{(i,j)}$ and $\hat{y}_{(i,j)}$ as:

$$\check{y}_{(i,j)} = I_{\{\check{s}_i \le \check{s}_j\}} \text{ and } \hat{y}_{(i,j)} = I_{\{\hat{s}_i \le \hat{s}_j\}}. \tag{3.5}$$

Furthermore, let b_i denote the given demand set, let s_0 be the unit measure of spectrum and let us seek for the smallest amount of sufficient spectrum in the form of s'.

Now we can set up an *Integer Linear Program* to find the allocation with the smallest amount of spectrum.

Accordingly,

$$\check{s} \le \check{s}_i \le \hat{s}_i \le \hat{s} \quad \forall i \in V \tag{3.6}$$

$$\hat{s}_i - \check{s}_i - \sum_{\forall (i,j) \in E} z_{(i,j)} \cdot c_{(i,j)} \ge b_i s_0 \quad \forall i \in V \tag{3.7}$$

$$\begin{aligned}
z_{(i,j)} &\geq \hat{s}_j - \check{s}_j - S \cdot (\hat{y}_{(i,j)} + (1 - \check{y}_{(i,j)})) \\
z_{(i,j)} &\geq \hat{s}_i - \check{s}_j - S \cdot [(1 - \hat{y}_{(i,j)}) + (1 - \check{y}_{(i,j)})] \\
z_{(i,j)} &\geq \hat{s}_j - \check{s}_i - S \cdot [\hat{y}_{(i,j)} + \check{y}_{(i,j)}] \\
z_{(i,j)} &\geq \hat{s}_i - \check{s}_i - S \cdot [(1 - \hat{y}_{(i,j)}) + \check{y}_{(i,j)}] \qquad (3.8)
\end{aligned}$$

$$\hat{s}_i \leq s' \quad \forall i \in V \qquad (3.9)$$

According to (3.7) the allocated spectrum size must be enough to serve all the demanded amount and, in addition, it also has to compensate the loss of spectrum quality caused by interference with additional allocated spectrum block. (Regarding the indices used before, NSP_m in region R_k is equivalent to player i where $i = (m-1)K + k$; or, by mapping indices to the other direction, $k = i \mod K$ and $m = \lceil i/K \rceil$.) Equation (3.8) holds the conditions for spectrum block overlapping.

Here, the target is to minimise s'. The solution of this Integer Linear Program determines the smallest spectrum size sufficient to serve the given demands (and therefore it maximises the regulator gain). The $S_i = (\check{s}_i, \hat{s}_i)$ variables contain the starting and end points of the spectrum blocks allocated to each provider.

3.1.3 Allocation with Minimal Overall Interference

Consider the accumulated interference in the model and target to find the allocation where the overall interference is minimal. So the goal is to find the starting and end points of the spectrum blocks that satisfy the feasibility conditions of (3.1) and (3.2), and minimise the overall interference.

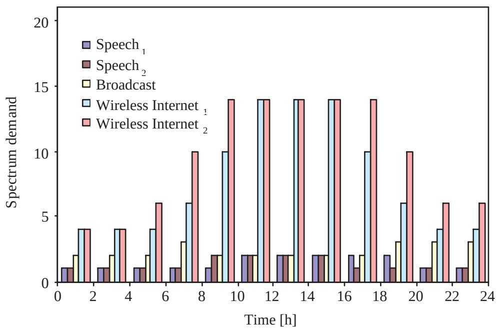
For finding the solution the undirected graph representation described in the previous section can also be used here. Recall, that vertices of the graph represent providers operating in specific regions and the degradation in spectrum quality is captured by the cost of the edges between two vertices. The initial descriptions and the definitions of the service degradation, (see 3.3) and overlapping, (see 3.4) also apply here.

Let us use the notations of Section 3.1.2 furthermore, introduce the f' variable for the cumulative interference. By equations (3.7) and (3.8) from Section 3.1.2 and the following two additional conditions we can set up an Integer Linear Program here, too:

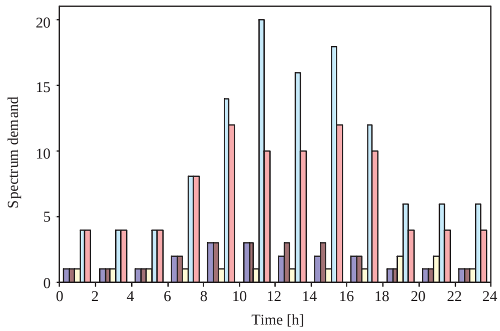
$$0 \leq \check{s}_i \leq \hat{s}_i \leq S_{CAB} \quad \forall i \in V \qquad (3.10)$$

$$\sum_{\forall (i,j) \in E} z_{(i,j)} \cdot c_{(i,j)} \leq f' \quad \forall (i,j) \qquad (3.11)$$

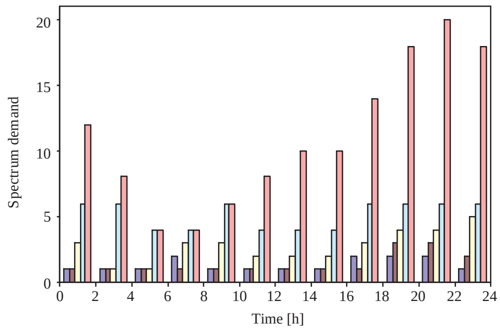
The target is to minimise f'.



(a) Region A



(b) Region B



(c) Region C

Figure 3.1: Capacity demands of providers in the different regions.

Equation (3.10) defines the limits of the bandwidth available for DSA, equation (3.11) calculates the cumulative interference. The solution of the above Integer Linear Program for minimising f' determines the feasibility of the allocation over the available spectrum and it also gives the allocation with minimal interference. If the problem is solvable it is possible to fulfil all demands within the available spectrum band (S_{CAB}); variables $S_i = (\check{s}_i, \hat{s}_i)$ contain the allocation with minimal interference.

3.1.4 Illustrative Example

Consider a hypothetical, simple scenario of three different regions (downtown, business quarter, residential area) with different spectrum demands (see Fig. 3.1) as an example. In each region five NSPs operate in the CAB. There are two mobile speech service providers, one digital broadcast provider and two wireless Internet service providers. NSPs demand spectrum in discrete units (5 MHz carriers). The spectrum is reallocated in every 2 hours.

Examine the minimal spectrum requirement to fulfil the demands in all regions for three

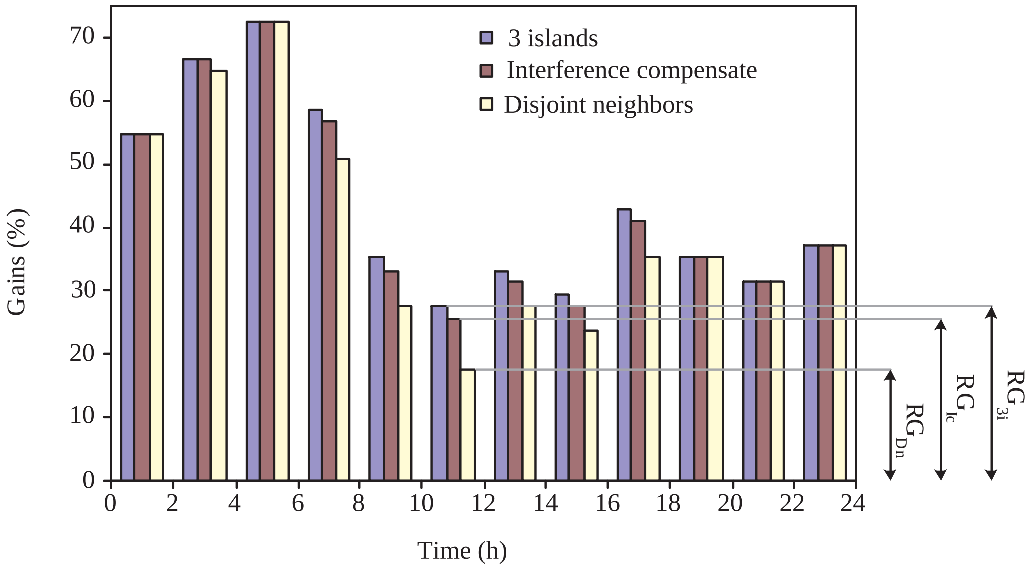


Figure 3.2: Regulator gains.

different situations. In the first case the regions are completely isolated, no interference can occur. This can be modelled by setting all of the geometrical coupling parameters to zero, i.e., $\varepsilon_{k,l} = 0$ for all $k \neq l$. This "ideal" case requires the least bandwidth, thus it can be seen as a lower bound for the more realistic cases. This scenario is referred to as '3-islands' setup.

In the second case the regions are neighbouring, the same frequencies used in more than one region would interfere, but no interference is allowed at all. This is achieved by setting both the geographic and radio technology coupling parameters to one, i.e., $\eta_{m,n} = \varepsilon_{k,l} \equiv 1$ for all NSPs and regions. This strict burden requires disjoint spectrum allocations for providers even if they operate in different regions. This assumption yields similar results as the OverDRiVE proposal in [3]. Later on, this proposal is referred to as 'disjoint neighbours' solution.

The third case refers to the interference compensation spectrum allocation method, where all geographic coupling parameters were set to 20% between all region pairs, while the radio technology coupling parameter was 0.5 for each NSP pair. The feasible and optimal spectrum allocation was calculated using the ILP description in Section 3.1.2. As for comparison, I note that in case of fixed spectrum allocation 51 carriers are necessary to fulfil the requests of all providers.

Fig. 3.2 shows the achievable regulator gain for the three situations as a function of time. When the traffic intensity is low (e.g., from 2 a.m. to 4 a.m.) or the demands

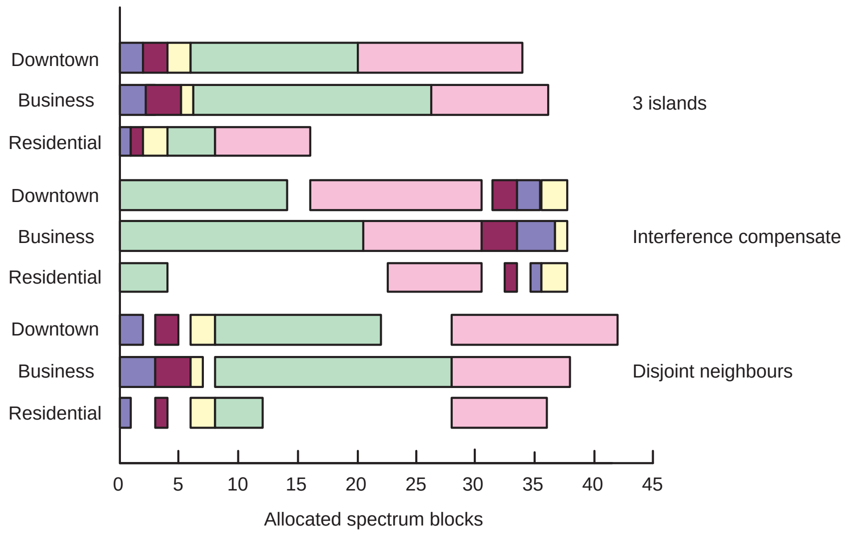


Figure 3.3: Allocated spectrum blocks during "busy-hours" (10 a.m. to 12 a.m.) for all three allocation rules.

are concentrating on one region (e.g., from 8 p.m. to 10 p.m. in the residential area) the three situations provide the same result. However, in the busy hours the interference compensation DSA model provides better results than the disjoint neighbours solution. The guaranteed regulator gain using my model is 25%, in contrast to the disjoint neighbours solution's 18% gain, and is close to the maximal achievable gain of 27% of the 3-islands model.

Fig. 3.3 details the individual allocations for all five NSPs during the busy-hours (10 a.m. to 12 a.m.) in all three regions, and for all three allocation strategies. The plot gives an explanation for the different gains achieved.

In the 3-islands case there is no need to pull apart spectrum blocks allocated for different providers in neighbouring regions, since no interference occurs between regions. Thus, blocks are allocated as tight as possible.

Although in the interference compensation DSA model overlapping between spectrum blocks in neighbouring regions is allowed, it is avoided as much as possible to reduce spectrum degradation. As a result, there are no gaps between spectrum blocks in the most heavily loaded region. I note, that the spectrum blocks allocated in the interference compensation model are slightly greater than the provider's original request, the possibility of having interference still allows the allocation to be tighter than in case of the disjoint neighbours solution.

When overlapping between neighbouring regions is strictly prohibited (see disjoint neighbours allocation), even in the most heavily loaded region there is a need to have gaps between allocated blocks to avoid interference. Thus, the total allocated spectrum size is the biggest in this case.

The results show that, although compensating interference means allocating slightly larger spectrum blocks than requested, allowing interference is rewarded by the higher gain of the regulator, especially during the busy hours.

3.2 Interference Tolerant Model

This model uses a different approach; it is assumed, that interference arising between the providers is tolerated until it is below a pre-defined threshold. The idea behind the allocation model is that different technologies can tolerate disturbance to different extent. The real question is how the service of the service provider degrades due to interference. It can happen that robust techniques with error-prone encoding, or wideband solutions are more tolerant to noisy spectrum than others. Therefore I proposed to introduce two parameters (α and β) to describe the interference tolerance level of the provider. Parameter β_m describes the maximal average interference that the provider is able to tolerate, the α_m parameter represents the maximal interference that must not be exceeded by the allocation in any frequency.

Section 3.2.1 determines the feasibility conditions of an allocation within the interference tolerant model. Methodology proposed in Section 3.2.3 determines the smallest spectrum amount sufficient to fulfil all demands (i.e., the guaranteed regulator gain is maximal), furthermore, gives the starting and end points of the spectrum blocks belonging to this allocation. Procedure proposed in Section 3.2.4 checks the feasibility of an allocation with a limited amount of available spectrum, and also gives the smallest interference allocation. Finally, Section 3.2.5 gives an illustrative example for an allocation within the interference tolerant model.

3.2.1 Feasibility Conditions

In this model the requirement of feasibility can be interpreted as follows.

Each provider must guarantee that its transmission powers are set so that the measurable power spectral density at the region boundaries are below a given threshold, i.e., for provider m operating in region R_k its power spectral density outside its region cannot be higher than $s_{m,k}^{max}$. This limit for the maximum spectral density can be easily checked by measurements carried out at the region borders by the regulator, and its value adjusted for each region and provider.

Introducing this new assumption, that the providers are restricted not to exceed a maximal spectral power density ($s_{i,j}^{max}$) at the region borders, the $\varepsilon_{k\leftarrow j}^{(i)}$ parameter of the framework can be split into the product of the limit of the spectral power density of the provider ($s_{i,j}^{max}$) and the signal attenuation between the two regions ($\varepsilon_{k\leftarrow j}$).

$$\varepsilon_{k\leftarrow j}^{(i)} = s_{i,j}^{max} \cdot \varepsilon_{k\leftarrow j} \tag{3.12}$$

Within the model we call an $\mathbf{S} = (\mathbf{S}_1, \ldots, \mathbf{S}_M)$ allocation (where $\mathbf{S}_m = (S_{m,1}, \ldots, S_{m,K})$) feasible if the spectrum blocks used by the providers ($\{S_{m,k}\}$) satisfy the following conditions:

$$\Xi_{m,k}(S_{m,k}, \varepsilon, \eta) \leq \beta_m, \quad \forall m, k, \tag{3.13}$$

$$\max_{\lambda \in S_{m,k}} \xi_{m,k}(\lambda, \varepsilon, \eta) \leq \alpha_m, \quad \forall m, k. \tag{3.14}$$

By substituting the $\varepsilon_{k\leftarrow j}^{(i)} = s_{i,j}^{max} \cdot \varepsilon_{k\leftarrow j}$ expression into (2.6) and (2.7) we get:

$$\Xi_{m,k}(S_{m,k}, \varepsilon, \eta) = |B|^{-1} \sum_{\forall i,j:(i,j)\neq(m,k)} \varepsilon_{k\leftarrow j} \cdot \eta_{m\leftarrow i} \cdot s_{i,j}^{max} \cdot |B \cap S_{i,j}| \tag{3.15}$$

for the average quality of the B spectrum block from the point of view of provider m operating in region k, and

$$\xi_{m,k}(\lambda, \varepsilon, \eta) = \sum_{\forall i,j:(i,j)\neq(m,k)} \varepsilon_{k\leftarrow j} \cdot \eta_{m\leftarrow i} \cdot s_{i,j}^{max} \cdot I_{\{\lambda \in S_{i,j}\}}. \tag{3.16}$$

for the quality of frequency λ which is in fact the interfering power density at the λ frequency.

Recall, that parameters α and β can be seen as tolerance levels, i.e., to what extent the interference is tolerated by the provided service. So (3.13) guarantees that the average interference remains below β_m, and (3.14) limits the maximal interference in any frequency to the value of α_m. [1]

3.2.2 Flexible Parameter Settings

To allow a great flexibility, our model has the geographical coupling (ε) and the radio technology coupling parameters (η) to capture and handle interference issues between different regions and providers, and interference tolerance parameters α and β to describe the sensitivity of providers to spectrum degradation. The parameter values can be different for each provider as well as for each region or between region pairs. However, to adjust all parameters properly is not an easy task.

[1] Setting the α tolerance parameter to zero this problem can also be related back to the one described in [42] which was proven to be NP-hard.

Couplings

Consider an area for the DSA task that consists of four regions as an example (see Figure 3.4). Assume that there are different network service providers (NSPs) and most of them provide some sort of service in more than one regions. They have different spectrum demands in different regions, and they have to compete for the spectrum resource. They claim for spectrum dynamically, and the Spectrum Broker is responsible to handle these requests and allocate appropriate spectrum blocks the NSPs are contented with.

First, let us concentrate on region A only. By definition, the geographical coupling parameter measures the attenuation of the signal going away from the border of the region where the transmitter operates. It is assured that the power level at the border (or just outside) the given region cannot exceed s^{max}, but the actual power spectral density can be much higher inside the region. To make our formula (3.16) more general by taking into account other NSPs within the *same* region, we allow $\varepsilon_{A \leftarrow A}$ to be higher than one (typically $\varepsilon^{max} >> 1$). This would cause heavy interference for most of the radio technologies used today, making the service provided by the NSP unavailable. But this is not always the case. There are many technologies used today in the ISM (Industrial-Scientific-Medical) unlicensed radio band that are designed to live together with competing technologies using the same spectrum block. The case is similar if we consider the Ultra Wide Band solutions that are getting more popular today and in the near future. This does not mean of course, that they do not hear each other. They are disturbed somewhat when the spectrum must be shared, the background noise is increasing. This disturbance is quantified by the radio technology coupling parameter η. The parameter $\eta_{m \leftarrow n}$ describes how much the service of NSP_m is affected by NSP_n using the *same* frequencies within the *same* region. A value close to zero means that the disturbance is negligible, while $\eta_{m \leftarrow n}$ close to one means that the service provided by NSP_m cannot be harmonised and would be ruined if they were interfering. Note also, that the radio technology coupling is not necessarily symmetric, i.e., $\eta_{m \leftarrow n} \neq \eta_{n \leftarrow m}$ in general.

Regions A and B are neighboring (see Figure 3.4), so there can be interference at least at the border regions. Hence $0 < \varepsilon_{A \leftarrow B} < 1$. It is also true that the geographical coupling values do not need to be symmetric, i.e., $\varepsilon_{A \leftarrow B} \neq \varepsilon_{B \leftarrow A}$ in general. The level of interference between non-neighboring regions can be set directly, as well, which is needed to model providers covering more than one region on the same frequency band.

However, the level of interference depends not only on the size of the border zone and the areas of the regions, but on the transmission power and the positions and types of radio transmitters as well. As an example, consider a broadcast service (e.g., a DVB-T provider) whose radio tower is located within area A but its service area covers the entire region B, too, as plotted on Figure 3.4. In that case the high s^{max} value ensures that the provider

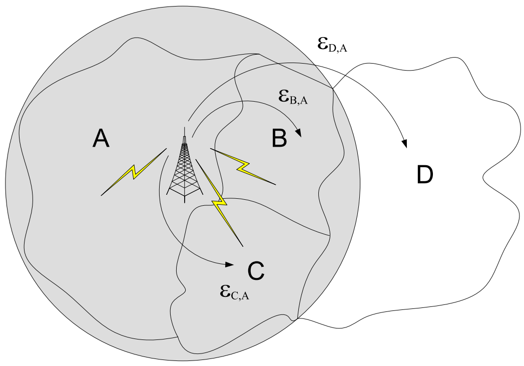


Figure 3.4: Geometrical coupling between regions.

can use the same spectrum over more regions and the coupling between non-neighbouring regions ensures the appropriate model for the interference caused by the broadcast provider in region D. So in our model the disturbance from further regions can also be taken into account (unlike in [30]) and allocating spectrum for more than one regions does not need inter-related auctions unlike in [39].

Tolerance parameters

In the model parameters α and β answer the question that how the service of the NSP degrades if the allocated spectrum block for the service is “noisy”, i.e., to what extent the interference is tolerated by the provided service. By setting the tolerance level low one can ensure “clear” spectrum block for the provided service. In the other hand high tolerance level makes the possibility to operate in a noisy spectrum.

Knowing the real tolerance levels of an NSP would be a great help in the DSA framework. However, from the operators’ point of view, it would be much easier to say that interference is not welcome at all, “clear” spectrum block is needed to provide the service ensuring maximal user satisfaction. If all providers were intolerant to interference, then strictly disjoint spectrum blocks were needed even in neighboring (or coupled) regions everywhere. This would greatly reduce the effectiveness of DSA, and the result would look like nearly the same as the rigid spectrum allocation methodology of today. This would cause the spectrum to be more scarce, and thus more expensive in the end. In a DSA scenario where tolerance is much rewarded by increasing spectral efficiency, certain mechanisms need to be implemented to make it desirable for the NSPs to use all available techniques to tolerate co-existence as much as possible. A proper pricing scheme (see Chapter 4) that charges providers who do not tolerate others and interfere to larger extent than necessary with other regions would be of great importance.

3.2.3 Allocation with Maximal Regulator Gain

The goal is to determine the allocation for the interference tolerant model that maximises the regulator gain. It is equivalent to determine the allocation which allows to serve the given allocation vector (**a**) using the minimum amount of spectrum.

In case of complex optimisation tasks a frequently used method is the definition of a state vector (state space) describing the system and a so-called target function within this domain, that reaches its minimum value at the optimum point. I defined the state vector for the above described problem as:

$$\mathbf{s} = (\check{s}_{1,1}, \ldots, \check{s}_{1,K}, \ldots, \check{s}_{M,1}, \ldots, \check{s}_{M,K}), \tag{3.17}$$

and

$$|S| = \max(\hat{s}_{m,k}) - \min(\check{s}_{m,k}). \tag{3.18}$$

Furthermore, let us define the allocation vector **a** the following way:

$$\mathbf{a}((m-1)K + k) = \hat{s}_{m,k} - \check{s}_{m,k} \tag{3.19}$$

Thus, the S spectrum allocation can be represented by the state vector **s** and the allocation vector **a**.

The target function that has to be minimised for the optimal allocation is defined as:

$$E(\mathbf{s}, \mathbf{a}) = -\frac{S_{CAB} - |S|}{S_{CAB}} + P_f \tag{3.20}$$

where

$$P_f = \sum_{m=1}^{M} \sum_{k=1}^{K} \left(I_{\{\Xi(S_{m,k}) < \beta_m\}} + I_{\{\min\limits_{\lambda \in S_{m,k}} \xi_{S_{m,k}}(\lambda) < \alpha_m\}} \right). \tag{3.21}$$

The first part of the target function defined in (3.20) measures the non-utilised fraction of the available spectrum (S_{CAB}), whilst the value of the P_f penalty function is zero only if the (3.13) and (3.14) feasibility conditions hold true for all spectrum blocks, otherwise the value of the penalty function is at least one.

The minimum of the defined target function determines the allocation for the interference tolerant model which allows to serve the given allocation vector (**a**) using the minimum amount of spectrum (maximal guaranteed regulator gain). Equation (3.18) determines the size of this spectrum band.

Corollary 1. *Consequently, the E target function has the following characteristics:*

- *if the value of the function is positive, then the feasibility conditions are not satisfied,*
- *if the minimum of the function is positive, then the given demand set is not feasible to serve within the given S_{CAB} available spectrum band,*

- *if the value of the energy function is negative, the arrangement is one possible solution for the allocation,*
- *smaller values of the energy function mean allocations closer to the optimal allocation.*

Optimisation can be done by means of simulated annealing where the energy of the system is defined by functions (3.20) and (3.21). Section 3.2.6 presents an overview on the simulated annealing method and details the parameter settings used for simulations as well as the complexity of the algorithm.

3.2.4 Allocation with Minimal Overall Interference

The goal is to determine, having a determined amount of spectrum (S_{CAB}), whether the given demand set is feasible or not; furthermore, if it is feasible, determine the allocation with minimal interference.

For characterising an allocation we can use the same state vector and allocation vector as defined in the previous section (see (3.17) and (3.19)). The size of the available spectrum for dynamic spectrum allocation is denoted by S_{CAB}.

I constructed the target function (3.22) so that the minimum of the function determines the allocation for the interference tolerant model with the minimal arising interference. Furthermore, the negative value of the function indicates that the allocation is feasible.

$$E(\mathbf{s}, \mathbf{a}) = -\frac{\Xi_{max} - \Xi(S_{CAB})}{\Xi_{max}} + P_f, \tag{3.22}$$

where

$$\Xi(S_{CAB}) = \sum_{\forall m,k} \Xi_{m,k}(S_{m,k}), \tag{3.23}$$

furthermore,

$$\Xi_{max} = \sum_{\forall m,k} |S_{m,k}|^{-1} \cdot \sum_{\forall i,j:(i,j)\neq(m,k)} \varepsilon_{k\leftarrow j} \cdot \eta_{m\leftarrow i} \cdot s_{i,j}^{max} \cdot |S_{CAB}| \tag{3.24}$$

The target function defined in (3.22) also consists of two parts. The first term measures how much less the interference is than the theoretical maximum, since Ξ_{max} is the theoretical maximum value of interference in the system, when all providers submit maximum demands (refer to (3.24)). The second term of the target function is the same penalty function as defined in (3.21), i.e., the value of the P_f penalty function is zero only if the (3.13) and (3.14) feasibility conditions hold true for all spectrum blocks, otherwise the value of the penalty function is at least one.

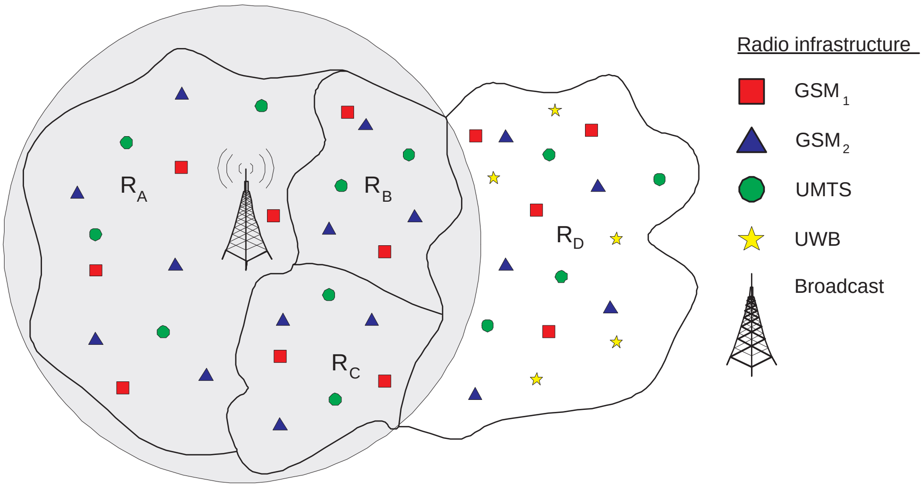


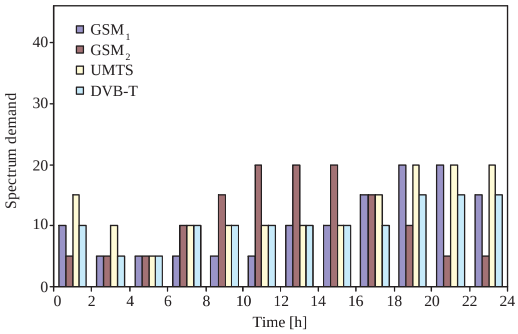
Figure 3.5: Example scenario for the interference tolerant model

Corollary 2. *Consequently, the E target function defined by (3.22) has the same characteristics as described in Section 3.2.3.*

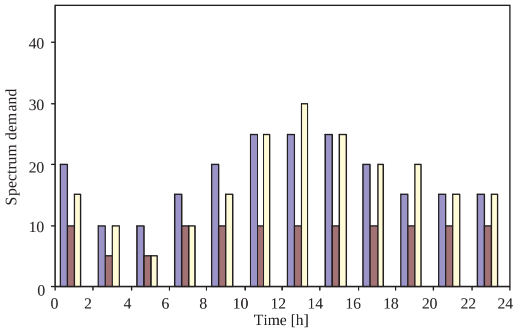
3.2.5 Illustrative Example

Consider a simple scenario with four regions as shown on Figure 3.5. One UMTS and two GSM providers operate in all regions within the Coordinated Access Band. In addition, in region A there is a broadcast provider (e.g., DVB-T) that covers region B and C, too. Furthermore, in region D a "UWB-like" provider is also present, that does not cause significant interference to other providers, and tolerates interference. (In the followings this provider is referred to as UWB.) I note, that this is a hypothetical scenario since these techniques are not prepared for operating in different frequencies in different time periods, but this example shows that even with the parameters of these technologies considerable gains can be achieved.

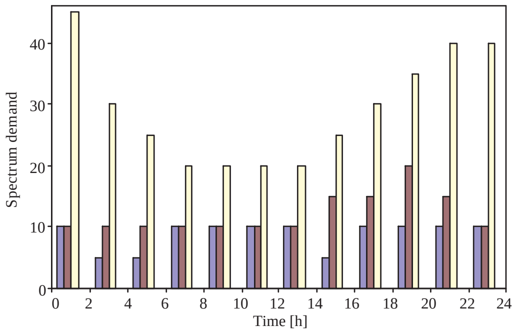
The size of the Coordinated Access Band is set to 110 MHz, since in case of fixed allocation, ignoring the UWB like provider, this is the necessary amount of spectrum to serve all demands arising during the simulated period. In this scenario providers demand spectrum in 5MHz blocks, but the starting point of the blocks can be placed by 1MHz increments. The spectrum was reallocated in every 2 hours. Figure 3.6 shows an example of the spectrum demands in different regions that were used as inputs. We can see that the same provider may have very different demands in different regions (e.g., in different parts of the city). This figure also shows that the demands greatly vary with time.



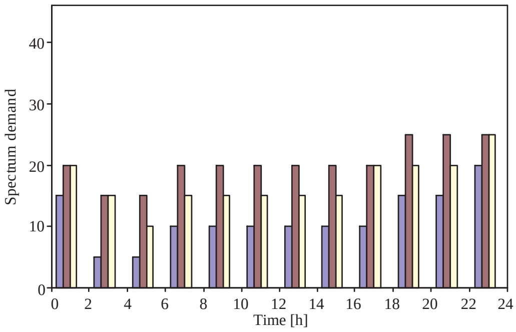
(a) Region A



(b) Region B



(c) Region C



(d) Region D

Figure 3.6: Different requests in the different regions.

I examined the minimal spectrum requirement to fulfil the demands, i.e., the achievable regulator gain in all regions for three different situations. In the first case the regions are completely isolated, no interference can occur. This can be modelled by setting all geometrical coupling parameters to zero. This “ideal” case is similar as proposed in [39] and requires the least bandwidth, thus it can be seen as a lower bound for the more realistic cases. This scenario is referred to as “4-islands” setup.

In the second case interference would be possible in neighbouring regions, but is not allowed at all. This means that in regions that are geographically coupled different providers cannot use the same frequencies. This is achieved by setting the geographic coupling parameters of the neighbouring regions to a high value. This strict burden for interference requires disjoint spectrum allocations for providers if they operate in neighbouring regions. This assumption yields similar results as the OverDRiVE case in [3]. I refer to this case as ‘disjoint neighbours’.

The third case refers to a more general case where the DSA model is characterised by matrices η (Table 3.1) and ε (Table 3.2) and vectors s_{max}, α and β (Table 3.3). (For the

$\eta^{[dB]}$	GSM-1	GSM-2	UMTS	UWB	BC
GSM-1	−20	−5	−20	−30	−3
GSM-2	−5	−20	−20	−30	−3
UMTS	−20	−20	−23	−30	−3
UWB	−200	−200	−200	−200	−200
BC	−10	−10	−23	−30	−1

Table 3.1: Radio technology coupling parameters $\eta_{m,n}$.

$\varepsilon^{[dB]}$	A	B	C	D
A	28.1	−0.05	−0.05	−165.4
B	−0.05	28.1	−0.05	−0.05
C	−0.05	−0.05	28.1	−0.05
D	−165.4	−0.05	−0.05	28.1

Table 3.2: Geographic coupling parameters ε.

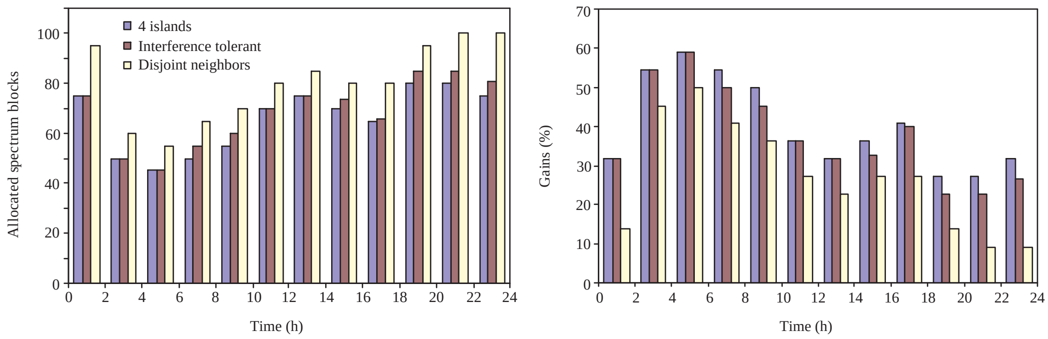
calculation of the values of these parameters please refer to Appendix A.) In words, matrix η shows the radio technology coupling parameters between the NSPs. The smaller this value, the better it is from the interference's point of view. By looking at the elements of matrix η in Table 3.1 we can see that the radio technology used by the UWB provider does not affect, and is not affected significantly by other providers ($\eta << 1$). I also note, that the technological coupling of a provider to itself is less than to a different provider even if they use the same technology; due to the fact, that the provider has information about the spectrum blocks assigned to it in different regions and therefore can arrange the allocation at the region borders to minimise the interference (This applies to providers that have several cells in one region).

Table 3.2 shows the geographical coupling parameters between the regions. Recall, that $\varepsilon_{k \leftarrow l}$ denotes a kind of general attenuation parameter for the radio signals of providers operating in region R_l that can be "heard"as interference in region R_k. The smaller this value the better it is from the interference's point of view. We assumed that the power spectral density at the border of a given region cannot exceed s^{max}, but inside the region this value can be much higher—this is modelled by $\varepsilon >> 1$. For neighbouring regions the value of ε is nearly one, for the reason and the exact calculation please refer to Appendix A.

Table 3.3 shows the average (β) and maximum (α) interference tolerance parameters of the providers. The larger this value, the more tolerant the provider is with respect to interference. From Table 3.3 we can see, that the interference tolerance of GSM-1 and GSM-2 are similar and less than that of UMTS, meaning that they tolerate interference

	GSM-1	GSM-2	UMTS	UWB	BC
s_{max}	-95.1	-95.1	-96.86	-196.31	-111.76
α	-103.1	-103.1	-83.86	-94.31	-123.76
β	-105.1	-105.1	-85.86	-96.31	-125.76

Table 3.3: Maximal signal density at the borders (s_{max}), average (β_m) and maximum (α_m) interference tolerance parameters in [dBm/kHz].



(a) Spectrum allocations

(b) Regulator gains

Figure 3.7: Aggregated spectrum allocations and regulator gains.

less. The "Broadcast" provider has much lower tolerance level, which practically means that it requires an exclusive use of the allocated spectrum block.

The feasible and optimal (or near optimal) spectrum allocation was calculated based on the Simulated Annealing process described in Section 3.2.6 by using the objective function proposed in Section 3.2.3. Figure 3.7 shows the overall spectrum requirements and the achievable regulator gain for the three situations as a function of time. (As for comparison, I note that in case of fixed spectrum allocation 110 Mhz are necessary to fulfil the requests of all providers.) We can see, that the interference tolerant scenario provides higher gains than the disjoint neighbours scenario and approaches the ideal case, until it is prevented by the interference arising in the middle region.

The "disjoint neighbours" case yields slightly smaller spectrum requirements than the fixed spectrum allocation. Especially in the busy hours the gain is only about 10 percent. This is because spectrum interference is not allowed at all between neighbouring regions, but the same spectrum can be used for different purposes in regions A and D since they are non-neighbouring. Overlapping spectrum blocks can be allocated in the "interference-tolerant" scheme, but the interference is limited, so the overlapping regions must be limited, too. However, significant gain can be achieved by tolerating certain level of interference between different providers in neighbouring regions. Finally, the "4-islands" setup gives the absolute

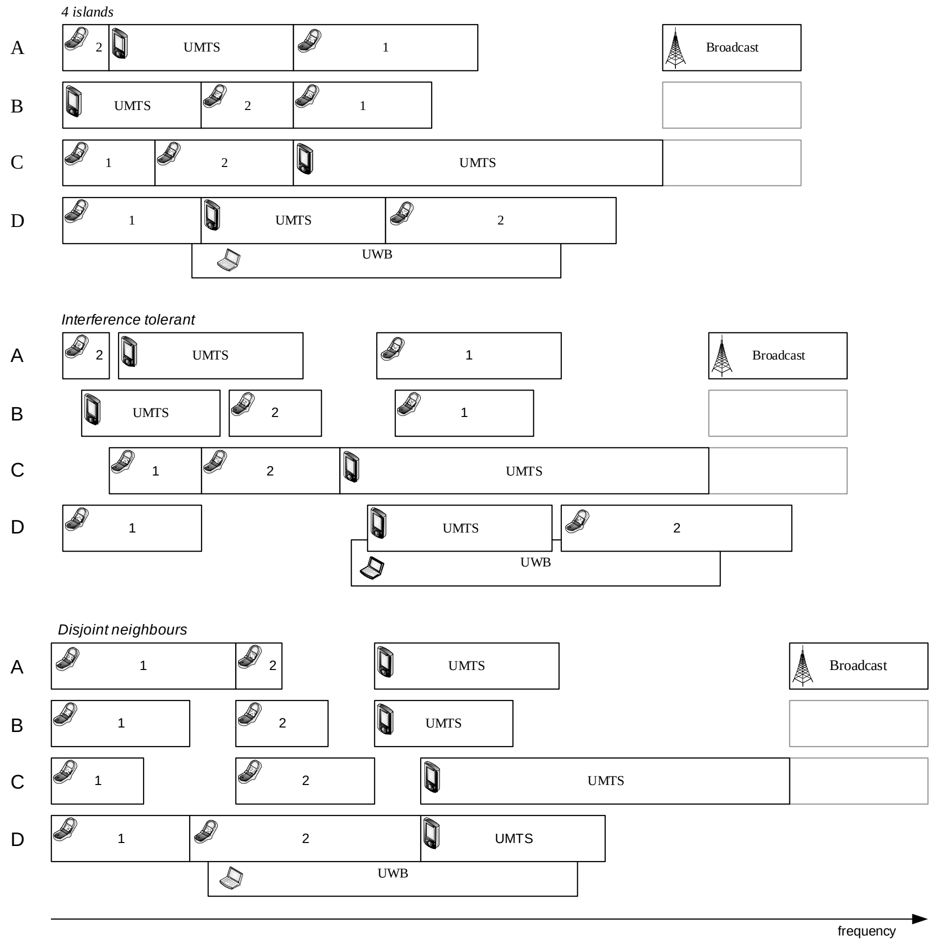


Figure 3.8: Allocated spectrum blocks during 20h-22h for all scenarios.

minimum aggregated spectrum demand, where interference is not a problem, so spectrum reuse can be employed wherever needed.

Quantitatively, if we calculate the average gain for all times (see (2.14) and (2.15)), we get 40% for the '4-islands model', 38% for the 'interference-tolerant' solution and 27% for the 'disjoint neighbours' case.

To see where this difference comes from, Figure 3.8 shows the detailed spectrum allocations for all four regions, between 8 p.m and 1' p.m., and for all three investigated scenarios. Different effects of the proposed allocation model can be explained on the figure. As mentioned before, the DVB-T operator operating in region A provides a broadcast service that covers regions B and C as well. The high value of the radio technology coupling and the low interference tolerance parameters ensure that none of the other providers in regions B or C can use the same spectrum block. As opposed to the case of the DVB-T broadcast, consider a provider in region D that provides service using the Ultra Wide Band (UWB) radio technology. The required spectrum block is allocated for it as well. However, since this radio technology is highly interference tolerant, and at the same time causes (relatively) small interference to others, the same spectrum block can also be allocated to different providers even within the same region, as this is the case in region D on Figure 3.8.

To summarise, the results have shown that—when interference is allowed but tolerated to a certain extent—the achievable gain is higher than when using the rigid allocation, as well as the strict DSA allocation proposed in the literature.

3.2.6 Simulation Method

This section briefly summarises the Simulated Annealing method and the parameter settings I used for calculating the optimal allocations. For a more detailed overview on Simulated Annealing in general please refer to [25].

Simulated Annealing (SA) is a generic probabilistic meta-algorithm for the global optimisation problem. Namely, it locates a good approximation to the global optimum of a given function in a large search space [25]. The name and inspiration come from annealing in metallurgy, a technique involving heating and controlled cooling of a material to increase the size of its crystals and reduce their defects. The heat causes the atoms to become unstuck from their initial positions (a local minimum of the internal energy) and wander randomly through states of higher energy; the slow cooling gives them more chances of finding configurations with lower internal energy than the initial one.

In the SA method, each point $\mathbf{s}$ of the search space is compared to a state of some physical system, and the function $E(\mathbf{s})$ to be minimised is interpreted as the internal energy of the system in that state. The goal is to bring the system to a minimal energy state, started from an arbitrary initial state.

I define the state vector as

$$\mathbf{s} = (\check{s}_{1,1}, \ldots, \check{s}_{1,K}, \ldots, \check{s}_{M,1}, \ldots, \check{s}_{M,K}). \tag{3.25}$$

Note, that the spectrum allocation S is uniquely defined by the state vector $\mathbf{s}$ and the allocation vector $\tilde{\mathbf{a}}$, since $S = \{(\check{s}_{m,k}, \hat{s}_{m,k})\}$ where $\hat{s}_{m,k} = \check{s}_{m,k} + \tilde{a}_{(m-1)K+k}$.

For the different optimisation goals I defined two energy functions according to Section 3.2.3 and 3.2.4. These energy functions are constructed so that they are negative only when the feasibility conditions (3.13) and (3.14) on page 31 are met for all allocated spectrum blocks. As a result, the energy function E is always positive if the allocation is not feasible, and negative if all feasibility conditions are satisfied. Minimising this energy function yields finding an optimal feasible allocation.

At each step, the SA heuristic considers some neighbour $\mathbf{s}'$ of the current state $\mathbf{s}$, and probabilistically decides between moving the system to state $\mathbf{s}'$ with energy $e' = E(\mathbf{s}')$, or staying in state $\mathbf{s}$ of energy $e = E(\mathbf{s})$.

In our solution new neighbours are generated from the current state vector by adding a Gaussian-distributed random variable to one of the elements, i.e.,

$$\mathbf{s}' = \mathbf{s} + X\mathbf{e}_Y, \quad X \sim \mathcal{N}(0, \sigma), \quad Y \sim \mathcal{U}_{MK}, \tag{3.26}$$

where $\mathbf{e}_i$ is the unit vector whose ith element is one, Y is a uniformly distributed discrete random variable in $[1, MK]$. The mean of the state-shift variable X is zero, and the standard deviation is set to be $S_{CAB}/4$.

To avoid local minima, one essential requirement for the transition probability P is that it must be nonzero when $e' > e$, which means that the system may move "uphill" to the new state even when it is worse (has a higher energy) than the current one. On the other hand, the probabilities must be chosen so that, on the long run, the system would move to lower energy states, i.e., the probability P must tend to zero if $e' > e$. That way the system will increasingly favour moves that go "downhill" (to lower energy values), and will eventually reduce to the greedy algorithm which makes the move if and only if it goes downhill.

To achieve this behaviour, the probability of making the transition from the current state s to a candidate new state s' is a function $P(e, e', T)$ of not just the state energies e and e', but a global time-varying parameter T called the temperature. A transition probability function that can be used has the form

$$P(e, e', T) = e^{\frac{e-e'}{T}}. \tag{3.27}$$

The time evolution of T is determined by the so-called annealing schedule. (Note, that the term Simulated Annealing stems from here.) The annealing schedule determines the degree of uphill movement permitted during the search. Roughly speaking, the evolution of $\mathbf{s}$ is sensitive only to coarser energy variations when T is large, and to finer variations when T is small. The principle underlying the choice of a suitable annealing schedule is easily stated—the initial temperature should be high enough to "melt" the system completely and should be reduced towards its "freezing point" as the search progresses—but choosing an annealing schedule for practical purposes is not a trivial task.

For the annealing schedule we used the simplest and most common temperature decrement rule $T_{k+1} = \alpha \cdot T_k$ with $T_0 = 1$ and $\alpha = 0.98$ (see [25] for parameter settings).

Evaluation of the Proposed Methods

The evaluation of both energy functions (3.20 for allocation with maximal regulator gain and 3.22 for allocation with minimal overall interference) is of $O(n^2)$ complexity because for each player the quality of the available spectrum needs to be calculated (accumulation of the interference affecting the band) and it also need to be checked whether the feasibility conditions are met. These are affected by the other n-1 players.

To evaluate the applicability of this method I used three different scenarios for testing. In every region 2 GSM, 2 UMTS and 1 UWB providers were operating and the regions were distributed along 3-by-3, 4-by-4 and 5-by-5 grids respectively in the 3 scenarios. (I.e., there were 9, 16 and 25 regions with 45, 80 and 125 players in the 3 scenarios.)

I examined 300 different cases in which the demand could not be excluded by the pre-processing method as being non-feasible (for details refer to section 4.4). I considered a demand non-feasible if an allocation that satisfied the feasibility conditions could not be found after 100 000 evaluations. The number of steps required to find the optimal allocations for the 3 scenarios

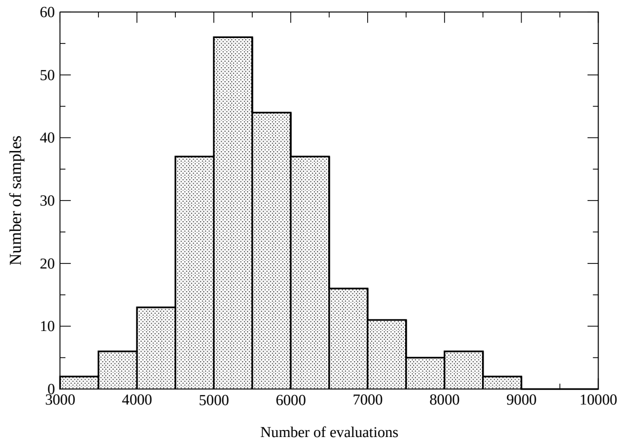


Figure 3.9: Number of steps needed to find the optimal allocation for regions 3x3.

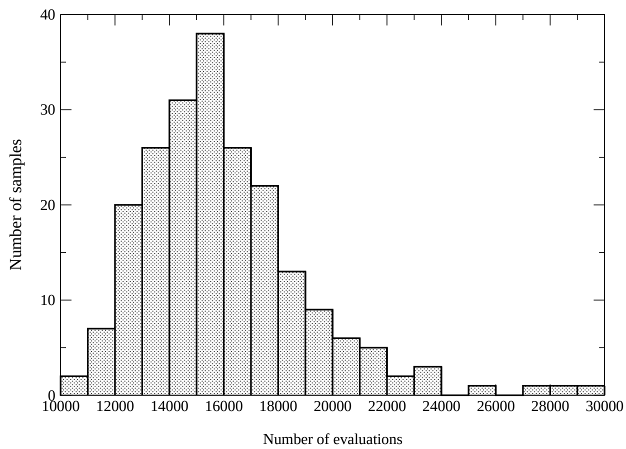


Figure 3.10: Number of steps needed to find the optimal allocation for regions 4x4.

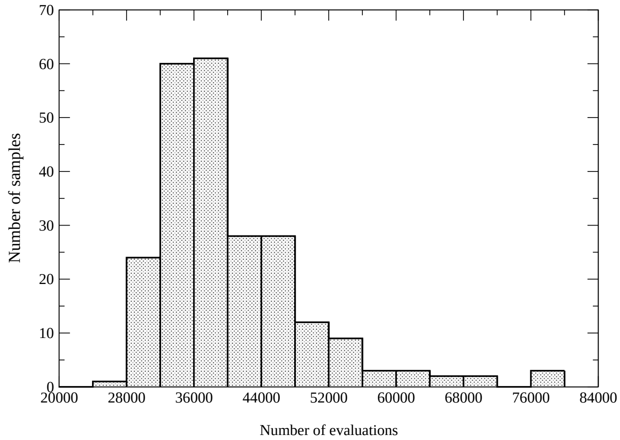


Figure 3.11: Number of steps needed to find the optimal allocation for regions 5x5.

The figures show that even for large scenarios the solution can be found with a relatively small number (average 40314) of evaluations.

3.3 Conclusions

In this chapter I proposed two different models to characterise the providers' relation to interference. The proposed two models have very different approaches to describe the effect of interference for the allocated spectrum blocks.

The *interference compensation model* discussed in Section 3.1 is based on the assumption that the interference causes service degradation and it can be compensated by allocating additional spectrum blocks for the provider. This model can be realised in the future when technical advances allowing its realisation are available.

The *interference tolerant model* discussed in Section 3.2 is based on the idea that interference arising between the providers is tolerated as long as it is below a pre-defined threshold. Recent advances in technology allow this model to be realised in the near future.

I also gave for both models the feasibility conditions and proposed algorithms to determine the optimal allocations from the following two points of view:

- I gave an algorithm to determine the allocation that results in the highest guaranteed regulator gain for both models. That is the smallest amount of spectrum enough to serve the given demand set and which spectrum block has to be allocated to which provider in order to respect the feasibility conditions.

- I also gave an algorithm to determine, having a determined amount of spectrum (S_{CAB}), whether the given demand set is feasible or not, i.e., is there an allocation that respects the feasibility conditions? Since usually if the demand set is feasible then several feasible allocations exist, the proposed algorithm can select the feasible allocation with minimal overall interference.

Finally, I demonstrated the operation of the models with a simulation example. The simulation scenarios examined the overall spectrum requirements and the achievable regulator gain for all proposals for a one day interval. The average gain for the simulation period was also calculated and allocation figures from a selected allocation period highlighted the differences between the different proposals.

Chapter 4

Real Time Auction and Pricing

Besides defining the framework, the modelling of interaction between the regions and determining the optimal allocation the other main topic is the “market for frequencies” for dynamic spectrum allocation; establishing an adequate, real time auction- and pricing DSA management framework.

An appropriate auction and pricing mechanism has to:

- take the specialities of DSA systems into account, i.e., it has to be able to adapt to the variations of spectrum demands in time and space,
- support a near real time operation, i.e., it has to determine the new prices and allocation scheme within one allocation period,
- enforce the providers to tell their real tolerance levels to the spectrum brokers, otherwise it greatly reduces the effectiveness of DSA, and the result would look nearly the same as the rigid spectrum allocation methodology of today.

According to the last item in a DSA scenario where tolerance is much rewarded by increasing spectral efficiency, certain mechanisms need to be implemented to make it desirable for the NSPs to use all available techniques to tolerate co-existence as much as possible. A proper pricing scheme that charges providers who do not tolerate others and interfere to a larger extent than necessary with other regions would be of great importance.

Although the progressive second-price auction mechanism [27] gives a suitable allocation for infinitely divisible resources, in case of dynamic spectrum allocation the size of the distributeable spectrum cannot be explicitly determined, due to interference. It may happen that inside one region there are carriers that cannot be distributed because of the interference arising from the neighbouring regions, while other carriers can be allocated to more than one providers that do not disturb each other. This was the reason to suggest an allocation rule and pricing mechanism that satisfies the special needs of dynamic spectrum allocation.

The aim of the model I propose in this Chapter is to follow variations during the day; the re-allocation period is typically 1-2 hours. The model is centralised, i.e. the demands and bids of the providers are submitted to a central spectrum broker that determines the optimal allocation, the prices to be paid by the providers and grants exclusive licenses to the bought spectrum blocks for the next re-allocation period.

The model discussed in this chapter is based on the previously proposed framework and uses the interference tolerant model proposed in Section 3.2 as an underlying spectrum allocation model. In this model the allocations were determined to yield an optimal solution in the sense that the overall social welfare is maximised and the allocation minimises the overall interference.

However, the modularity of the DSA framework and the auction model ensures that alternative solutions could also be applied either for the allocation objective or for the pricing model. For example, one could go for an allocation that satisfies the demands within the smallest spectrum band in total, or have the objective to maximise income from the auctioneer's point of view instead of maximising welfare. The only thing to do in this case is to use the underlying DSA modelling framework and replace the allocation and pricing rules accordingly.

Section 4.1 describes the proposed allocation model and Section 4.2 gives the allocation and pricing rules that yield an optimal solution that maximises the social welfare. In order to find the optimal allocation a number of feasibility checks have to be carried out within one bidding period. The quick feasibility check is essential for real-time operation. For this problem Section 4.3 and 4.4 propose solutions. The second task is finding the most efficient allocation; I propose a quick, rule-based algorithm for this in Section 4.5.

4.1 Auction Model

In the DSA framework the available spectrum is re-allocated at given time periods. Before the start of each allocation period the providers submit their bids to a centralised spectrum broker entity. The spectrum broker determines the prices to be paid by the providers and the optimal allocation that maximises "social welfare".

Figure 4.1 shows the process the spectrum broker follows during an allocation period. At the beginning of each period the providers submit their bids to the spectrum broker. A bid consists of the spectrum amount the provider requests and the price it is willing to pay for it.

The providers' bids may contain more than one spectrum amount-price pairs. The

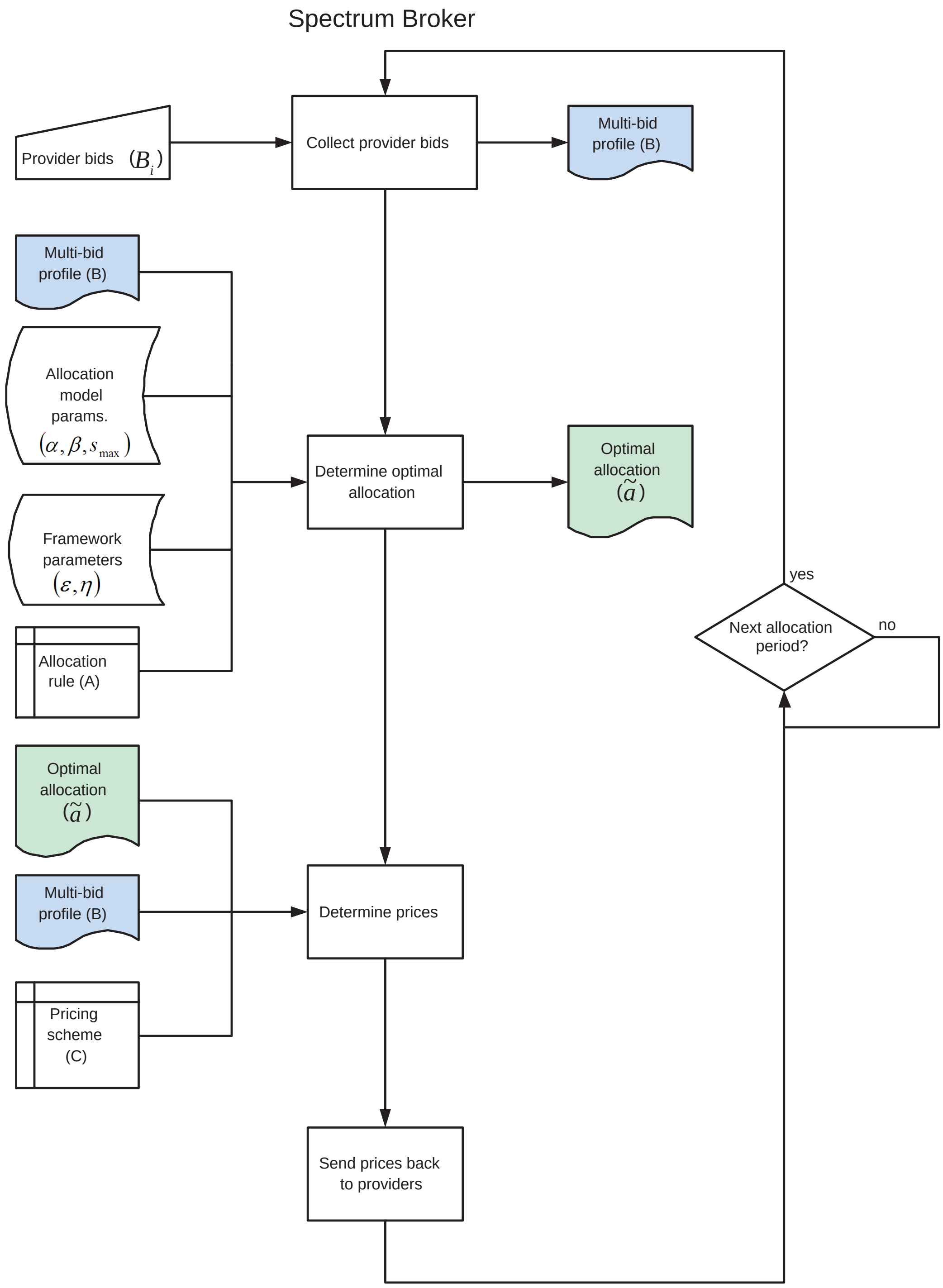


Figure 4.1: The spectrum allocation process.

spectrum broker aggregates these bids into a so-called "multi-bid profile". In the following step the spectrum broker uses this multi-bid profile together with the framework's and the allocation model's parameters and the allocation rules to determine the optimal allocation.

Based on the optimal allocation and the appropriate pricing scheme the spectrum broker then selects the one "winning bid" of each provider from the multi-bid profile. At the end of the process the spectrum broker sends back to the providers the parameters of the spectrum blocks they are provided with for the next allocation period and also the prices they need to pay for the spectrum. After this, the spectrum broker waits for the next re-allocation period to begin.

Since the convergence time of the interactive auctions may be long and may cause significant signalling traffic; furthermore, the demand function of the providers is typically non-continuous and contains only a few bids, I proposed a one-shot multi-bid auction model for pricing.

Following the above described scheme, let $\mathcal{I} = \{1, \ldots, i, \ldots, I\}$ denote the set of players. Since the demands of one provider may be different in different regions, I handle the providers separately in each region, i.e. $I = M \cdot K$.

The ith player submits $N^{(i)}$ two-dimensional bids to the spectrum broker:

$$B_i = \{b_{i,1}, \ldots, b_{i,N^{(i)}}\}, \tag{4.1}$$

where

$$b_{i,n} = (q_{i,n}, p_i(q_{i,n})), \quad n = 1, \ldots, N^{(i)}, \tag{4.2}$$

and q denotes the size of the requested resource and $p(q)$ represents the price offered for this resource.

The amount of spectrum requested by one provider strongly depends on the price of the resource. If the unit price of a spectrum block increases, the providers' demands decrease. Figure 4.2 shows an example for a demand function that represents the amount of spectrum that a provider would request as a function of the unit spectrum price. On the right side the bids $q_{1,j}$ are shown on a bar graph using different colours that can be interpreted as follows. If the prices are high the provider only pays for the minimum amount of spectrum that is absolutely necessary to provide minimal basic services (black). In case of cheaper spectrum it would pay for an additional spectrum block to provide, e.g., value-added services (grey). When the radio resource is cheap it is worth for the provider to buy even more spectrum for some kind of premium services (white).

From the collected bids the spectrum broker creates the input parameter of the pricing algorithm, the multi-bid profile:

$$B = (B_1, \ldots, B_I). \tag{4.3}$$

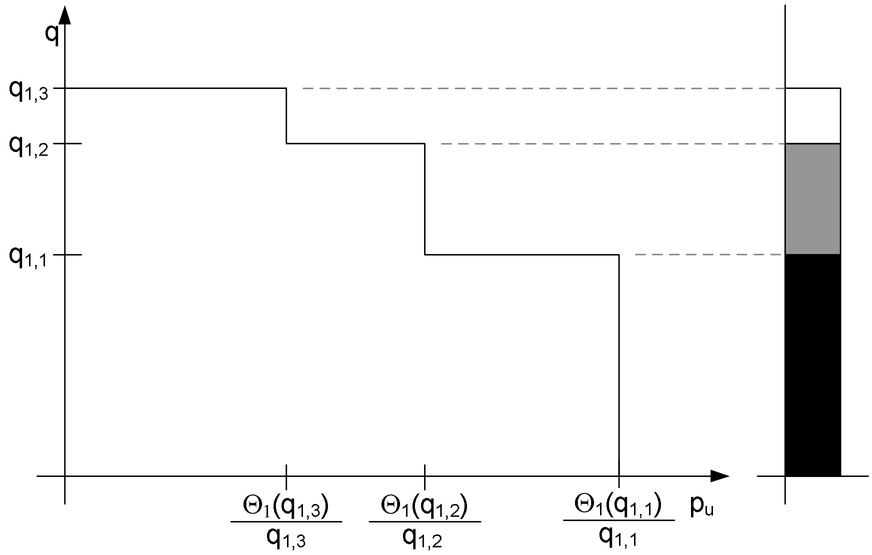


Figure 4.2: Example demand function.

4.2 Allocation and Pricing Rule

On this basis and using the A allocation rule and the corresponding C pricing scheme the spectrum broker determines for all $i \in \mathcal{I}$ players the optimal a_i allocation and the corresponding c_i price.

The A allocation rule returns an allocation vector,

$$A(B) = \mathbf{a} = (a_1, \ldots, a_I), \tag{4.4}$$

where

$$a_i \in \{0, b_{i,1}, \ldots, b_{i,N^{(i)}}\}, \quad i = 1, \ldots, I, \tag{4.5}$$

that is, the size of one of the resources requested by the ith player or zero, when neither of the bids are feasible.

The C pricing scheme for one allocation:

$$C(A(B)) = C(\mathbf{a}) = (c_1, \ldots, c_I), \quad i = 1, \ldots, I, \tag{4.6}$$

where $c_i \leq p_i(a_i)$ is the price the $i-th$ player has to pay for using the a_i sized spectrum slice. This value cannot be higher than the maximum price offered by the provider.

The allocation rule and pricing scheme must be constructed to yield an allocation that is feasible for all the players on one hand, and on the other hand is efficient in some sense, depending on what we are aiming at. My goal here is to construct an allocation rule that is optimal in the sense that the overall spectrum efficiency (or utility) is maximal. (I note, that the measure I use for efficiency corresponds to the usual social welfare criterion (see [40])).

We define our allocation rule A for a given bid profile B as

$$A(B) = \arg\max_{\mathbf{a}\in Q^f} \sum_{i=1}^{I} p_i(a_i), \tag{4.7}$$

where Q^f is the set of feasible allocations, i.e., for all $\mathbf{a} \in Q^f$ there exists a *spectrum allocation* $S(\mathbf{a}) = \{S_{1,1}, \ldots, S_{M,K}\}$ where $|S_{m,k}| = a_{(m-1)K+k}$, which satisfies the feasibility conditions (3.13) and (3.14). In words, (4.7) finds the allocation vector that would maximise the total income *if* the players had to pay the maximum that they were willing to pay for the acquired spectrum amount. However, we propose to use a different pricing scheme that, instead of maximising the total income, maximises the allocation's *efficiency*.

The efficiency $\Theta(\mathbf{a})$ of an allocation is defined as

$$\Theta(\mathbf{a}) = \sum_{i=1}^{I} \theta_i(a_i), \tag{4.8}$$

where $\theta_i(a_i)$ is the *valuation* of player i.

We call an allocation $\tilde{\mathbf{a}}$ *optimal* if it is efficient and feasible, that is

$$\tilde{\mathbf{a}} = (\tilde{a}_1, \ldots, \tilde{a}_I) = \arg\max_{\mathbf{a}\in Q^f} \Theta(\mathbf{a}). \tag{4.9}$$

Comparing (4.7) and (4.9), our allocation rule would result in an optimal allocation only if the players bid $p_i(q) = \theta_i(q)$ as the price they offer for the requested quantity. This can be achieved with a proper pricing scheme that eventually leads the players to bid "honestly", i.e., tell the auctioneer how valuable the spectrum is for them. Using "second-price" (or Vickrey) pricing scheme can be a solution.

However, there can be many different feasible allocations that are optimal in the sense that they have the same maximal overall valuation (or social welfare). Although all of them satisfy the feasibility conditions (3.13) and (3.14), they can be significantly different when the actual interference levels are taken into account. The question is then, which one of them is the best concerning interference and spectrum efficiency.

Having the optimal allocation vector

$$\tilde{\mathbf{a}} \equiv (|S_{1,1}|, \ldots, |S_{1,K}|, \ldots, |S_{M,1}|, \ldots, |S_{M,K}|) \tag{4.10}$$

the goal is to find the minimal interference *spectrum* allocation, i.e., a realisation $\tilde{S}(\tilde{\mathbf{a}})$ of the optimal and feasible allocation vector $\tilde{\mathbf{a}}$ that minimises the *overall* interference. The calculation can be based for example on a Simulated Annealing method with the energy function proposed in Section 3.2.4.

To determine the prices of the allocated spectrum blocks I propose a second-price pricing scheme. The intuition behind is an exclusion-compensation principle which lies behind all second-price mechanisms: player i pays so as to cover the "social opportunity cost", that is to say the loss of utility he imposes on all other players by his presence. The price that player i has to pay can be calculated based on the declared willingness to pay (bids) of all players who are excluded by i's presence. It can be shown that, by using this scheme, telling the truth (i.e., setting the bid price equal to the valuation) is a dominant strategy [27]. Thus, from now on we assume that all players bid $(q_i, \theta_i(q_i))$ pairs in their bid profiles. This results in that the allocation is economically efficient in that it maximises total user valuation (social welfare).

The multi-bid profile obtained by deleting the bid of player i, also called as the *opponents' profile*, is defined as

$$B^{(-i)} = (B_1, \ldots, B_{i-1}, 0, B_{i+1}, \ldots, B_I). \tag{4.11}$$

Similar to (4.9), we can calculate the optimal feasible allocation for the $B^{(-i)}$ profile as well:

$$\begin{aligned} \tilde{\mathbf{a}}^{(-i)} &= \left(\tilde{a}_1^{(-i)}, \ldots, \tilde{a}_{i-1}^{(-i)}, 0, \tilde{a}_{i+1}^{(-i)}, \ldots, \tilde{a}_I^{(-i)}\right) = \\ &= \arg\max_{\mathbf{a}^{(-i)} \in Q^f} \Theta\left(\mathbf{a}^{(-i)}\right) \end{aligned} \tag{4.12}$$

where

$$\mathbf{a}^{(-i)} = A\left(B^{(-i)}\right). \tag{4.13}$$

As explained above, in a second-price auction player i is charged a total price of

$$\begin{aligned} c_i(A(B)) &= \Theta_i(\tilde{a}_i) - \left[\Theta(\tilde{\mathbf{a}}) - \Theta\left(\tilde{\mathbf{a}}^{(-i)}\right)\right] = \\ &= \sum_{\substack{j=1 \\ j \neq i}}^{I} \left[\Theta_j\left(\tilde{a}_j^{(-i)}\right) - \Theta_j(\tilde{a}_j)\right]. \end{aligned} \tag{4.14}$$

In words, player i must pay exactly the amount that those players would pay who were excluded by player i's presence. This price can be calculated by obtaining the allocations and prices with (i.e., using B) and without (i.e., using $B^{(-i)}$) player i's bid, and taking the difference at the end.

To sum up, during the spectrum reallocation process first NSPs submit their multi-bids to the Spectrum Broker. Based on these multi-bids the highest efficiency feasible allocation

($\tilde{\mathbf{a}}$) has to be found[1] (see (4.9)) together with the prices[2] that the providers must pay for the allocated spectrum (see (4.14)). Knowing $\tilde{\mathbf{a}}$ the optimal (or near optimal) spectrum allocation can be given by running the simulated annealing heuristics until it reaches the minimum or a carefully chosen threshold value. At the end of the reallocation procedure the spectrum slices $\{(\check{s}_{m,k}, \hat{s}_{m,k})\}$ are allocated for the NSPs in all regions and they pay $\{c_{m,k}\}$ amount for it. At the beginning of each reallocation interval the whole allocation procedure is repeated.

4.2.1 Properties of the Second-Price Auction Mechanism

The price scheme I propose realises a progressive second-price pricing mechanism, the natural generalisation of second price pricing mechanisms. Semret et al. described in [33] that by defining the efficiency as the sum of the valuation of the players this definition corresponds to the usual social welfare criterion. The detailed proof and the definition of the social welfare criterion can be found in Nemo Semret's Ph.D. dissertation [40].

In the second-price auction a winning bidder can never affect the price it pays, so there is no incentive for any bidder to misrepresent its value. From a bidder's point of view the amount it bids only affects whether it wins, and only by bidding its true value can it make sure to win exactly when it is willing to pay the price.

As summarised by [8] the main properties of the auction are:

- "Truthful reporting is a dominant strategy for each bidder in the VCG (Vickrey-Clarke-Groves) mechanism. Moreover, when each bidder reports truthfully, the outcome of the mechanism is one that maximises total value."

- If the set of possible value functions V is smoothly path connected and contains the zero function, then the unique direct revelation mechanism for which truthful reporting is a dominant strategy, the outcomes are always efficient, and there are no payments by or to losing bidders is the mechanism.

- "A final virtue of the Vickrey auction is that its average revenues are not less than that from any other efficient mechanism, even when the notion of implementation is expanded to include Bayesian equilibrium. A formal statement of this famous revenue equivalence theorem is given below." "Consider a Bayesian model in which the support of the set of possible value functions, V, is smoothly path connected and contains the

[1] In order to check the feasibility of an allocation it is enough to run the algorithm until the energy function E defined by (3.20) becomes negative.

[2] It is enough to carry out only a feasibility check to determine $\tilde{\mathbf{a}}^{(-i)}$s that are required for calculating the prices.

zero function. Suppose the bidder value functions are independently drawn from V. If, for some mechanism, the Bayesian-Nash equilibrium outcomes are always efficient and there are no payments by or to losing bidders, then the expected payment of each bidder n, conditional on his value function $v_n \in V$, is the same as for the VCG mechanism. In particular, the sellers revenue is the same as for the VCG mechanism." (See proofs in [8])

I note, that this dissertation does not focus on the fairness of the proposed mechanism. By using second-price auction it ensures that a winning bidder can never affect the price it pays, so there is no incentive for any bidder to misrepresent its value. It is also proven that the dominant strategy is telling the true valuation of the resource. However, it does not exclude that providers dominant in the market take advantage of their economic powers and submit untrue bids for long term benefits.

4.3 Fast Feasibility Check

In order to find an optimal allocation we have to evaluate the feasibility of several allocation vectors. In worst case—when no feasible allocation can be found based on all submitted bids—the number of required evaluations can be $\prod_{i=1}^{MK} N^{(i)}$.

To be able to find the optimal allocation an efficient feasibility check is needed due to the large number of evaluations. However, the feasibility check is a complex task; on the first hand it is an exhaustive search in an $M \cdot K$ dimensional hyper-cube with an edge length of S_{CAB} (the size of the Coordinated Access Band).

4.3.1 Feasibility Check as a Set Separation Problem

In the proposed model the model parameters can be grouped into two categories: fast varying parameters (spectrum requests) may change at each allocation time, whereas slow varying parameters (technology specific parameters and geographic coupling parameters) change occasionally. For example the technology specific parameters can change when a new transmission technology is introduced; geographical coupling may change by modification of the terrain/environment, construction of new buildings, etc.

However, assuming that $\beta = \alpha$ a near real-time feasibility estimation method can be constructed utilising the characteristics that fixing the slow varying parameters $(\alpha, \epsilon, \eta, S_{CAB})$ a hyper-space can be defined in which the feasible and non-feasible allocations are separated by a hyper-surface.

Theorem 4.3.1. *By fixing the slow varying parameters the feasibility check becomes a set separation problem in the request-space; i.e., there is a hyper-surface that separates the feasible and non-feasible allocations.*

Proof. All of the feasible allocations are enclosed in a hyper-cube with an edge length of S_{CAB}. If a request exceeds the size of the coordinated access band (S_{CAB}) then the allocation will not be feasible.

If a spectrum allocation $S = \{S_{1,1}, \ldots, S_{M,K}\}$ is feasible (i.e., the spectrum blocks satisfy (3.14)) then $S^f = \{S^f_{1,1}, \ldots, S^f_{M,K}\}$ is also feasible for all $(S^f_{1,1} \leq S_{1,1}, \ldots, S^f_{M,K} \leq S_{M,K})$. E.g., the starting points of the allocation are the same as the original allocation.

If a spectrum allocation $S = \{S_{1,1}, \ldots, S_{M,K}\}$ is not feasible (i.e., the spectrum blocks do not satisfy (3.14)) then $S^{nf} = \{S^{nf}_{1,1}, \ldots, S^{nf}_{M,K}\}$ is not feasible either for all $(S^{nf}_{1,1} \leq S_{1,1}, \ldots, S^{nf}_{M,K} \leq S_{M,K})$.

It follows from the above statements that in the request-space the feasible and non-feasible allocations are separated into two disjoint sets by a hyper-surface.

□

The feasibility check is a complicated function:

$$Y(\mathbf{a}, \alpha, \epsilon, \eta, S_{CAB}) = \begin{cases} 1, & \text{if } \mathbf{a} \text{ is feasible,} \\ -1, & \text{if } \mathbf{a} \text{ is not feasible.} \end{cases} \tag{4.15}$$

By fixing the slow varying parameters $(\alpha, \epsilon, \eta, S_{CAB})$ we can construct a fast feasibility estimation method, i.e.:

$$\hat{Y}(\mathbf{a}) = \hat{y} \tag{4.16}$$

Separation by Means of a Convex Polytope

The basic idea of the estimation is that we construct an interpolation of the separation surface as a union of hyper-planes, and this leads to a fast feasibility estimation. I note, that the above described characteristics does not ensure that the feasible allocations form a convex polytope. When using this approximation it must always be considered that the error of the approximation may be high.

The fast feasibility estimation consists of two phases:

- In the pre-calculation phase the coefficients of the optimal interpolating hyper-surface (as a union of L hyper-planes) are determined. These coefficients need to be re-calculated only if the slow varying parameters change. One hyper-plane is defined as a Cartesian form of the equation of a plane:

$$\sum_{i=1}^{M \cdot K} a_i \cdot w_i = w_0, \tag{4.17}$$

where a_i-s are the spectrum requests and w-s are the coefficients of the hyper-plane.

- After the determination of the coefficients (for L hyper planes) the feasibility check is simply a substitution into

$$\hat{Y}(\mathbf{a}) = \operatorname{sgn}\left\{\sum_{l=1}^{L} \operatorname{sgn}\left(\sum_{i=1}^{MK} a_i w_i^{(l)} - w_0^{(l)}\right) - L + 0.5\right\}, \tag{4.18}$$

where $w_i^{(l)}$-s are the coefficients of the separation surface.

The linear formula of equation (4.18) allows a very fast feasibility estimation that can be easily realised by hardware, e.g., using digital signalling processors.

There are several proposals for the estimation of the hyper-surface in set separation problems [31]. For example in a backpropagation-based solution we can start from a learning set $\tau^{(q)} = \{(\mathbf{a}_q, y_q); q = 1 \dots Q\}$, where $\mathbf{a}_q$ is an allocation vector, and $y_q = 1$ if $\mathbf{a}_q$ is feasible, and $y_q = -1$ if $\mathbf{a}_q$ is not feasible.

Let us define $MSE(\mathbf{W})$ as the mean squared error of the estimator, i.e.,

$$MSE(\mathbf{W}) = \frac{1}{Q}\sum_{q=1}^{Q}(y_q - \hat{y}_q)^2. \tag{4.19}$$

We search for the optimal $\mathbf{W}_{opt}$ matrix, that minimises the mean squared error:

$$\mathbf{W}_{opt} = \min_{\mathbf{W}} MSE(\mathbf{W}). \tag{4.20}$$

Since backpropagation requires that the activation function (φ) is differentiable we use

$$\mathbf{W}_{opt} = \min_{\mathbf{W}} \frac{1}{Q}\sum_{q=1}^{Q}\left(y_q - Net(\mathbf{a}_q, \mathbf{W})\right)^2, \tag{4.21}$$

where

$$Net(\mathbf{a}, \mathbf{W}) = \varphi\left\{\sum_{l=1}^{L} \varphi\left(\sum_{i=1}^{MK} a_i w_i^{(l)} - w_0^{(l)}\right) - L + 0.5\right\} \tag{4.22}$$

is the estimator, that results by substituting the sgn function of (4.18) with a differentiable sigmoidal function φ. With this substitution W_{opt} can be determined by the following iteration:

$$\mathbf{W}(k+1) = \mathbf{W}(k) - \delta\,\mathbf{grad}(MSE(\mathbf{W}(k))), \tag{4.23}$$

where δ is a backpropagation constant and the mean squared error can be calculated by substituting the estimator in (4.22) into (4.19), i.e.,

$$MSE(\mathbf{W}) = \frac{1}{Q}\sum_{q=1}^{Q}(y_q - Net(\mathbf{a}_q, \mathbf{W}))^2. \tag{4.24}$$

Basically it is a two layer neural network taught via the backpropagation algorithm. Layer one checks if the sample is above or below the hyperplane and layer two accumulates the outputs of the first layer. I note, that there are several other algorithms that can be used efficiently for set separation problems.

Separation by Means of a Multi-Layer Feed-Forward Neural Network

It has been proven in [18] that standard multi-layer feed-forward networks with as few as one hidden layer using arbitrary squashing functions are capable of approximating any function from one finite dimensional space to another to any desired degree of accuracy, provided sufficiently many hidden units are available. In this sense, multi-layer feed-forward networks are a class of universal approximators.

That is, modifying the Net function in equation 4.21 as follows we can define a universal approximator for the set separation problem:

$$Net(\mathbf{a}, \mathbf{W}) = \varphi \left\{ \sum_{l=1}^{L} w_{2,l} \varphi \left(\sum_{i=1}^{MK} a_i w_{1,i}^{(l)} - w_{1,0}^{(l)} \right) - w_{2,0} \right\} \tag{4.25}$$

I checked the error of approximation of set separation surfaces characterised in 4.3.1 with 3-layer feed-forward neural networks. For the investigation 10 different surfaces with the defined characteristics were generated and the learning sets constructed the following way. The feasibility of a randomly chosen demand set (item of the learning set) was determined; if it was feasible, a few additional items were chosen from the region below (i.e. sets of smaller demands, which were also feasible) into the learning set. If it was not feasible a few additional items were chosen from the region above the given demand (i.e. sets of higher demands that were not feasible either) into the learning set. Furthermore, in case of a feasible allocation some demands were increased by a small randomly generated number and the feasibility of the new demand set was also evaluated. In case of a non-feasible allocation some of the demands were decreased by a small randomly generated number. With this intelligent learning set construction I tried to identify the separation surface. For training the network I used the resilient backpropagation training algorithm.

I investigated the affect of dimension and the number of hidden neurons; after training the network I checked the correctness of the estimation by 100000 randomly generated samples. The average of the percentage of correct predictions are shown on figure 4.3 for three different dimensions and for different number of neurons in the hidden layer. For the learning set generated the above described way it was not worth it to use more than 20 neurons in the hidden layer even in case of large dimensions.

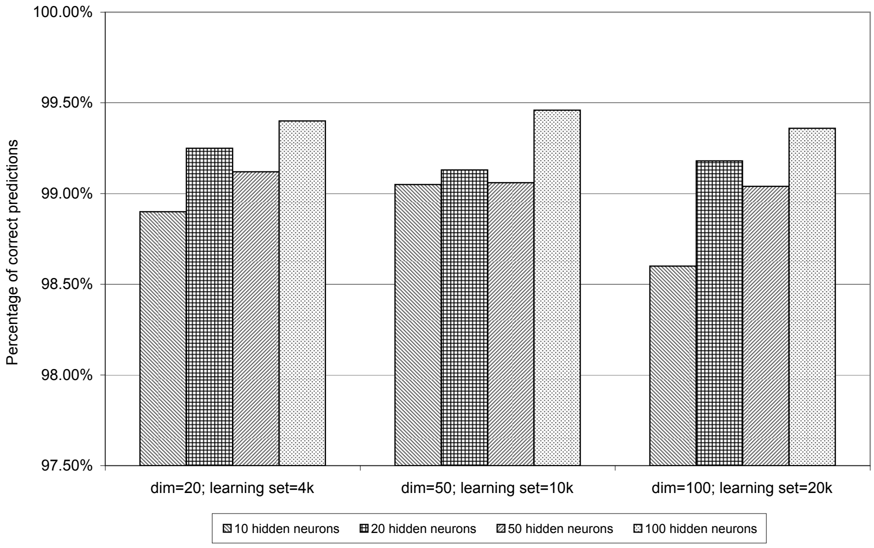


Figure 4.3: Approximation with a 3-layer neural network.

4.4 Exclusion Matrix

During the learning set construction in the pre-calculation (non-real time) phase the feasibility can be evaluated by an exhaustive search or a heuristic method as proposed in [C5]. In case of a feasible allocation the evaluation is relatively quick as usually more than one feasible allocation exists with the given conditions. However, when the allocation is not feasible an exhaustive search over the hyper-space is required. The scalability of this calculation can be improved by the exclusion matrix introduced below. For example see the learning set (Table 5.7) of the simulation in Section 5.3 In this case 87% of the non-feasible allocations can be filtered by the exclusion matrix.

The main idea is if there is a subset of players whose allocations are mutually exclusive i.e., they do not get the same spectrum due to interference then the sum of the requested spectrum blocks of these players can not exceed the size of the coordinated access band. Based on this observation a fast pre-filtering method can be constructed as follows.

Let us consider an undirected graph whose vertices represent the service providers of each region. There is an edge between the m-th provider of the k-th region and the n-th provider of the l-th region if the two providers cannot get the same spectrum slice due to the feasibility conditions, i.e.:

$$e_{\{m,k\}\{n,l\}} \in E \Leftrightarrow \\ \left(\left(i_{\{m,k\}\leftarrow\{n,l\}} > \alpha_m\right) \vee \left(i_{\{n,l\}\leftarrow\{m,k\}} > \alpha_n\right)\right) \quad (4.26)$$

where

$$i_{\{m,k\} \leftarrow \{n,l\}} = \varepsilon_{k \leftarrow l} \cdot \eta_{m,n} \cdot s_{n,l}^{max}. \qquad (4.27)$$

Let us define an exclusion vector ($\mathbf{x}$) so that the number of the vector elements is NK, each element corresponds to a service provider-region pair (player) and in the vector those players get value 1 who cannot get the same spectrum slice.

This vector represents a clique in the above defined graph. Bron and Kerbosch [9] gave an algorithm to compute all cliques in linear time (relative to the number of cliques). I note that it is not necessary to determine all cliques in the graph but the more cliques are determined the more the speed of the non-real time pre-processing can be improved. I also note, that cliques are typically small and usually restricted to a region and its neighbours.

To each identified clique let us assign the corresponding exclusion vector, then construct an exclusion matrix so that the rows of the matrix are the exclusion vectors:

$$\mathbf{X} = (\mathbf{x_1}; \ldots \mathbf{x_s}). \qquad (4.28)$$

When

$$\max(\mathbf{Xa}) > S_{CAB} \qquad (4.29)$$

the $\mathbf{a}$ allocation is not feasible.

Figure 4.4 illustrates the construction of the exclusion matrix for the same scenario that is described in Section 3.2.5. The setup is that one UMTS and two GSM providers operate in all four regions within the Coordinated Access Band. In addition, in region A there is a broadcast provider (e.g., DVB-T) that covers regions B and C, too. Substituting the model parameters described in Section 3.2.5 into (4.26) and (4.27) we can construct the above mentioned graph as can be seen in Figure 4.4.

In words, the graph describes that service providers operating in the same region do not get the same spectrum block, as well as the spectrum block used by the broadcast provider operating in region A can not be overlapping with the spectrum blocks of the providers operating in region B and C.

The identified cliques in the graph are denoted by the coloured circles. From these cliques we can construct exclusion vectors so that if the vertex representing player i is an element of the clique then the i-th element of the vector is one, otherwise it is zero. For exclusion vectors see the matrix rows in the figure with the corresponding colours. From these exclusion vectors an exclusion matrix can be constructed according to (4.28) and a fast pre-filtering can be performed according to (4.29).

For example, let us assume, that the size of the coordinated access band is 30 units of spectrum ($S_{CAB} = 30$). Furthermore, the broadcast provider requests 10 units of spectrum ($a(4) = 10$), and the requests of the providers operating in region B are 10, 15 and 5,

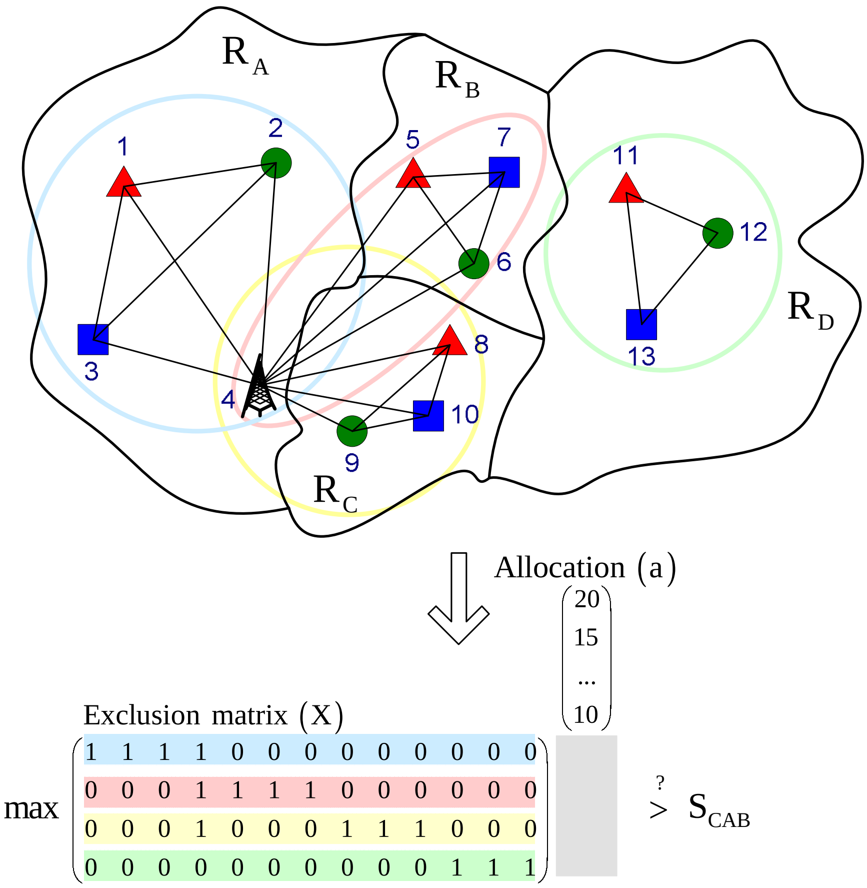


Figure 4.4: Illustration of the Exclusion Matrix.

respectively; i.e., $a(5) = 10$; $a(6) = 15$; $a(7) = 5$. In that case the product of the second row of a matrix (representing the pink clique in the graph) and the allocation vector is 40, which is greater than the size of the coordinated access band, so a feasible allocation does not exist.

4.5 Search for an Optimal Allocation

According to (4.9) we have to find a feasible allocation vector that maximises the sum of the valuation of the players (called the efficiency of an allocation). Theoretically this can be determined by sorting the possible allocation vectors by the efficiency of the allocation, then selecting the first feasible allocation from the sorted list. This theoretical method is not adequate for large data sets. However, the structure of the possible allocation vector set ensures that we can find the optimal allocation without having to sort the list. Based on this special structure I propose the following iterative method to find an optimal (or near optimal) allocation.

The bid vector submitted by player i based on (4.1) and (4.2):

$$B_i = \{b_{i,1}, \ldots, b_{i,N^{(i)}}\}, \tag{4.30}$$

where

$$b_{i,n} = (q_{i,n}, p_i(q_{i,n})), \quad n = 1, \ldots, N^{(i)}. \tag{4.31}$$

Assume that bids are ordered so that

$$q_{i,n} \leq q_{i,n+1} \quad \forall n \in \{1, \ldots, N^{(i)} - 1\} \tag{4.32}$$

Furthermore, $p(q)$ (the offered price for the spectrum) is monotonously increasing.

Define the $\mathbf{r}$ "spectrum request" vector as $r(i) = i_n$, where i_n is the number of the n-th bid of the i-th player. It follows from the above description that:

- if an $\mathbf{r_f}$ allocation is feasible then all $\tilde{\mathbf{r_f}}$ allocations are also feasible, for which the $\tilde{r_f}(i) \leq r_f(i)$ equation holds for all $1 \leq i \leq I$. Furthermore, because of the monotonity of $p(q)$ and the second price auction $\mathbf{r_f}$ is more efficient than $\tilde{\mathbf{r_f}}$s.

- Similarly, if $\mathbf{r_{nf}}$ is not feasible then all $\tilde{\mathbf{r}}_{\mathbf{nf}}$ allocations are not feasible for which $\tilde{r_{nf}}(i) \geq r_{nf}(i)$ for all $1 \leq i \leq I$.

The above statements mean that by the evaluation of an allocation a rule can also be constructed that determines whether several additional allocations are feasible or not. If we choose the allocation vectors from the space not covered by the above rules the $\mathbf{r_f}$ vectors will converge to the most efficient feasible allocation (optimal allocation).

Figure 4.5 illustrates the operation of the proposed algorithm for a very simple scenario. Here we have only three players, the multibid of player 1 and player 3 contains three bids, while player 2 bids only for 2 different quantities of spectrum. In the figure one circle represent one request vector. The request vectors are organised the way that the difference between the root element and the elements of a row is the same and this distance is increasing downwards. Here the difference is defined as the L1 distance of the two request vectors, i.e.:

$$d_1(\mathbf{r_1}, \mathbf{r_2}) = \|\mathbf{r_1} - \mathbf{r_2}\|_1 = \sum_{i=1}^{N \cdot K} |r_1(i) - r_2(i)| \tag{4.33}$$

In words, if the distance between two request vectors is one it means that the two vectors differ only at one place and that difference is one.

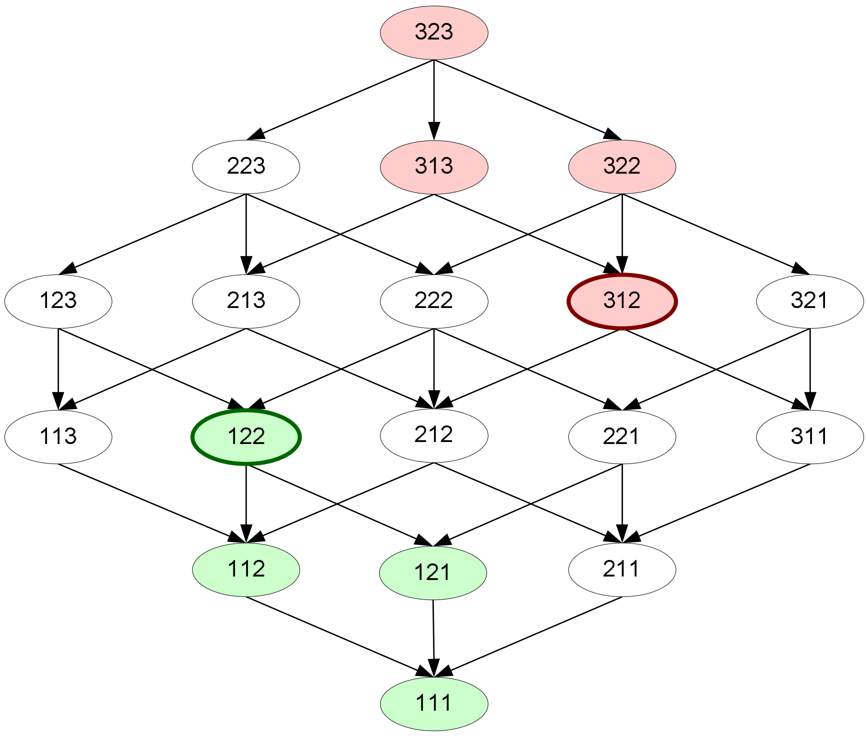


Figure 4.5: Search for an optimal allocation.

Furthermore, in the figure edges connect vertices that are 1 unit distance from each other. The upper "root" element represents the highest efficiency bid combination (since bids are ordered according to (4.32) and the request vector contains the highest possible values for each player) while the lower "root" represents the lowest efficiency allocation. Arrows point towards the lowest efficiently allocation.

Let us suppose that the algorithm first selects the 312 node denoted by the red circle in the figure. If this $\mathbf{r_{nf}} = [3, 1, 2]$ request is not feasible then, as mentioned above, all $\mathbf{\tilde{r}_{nf}}$ allocations are non-feasible for which $\tilde{r_{nf}}(i) \geq r_{nf}(i)$ for all $1 \leq i \leq I$. It is denoted by red in Figure 4.5.

Similarly, if an $\mathbf{r_f} = [1, 2, 2]$ allocation is feasible then all $\tilde{\mathbf{r_f}}$ allocations are also feasible, for which the $\tilde{r_f}(i) \leq r_f(i)$ equation holds for all $1 \leq i \leq I$, denoted by green in the figure.

By storing this allocation and its efficiency, and iteratively selecting allocations from the remaining space this method will converge to the most efficient feasible allocation.

4.5.1 Extension of the Results

The results of this chapter were discussed assuming that the spectrum allocation model in the DSA framework is the interference tolerant model (see section 3.2 for details). The fast feasibility estimation (section 4.3) and the rule-based search (section 4.2) can be used with the interference compensation DSA model (or any other model that may be set up) without modifications. The graph model of the exclusion matrix (section 4.4) after a modification that two vertices are connected by an edge if the corresponding two providers totally disturb each other (the spectrum becomes unusable for the other provider), is also applicable with the interference compensation model (section 3.1) as these are based on the idea that if an allocation is feasible then all other allocations are also feasible that require equal amount or less spectrum. Similarly, if an allocation is not feasible then all other allocations are not feasible either, that require equal amount or more spectrum.

4.6 Conclusions

In this chapter I proposed an auction and pricing method for DSA systems. The model is centralised, i.e., there is a central entity, called spectrum broker, that based on the submitted demands and bids of the providers determines the optimal allocation, the prices to be paid by the providers and grants exclusive licenses to the bought spectrum blocks for the next re-allocation period.

The proposed method is suitable to use in a DSA environment, i.e.:

- it takes the specialities of DSA systems into account, it has to be able to adapt to the variations of spectrum demands in time and space;
- it supports a near real time operation, i.e., it has to determine the new prices and allocation scheme within one allocation period (about 1-2 hours in the framework);
- it enforces the providers to tell their real tolerance levels to the spectrum brokers, ensuring an effective DSA solution by making it desirable for the NSPs to use all available techniques to tolerate co-existence as much as possible.

Section 4.1 described the proposed model in more details, and discussed the operation of the spectrum brokers. Section 4.2 introduced allocation and pricing rules that yield an optimal solution that maximises the social welfare. The proposed pricing scheme also ensures that providers who do not tolerate others and interfere to a larger extent than necessary with other regions charged more.

For near real time operation a fast feasibility estimation method was proposed based on the fact that by fixing the slow varying parameters in the hyperspace of the requests the feasible and non-feasible allocations form two disjoint sets. It means that a feasibility estimation can be reduced to a set separation problem in a special hyperspace. Section 4.3 also gives a method to determine an interpolation of the separation hyper-surface by a union of hyper-planes ensuring a fast linear feasibility estimation.

The optimal allocation determination process was extended by a fast pre-filtering method based on an exclusion matrix derived from a grpah representation and a rule-based iterative algorithm for searching the most efficient feasible allocation.

I note, that the modularity of the DSA framework and the auction model ensures that alternative solutions could also be applied either for the allocation objective or for the pricing model. For example, one could go for an allocation that satisfies the demands within the smallest spectrum band in total, or have the objective to maximise income from the auctioneer's point of view instead of maximising welfare. The only thing to do in this case is to use the underlying DSA modelling framework and replace the allocation and pricing rules accordingly.

Chapter 5

Auction and Allocation in the Proposed Framework

The DSA framework proposed in Chapter 2, the spectrum allocation model proposed in Chapter 3, and the auction and pricing mechanisms proposed in Chapter 4 form the base building blocks of a DSA system. The aim of this Chapter is to describe how these building blocks cooperate with each other to enable an operating DSA system and to reveal the main properties of the proposed system.

First, Section 5.1 gives an overview on the allocation process and discusses each step in more details from the pre-calculation phase to the determination of the optimal allocation and the price that the providers have to pay for the allocated spectrum blocks.

Then Section 5.2 reveals the characteristics of the proposed auction and pricing method by a simple simulation example focusing on the property that the proposed pricing method charges providers who do not tolerate others and interfere with their neighbours more than necessary.

Finally, Section 5.3 presents some results from a larger simulation experiment.

5.1 Overview of an Allocation Process

This section follows the steps of a re-allocation process from the arrival of the providers' multi-bids until the spectrum block allocations and the prices to be paid for them is returned to the providers. We will detail the tasks of the spectrum broker and follow-up on the application of the concepts and methods introduced in earlier sections.

During the investigation of the re-allocation process we assume that the slow varying parameters (geographical and technology coupling parameters, interference tolerance parameters, size of the coordinated access band) remain constant. However, it is also non-trivial how these parameters are updated when they change. The second part of this section introduces this mechanism in details, too.

The flow chart of Figure 5.1 shows the detailed steps of a re-allocation process. The allocation procedure starts when the new multi-bids arrive from the providers at the beginning of an allocation period.

The first task is to find the most efficient feasible allocation. Following the methodology described in Section 4.5 the spectrum broker selects an allocation vector that is not covered by any rules, yet. Then it investigates the feasibility of the selected allocation vector. An exclusion matrix based pre-filtering proposed in Section 4.4 can also be used to exclude clearly not feasible allocations, but the core of this task is the fast feasibility estimation based on the methodology explained in Section 4.3.

If the selected allocation vector is not feasible a rule is added to the rule base and a different vector is selected. If the allocation is feasible after storing the corresponding rule, the process continues with checking the efficiency of the allocation. The feasible allocations are stored in descending order of efficiency. Due to the error of the estimation it is useful to store not only the most feasible allocation but a sort list of the best ones. If the efficiency of the allocation is higher than the most efficient one stored, the list is updated. If it is not the highest efficiency allocation another allocation vector is selected.

This continues until the most efficient allocation is found or a pre-defined threshold is reached.

Having collected the list of feasible allocations, the next task is to find the allocation with the minimal overall interference. For this the allocation with the highest efficiency is selected. Now its feasibility is checked with a detailed method that can be an exhaustive search or a heuristic method, e.g., Simulated Annealing described in Section 3.2.6. If the selected allocation turns out to be non-feasible the allocation with the next highest efficiency is selected and the feasibility check is repeated.

If the allocation is confirmed to be feasible, the minimal interference allocation is determined (according to Section 3.1.3). For this the same methods can be used as in the previous case of feasibility check. The most efficient feasible allocation with minimal interference is stored for sending it to the providers later, and the winning bids are selected, too.

Having the most efficient feasible allocation, the next step is the calculation of prices to be paid by the providers. For this an "opponent profile" is determined for each of the winning bids (see Section 4.2). For the opponent profile the whole procedure is repeated from the determination of the most efficient feasible allocation except that the minimal interference allocation does not need to be calculated in this case.

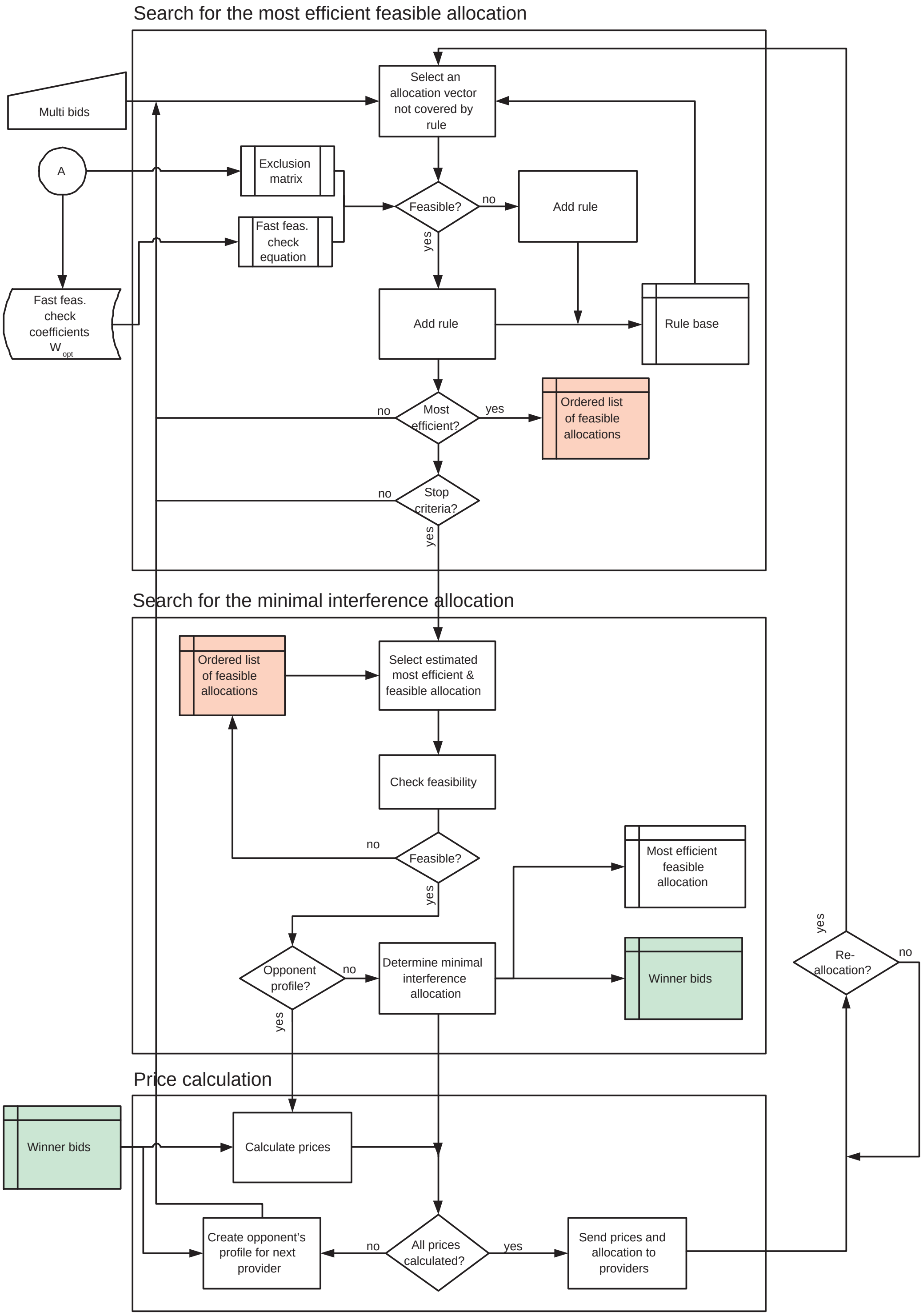


Figure 5.1: Allocation process.

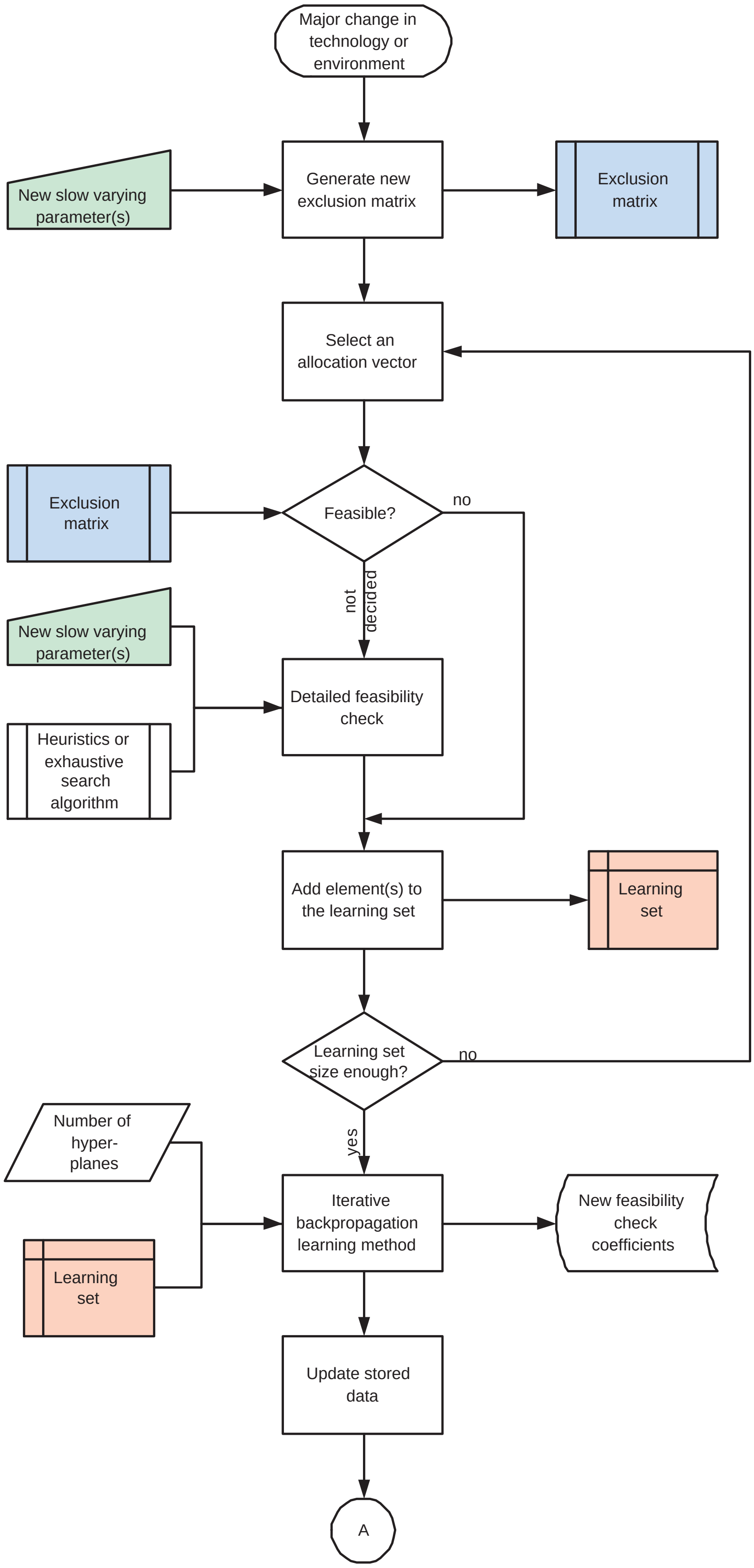


Figure 5.2: Updating the slow varying parameters.

The prices for one winning bid are calculated based on the opponent's profile. When the prices are calculated for all winning bids the spectrum broker sends the prices to be paid for the spectrum blocks of the next allocation period to the providers together with the assignment determining which provider can use which spectrum blocks to respect the feasibility conditions.

After sending the new parameters to the providers the spectrum broker waits for the next re-allocation period when the procedure starts over again.

During each of the re-allocation periods the slow varying parameters can be considered constant. Their value only changes when a major change occurs in the operating environment, e.g., a new transmission technology is introduced or a new building is constructed. In these rare cases the update of the coefficients of the fast feasibility estimation is needed; this is shown in Figure 5.2.

The update process is triggered by a major change in the technology or environment. Knowing the changed parameter first a new exclusion matrix is generated and stored for use in the learning set construction phase. Then an allocation vector is chosen randomly and, with the new exclusion matrix, a pre-filtering on the selected allocation is performed. This method is only able to determine if an allocation is non-feasible. If it is "not non-feasible" a detailed feasibility check needs to be run to state if the allocation is feasible. Either case the allocation with the feasibility information is added to the Learning Set used later. I note, that by evaluating one allocation we get information about the feasibility of several other allocations because of the special structure of the allocation vectors described in Section 4.3.1. Therefore we can add several samples to the learning set by evaluating one.

After extending the learning set, a next allocation vector is selected with which the above described process is repeated. The iteration stops when the size of the Learning Set is considered big enough (e.g., a pre-defined threshold of parameters, allocation and feasibility information pairs is reached).

Then the constructed Learning Set together with the specified number of hyper planes is fed to an iterative backpropagation learning method (e.g., a neural network) that will determine the equations of the set separating hyper surfaces and so give the new feasibility estimation coefficients (as described in details in Section 4.3.1).

The only remaining task is to update the co-efficients of the feasibility estimation and the exclusion matrix in the allocation process according to the new parameters.

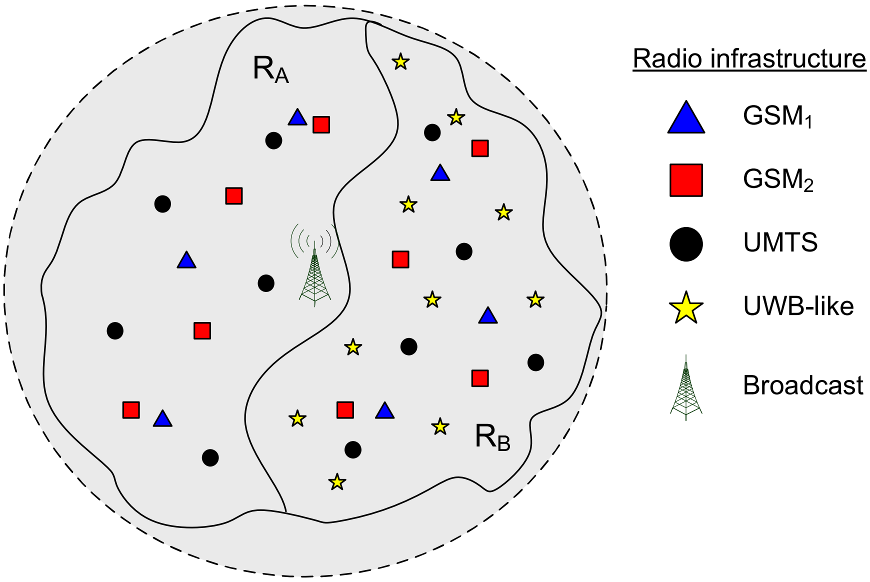


Figure 5.3: Simple scenario.

5.2 Properties of the Proposed Auction and Pricing Method

The goal of this section is to show how the proposed model takes the specialities of the dynamic spectrum allocation into account. The features of the proposed pricing and allocation scheme are demonstrated by a simple simulation scenario. The simplicity of this scenario allows us to examine an allocation in a detailed way. It also enables us to observe the characteristics of the allocation and pricing methods, to show the effect of the model parameters on the unit price of the allocated spectrum blocks. That is to show that the model charges providers who do not tolerate others and interfere to a larger extent than necessary and on the other hand it favours techniques with high interference tolerance. This makes it desirable for the NSPs to use all available techniques to tolerate co-existence as much as possible.

5.2.1 Simulation Scenario

Consider a simple scenario with two regions as shown on Figure 5.3. One UMTS and two GSM providers operate in both regions within the CAB (the size of the CAB is set to 35 MHz). In addition, in region A there is a broadcast provider (e.g., DVB-T) that covers region B, too. Furthermore, in region B a "UWB-like" provider is also present, that does not cause significant interference to other providers, and tolerates interference. (In the followings we refer to this provider as UWB.)

$\eta^{[dB]}$	GSM-1	GSM-2	UMTS	UWB	BC
GSM-1	−20	−5	−20	−30	−3
GSM-2	−5	−20	−20	−30	−3
UMTS	−20	−20	−23	−30	−3
UWB	−200	−200	−200	−200	−200
BC	−10	−10	−23	−30	−1

Table 5.1: Radio technology coupling parameters $\eta_{m,n}$.

ε	A	B
A	640	0.988
B	0.988	640

Table 5.2: Geographic coupling parameters ε.

5.2.2 Input Parameters

The DSA model is parameterized by matrices η (Table 5.1) and ε (Table 5.2) and vectors s_{max}, α and β (Table 5.3). In this scenario we set α equal to β.

Recall, that the calculation of the values of these parameters is described in Appendix A. For a detailed discussion on the meaning of the parameters please refer to Section 3.2.2.

Briefly, matrix η shows the radio technology coupling parameters between the NSPs. The smaller this value, the better it is from the interference's point of view. By looking at the elements of matrix η in Table 5.1 we can see that the radio technology used by the UWB provider does not affect, and is not affected significantly by, other providers ($\eta << 1$).

Table 5.2 shows the geographic coupling parameters between the regions. $\varepsilon_{k \leftarrow l}$ denotes a kind of general attenuation parameter for the radio signals of providers operating in region R_l that can be "heard"as interference in region R_k. The smaller this value the better it is from the interference's point of view. I assumed that the power spectral density at the border of a given region cannot exceed s^{max}, but inside the region this value can be much higher—this is modelled by $\varepsilon >> 1$.

Table 5.3 shows the maximum (α) interference tolerance parameters of the providers.

	GSM-1	GSM-2	UMTS	UWB	BC
s_{max}	−95.1	−95.1	−96.86	−196.31	−111.76
α	−105.1	−105.1	−85.86	−96.31	−125.76

Table 5.3: Maximal signal density at the borders (s_{max}) and maximum interference tolerance parameters (α_m) in [dBm/kHz].

	R_A	R_B
GSM-1	$B_1 = \{(5,40),(\mathbf{7},54)\}$	$B_2 = \{(5,40),(\mathbf{7},54),(10,72)\}$
GSM-2	$B_3 = \{(\mathbf{5},35),(7,47)\}$	$B_4 = \{(5,40),(7,54),(\mathbf{10},72)\}$
UMTS	$B_5 = \{(5,30),(10,55),(\mathbf{15},75),(20,90)\}$	$B_6 = \{(5,30),(\mathbf{10},55),(15,75)\}$
UWB	$B_7 = \emptyset$	$B_8 = \{(\mathbf{20},50)\}$
Broadcast	$B_9 = \{(\mathbf{8},80),(12,100)\}$	$B_{10} = \emptyset$

Table 5.4: Multi-bids at 6am (winning bids in bold).

The larger this value, the more tolerant the provider is with respect to interference. From Table 5.3 we can see, that the interference tolerance of GSM-1 and GSM-2 are similar and less than that of UMTS, meaning that they tolerate interference less. The “Broadcast” provider has much lower tolerance level, which practically means that it requires an exclusive use of the allocated spectrum block.

Recall that Figure 4.2 in Section 4.1 shows an example for the demand function, that represents the amount of spectrum that a provider would request as a function of the unit spectrum price. As the unit price of a spectrum block increases, the providers' demands decrease. On the right side the bids $q_{1,j}$ are shown on a bar graph using different colors that can be interpreted as follows. If the prices are high the provider only pays for the minimum amount of spectrum that is absolutely necessary to provide minimal basic services (black). In case of cheaper spectrum it would pay for an additional spectrum block to provide, let us say, value-added services (grey). When the radio resource is cheap it is worth for the provider to buy even more spectrum for some kind of premium services (white).

According to Figure 4.2, Figure 5.4 shows the spectrum demands for all NSPs in both regions I used as inputs for this simulation.

5.2.3 Simulation Results

In this scenario the spectrum was reallocated in every two hours. The optimal allocations and the total prices were calculated based on the allocation and pricing rules described in Section 4.2.

As an example, Table 5.4 lists the multi-bids of the providers at 6am (see also Figure 5.4), while Table 5.5 shows the optimal and feasible allocations and the prices for the providers. The c/q columns in Table 5.5 show the unit price for each provider.

Results show that the “Broadcast” provider pays far the most, since it covers both regions and its tolerance level is low. Note, however, that the “Broadcast” provider uses the allocated frequencies in both regions, so the average unit price is only 4.56 for one

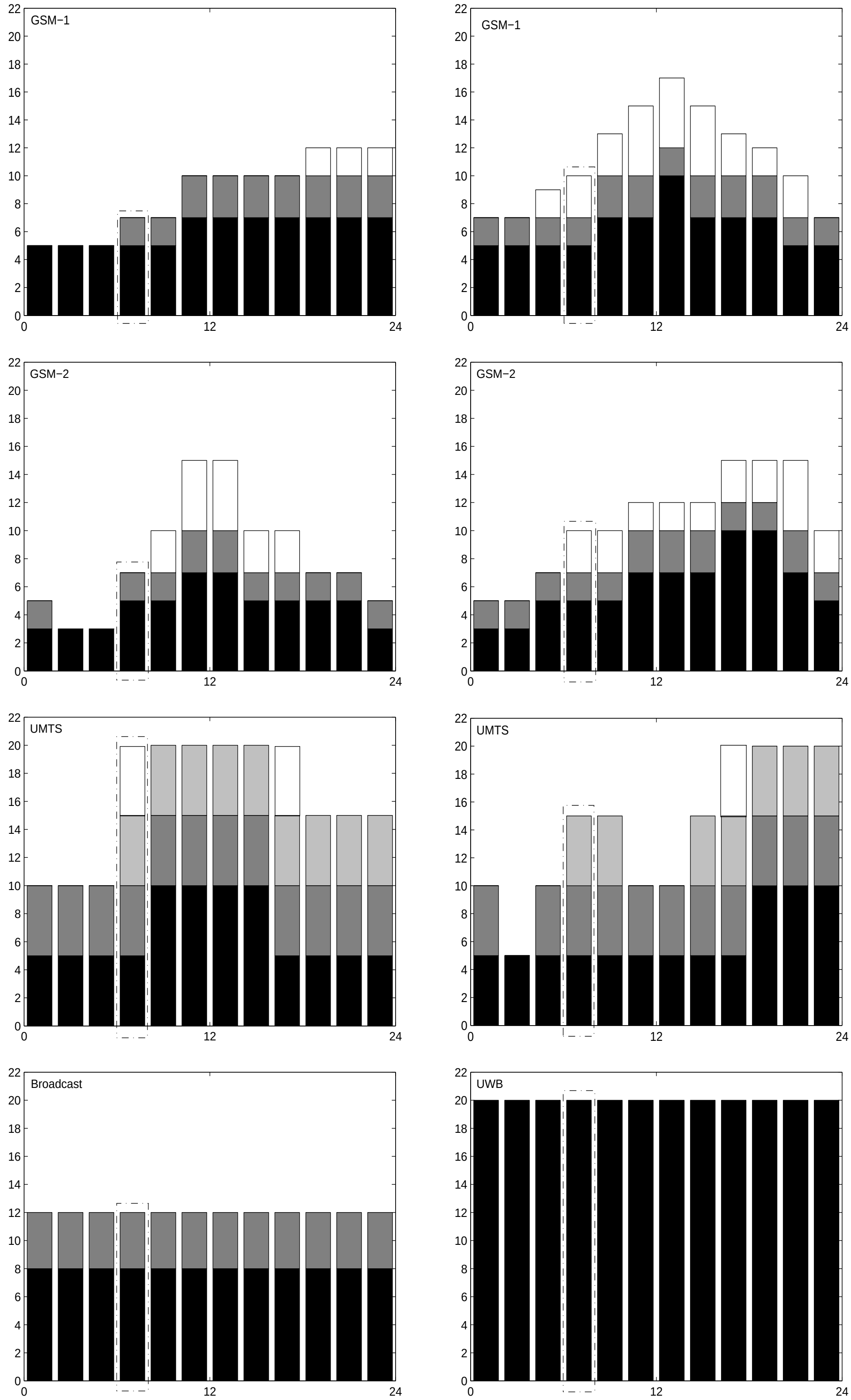


Figure 5.4: Spectrum demands in regions A (left) and B (right).

	R_A		R_B	
	(q, c)	c/q	(q, c)	c/q
GSM-1	$(7, 27)$	3.85	$(7, 20)$	2.85
GSM-2	$(5, 15)$	3.00	$(10, 38)$	3.80
UMTS	$(15, 12)$	0.80	$(10, 18)$	1.80
UWB	–	–	$(20, 0)$	0.00
Broadcast	$(8, 73)$	9.12	–	–

Table 5.5: Optimal allocation and the prices for the providers at 6am.

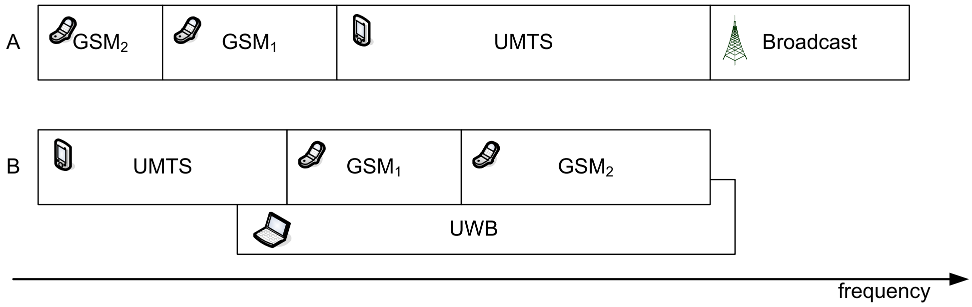


Figure 5.5: The minimal interference spectrum allocations between 6am and 8am.

region. In contrast, the price to pay for the UWB provider in Table 5.5 is zero, since it practically does not interfere with the other NSPs. I note that it can also be interpreted the way that there is a base fee for a spectrum block that each provider has to pay and an additional amount is charged according to the tolerance levels. Since the UMTS provider is more tolerant than the GSM providers, the unit price it has to pay is smaller than that of the GSM providers.

I note, that price depends not only on the model parameters, but on the interference the providers cause to each other, as well—since the idea of determining the cost of the players in case of second-price auctions is that the player (in our case the provider) should pay for the "loss" its presence causes to other providers.

The minimal interference spectrum allocation is shown on Figure 5.5. The allocated frequency bands reveal, that the UWB provider can live together with other providers using essentially the same spectrum. On the other hand, the "Broadcast" provider plays a lone hand, but pays for doing that.

The allocated spectrum blocks for GSM and UMTS are disjoint within the regions, but they are partially overlapping between regions (as well as the same GSM providers). Since the geographic coupling between the two regions is nonzero, there is some interference between providers operating in neighboring regions within the same frequency band. However, the interference tolerance parameters allow this to a certain extent.

ε	R_0	R_1	R_2	R_3	R_4	R_5	R_6
R_0	640	0.988	0.988	0.988	0.988	0.988	0.988
R_1	0.988	640	0.988	$4.425e-17$	$2.666e-17$	$4.425e-17$	0.988
R_2	0.988	0.988	640	0.988	$4.425e-17$	$2.666e-17$	$4.425e-17$
R_3	0.988	$4.425e-17$	0.988	640	0.988	$4.425e-17$	$2.666e-17$
R_4	0.988	$2.666e-17$	$4.425e-17$	0.988	640	0.988	$4.425e-17$
R_5	0.988	$4.425e-17$	$2.666e-17$	$4.425e-17$	0.988	640	0.988
R_6	0.988	0.988	$4.425e-17$	$2.666e-17$	$4.425e-17$	0.988	640

Table 5.6: Geographic coupling parameters ε.

5.3 Operating in a Realistic Environment

The goal of this section is to examine how the proposed model takes the specialities of DSA into account in a realistic environment. Due to the large number of players it is hard to follow each step of the allocation process, as done in the previous section, but we can observe the operation of the allocation and pricing method through the average unit price of the different providers.

5.3.1 Simulation Scenario

In this scenario we have 7 regions, R_0 is in the middle and there are 6 regions around it. The diameter of each region was set to 10 km, the geographic coupling parameters (see Table 5.6) were calculated according to equation (A.1).

There are two GSM, two UMTS, one DVB-T and one "UWB -like" providers operating in the modelled area. Some providers are present in all regions while others operate only in some areas. The DVB-T provider (called as Broadcast provider) operates only in region R_0 but covers all regions.

The radio specific parameters of the providers – e.g., transmitting power (P_T $[dBm]$), minimal signal to interference and noise ratio ($SINR_{min}$ $[dB]$), typical cell area radius (r_{typ} $[km]$), maximal required frequency bandwidth (B_r $[kHz]$), base station antenna gain (G_B $[dBi]$),base station antenna height (h_B $[m]$), terminal station antenna height (h_T $[m]$) and typical carrier frequency (f $[kHz]$) – used for the calculation of the technology coupling parameters and maximum signal density parameters are discussed in Appendix A. Since I used the same settings for the detailed example in Section 5.2 the parameter values are the same as in Table 5.3 and Table 5.1.

The size of the Coordinated Access Band is the same as in the previous scenario, i.e., 35 Mhz.

LEARNING SET		
Number of samples:	6600	(100%)
Feasible samples:	2945	(44.6 %)
Non-feasible samples:	3655	(55.4 %)
- by exclusion matrix:	3179	(48.2%)
- by simulated annealing:	476	(7.2%)

Table 5.7: Learning set.

The reallocation period was set to two hours, and the simulation time was a whole day. Requests are determined the way that three different types of regions can be separated. There is a “business quarter”like area, where requests are typically high during the day, and lower in the evening hours. In the “residential”part of the simulated area requests are typically high in the evening. The third part of the area is a “transient” area where there are medium requests during the whole day except at dawn[1].

The shapes of the provider’s bids are the following (for details please refer Appendix B):

- The bids of the DVB-T provider are 8 Mhz from 0:00 a.m. to 6:00 p.m. and 8 Mhz basic plus 4 Mhz extra spectrum from 6:00 p.m. to 12 p.m.;
- the UWB provider requests always 20 Mhz spectrum;
- the other provider’s requests follow one of the ”business area shape“ or ”residential area shape”or “constant shape”demands.

The fast feasibility estimation coefficients were calculated based on a learning set that contained 6600 elements (see Table 5.7 for the components of the learning set). In this scenario we can see, that 87% of the non-feasible allocations was filtered out by the exclusion matrix, greatly improving the speed of the learning set construction.

5.3.2 Simulation Results

In this scenario the spectrum was reallocated in every two hours. The optimal allocations and the total prices were calculated based on the allocation and pricing rules described in Section 4.2.

Table 5.8 shows the average unit price of the providers for all regions over the whole time period. Similar to the results of Section 5.2, the DVB-T provider pays far the most, since it covers all regions and its tolerance level is low. In contrast, the price to pay for

[1]These shapes are valid only for the sum of the requests, different providers can have different demand shapes in the same region.

Provider	$c_{avg} = \sum p / \sum q$
GSM-1	2.65
GSM-2	2.4
UMTS-1	1.35
UMTS-2	0.9
Broadcast	22.8
UWB	–

Table 5.8: Average prices for all regions

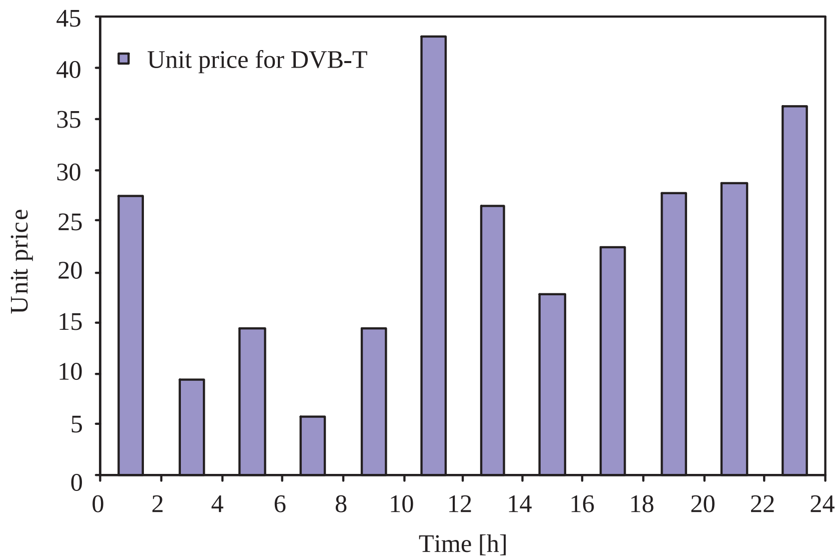


Figure 5.6: The unit price for Broadcast provider as a function of time.

the UWB provider in Table 5.8 is zero, since it practically does not interfere with the other NSPs. Since the UMTS providers are more tolerant than the GSM providers, the unit price they have to pay are smaller than that of the GSM providers.

As an example, Figure 5.6 shows the unit price of the "Broadcast" provider as a function of time. Results show that the "Broadcast" provider has to pay very much, since it covers all regions and its tolerance level is low. Since it covers all regions we can also seen that the spectrum is especially costly when there are busy hours in the neighboring regions. That is in the middle of the day (when the requests in the "business quarter" regions are very high, and in the evening hours, when there is a peak of the requests in the "residential area" regions.

Chapter 6

Summary of the Dissertation

Spectrum is an important factor for new business development. It is a limited, valuable and thus expensive resource and must be managed efficiently. The major challenge is to develop a spectrum management framework that is commonly applicable independently of technologies and services. Such a framework is needed not only to satisfy the engineering, economic and policy challenges of future spectrum usage, but also to satisfy increasing end user demands. Dynamic spectrum allocation is a promising approach to fully utilise the scarce spectrum resources.

The objective of the dissertation was twofold. In the first part the goal was to establish a dynamic spectrum allocation framework that provides the possibility to replace today‘s rigid spectrum allocation method by a market based dynamic solution. The goal of the second part was to propose an adequate, real time auction and pricing DSA management framework that takes the specialities of dynamic spectrum allocation into account.

6.1 Spatio-Temporal DSA Framework

Chapter 2 described a general modelling framework that is able to model the interaction between different service providers operating in different parts of the area of a dynamic spectrum access network and introduced two general coupling parameters (geographical coupling and radio technology coupling) to describe the interference arising in the system in a flexible and general way. Furthermore, based on these parameters it proposed metrics characterising the quality of the spectrum band B available for the m-th provider in the k-th region. The main assumptions of the proposed framework were the following:

- equal-right, centralised DSA;
- the available area is divided into smaller regions, inside a region the spatial distribution

of the demands is homogeneous;

- time is divided into allocation periods; one allocation period is in the order of hours (batched request processing);
- service providers can have different demands in different regions and demands may vary in time;
- inside the regions, besides given conditions, service providers can use the allocated spectrum for whatever they want (service and technology neutrality requirement).

In Chapter 2 I also proposed several metrics to use for the comparison of DSA and rigid allocation systems.

6.2 Spectrum Allocation Models

A great advantage of the framework I proposed comes from its flexibility and modularity. Within this framework different allocation models may be used. In Chapter 3 I proposed two different models to characterise the providers' relation to interference. The proposed two models have very different approaches to describe the effect of interference for the allocated spectrum blocks.

The *interference compensation model* discussed in Section 3.1 based on the assumption that the interference causes service degradation and it can be compensated by allocating additional spectrum blocks for the provider.

The *interference tolerant model* discussed in Section 3.2 is based on the idea that interference arising between the providers is tolerated as long as it is below a pre-defined threshold.

I also gave for both models the feasibility conditions and proposed algorithms to determine the optimal allocations from the following two points of view:

- I gave an algorithm to determine the allocation that results the highest guaranteed regulator gain for both models. That is the smallest amount of spectrum enough to serve the given demand set and the assignment determining which spectrum block has to be allocated to which provider in order to respect the feasibility conditions.
- I also gave an algorithm to determine, having a determined amount of spectrum (S_{CAB}), whether the given demand set is feasible or not, i.e., is there an allocation that respects the feasibility conditions? Since usually if the demand set is feasible then several feasible allocations exist, the proposed algorithm can select the feasible allocation with minimal overall interference.

Finally, I demonstrated the operation of the models with simulation examples. The results were also compared to two other proposals.

6.3 Real Time Auction and Pricing

In a DSA scenario where tolerance is much rewarded by increasing spectral efficiency, certain mechanisms need to be implemented to make it desirable for the NSPs to use all available techniques to tolerate co-existence as much as possible. A proper pricing scheme that charges providers who do not tolerate others and interfere to a larger extent than necessary with other regions would be of great importance.

In Chapter 4 I proposed an auction and pricing method for DSA systems. The model is centralised, i.e., there is a central entity, called spectrum broker, that, based on the submitted demands and bids of the providers, determines the optimal allocation, the prices to be paid by the providers and grants exclusive licenses to the bought spectrum blocks for the next re-allocation period.

The proposed method is suitable to use in a DSA environment, i.e.:

- it takes the specialities of DSA systems into account, it has to be able to adapt to the variations of spectrum demands in time and space,

- it supports a near real time operation, i.e., it has to determine the new prices and allocation scheme within one allocation period (about 1-2 hours in the framework),

- and it enforces the providers to tell their real tolerance levels to the spectrum brokers.

Section 4.1 described the proposed model in more details, and discussed the operation of the spectrum brokers. Section 4.2 introduced allocation and pricing rules that yield an optimal solution that maximises social welfare.

For near real time operation a fast feasibility estimation method was proposed based on the fact that by fixing the slow varying parameters in the hyperspace of the requests the feasible and non-feasible allocations form two disjoint sets. It means that a feasibility estimation can be reduced to a set separation problem in a special hyperspace. Section 4.3 also gives a method to determine an interpolation of the separation hyper-surface by a union of hyper-planes ensuring a fast linear feasibility estimation.

The optimal allocation determination process was extended by a fast pre-filtering method based on an exclusion matrix derived from a graph representation and a rule based iterative algorithm for searching the most efficient feasible allocation.

6.4 Applicability of the Results

The general framework and proposed metrics in Chapter 2 can form the basis of comparison of future systems using dynamic spectrum allocation and the valuation of achievable gains. The interference tolerant and interference compensation models, discussed in Chapter 3, present two different approaches; with the current technological advances the interference tolerant model will soon allow the realisation of dynamic spectrum allocation systems. The interference compensation model can be realised in the future when the technological issues of its application are solved.

Chapter 4 proposes an auction and pricing solution that is capable to transact periodic spectrum auctions in future dynamic spectrum allocation systems. The proposed method takes the specialities of dynamic spectrum allocation into account, the real price to be payed depends on interference caused by the providers and their noise tolerance level, too. These characteristics encourage the appearance of new, innovative technologies in the market that are able to tolerate disturbances and impose a minimal interference on other technologies present around them.

I note, that the modularity of the DSA framework and the auction model ensures that alternative solutions could also be applied either for the allocation objective or for the pricing model. The only thing to do in this case is to use the underlying DSA modelling framework and replace the allocation model and the allocation and pricing rules accordingly.

Appendix A

Some Remarks on Simulation Parameter Settings

The following radio parameters are taken into account for each NSP in the simulation examples: transmitting power (P_T $[dBm]$), minimal signal to interference and noise ratio ($SINR_{min}$ $[dB]$), typical cell area radius (r_{typ} $[km]$), maximal required frequency bandwidth (B_r $[kHz]$), and base station antenna gain (G_B $[dBi]$). Note, that for broadcast systems where the covered area is larger than the size of the region where the transmitter operates, r_{typ} is set to be equal to the area radius.

Although the following parameters could be provider dependent as well, I calculate with constant base station antenna height (h_B $[m] = 30$), terminal station antenna height (h_T $[m] = 1.5$) and carrier frequency (f $[kHz] = 2000$) for all NSPs for simplicity.

In the example scenarios there are five different NSPs whose radio technology parameters are listed in Table A.1.

	GSM_1	GSM_2	UMTS	Broadcast	UWB-like
P_T $[dBm]$	40	40	40	50	-63
G_B $[dBi]$	17	17	17	17	5
$SINR_{min}$ $[dB]$	10	10	-11	14	-100
r_{typ} $[km]$	0.3	0.3	0.3	1.5	0.1
B_r $[kHz]$	10000	10000	15000	16000	20000

Table A.1: NSP dependent radio technology model parameters.

A.1 Geometrical Coupling and Radio Technology Coupling Parameters

The geographical coupling parameter $\varepsilon_{k\leftarrow l}$ gives the signal attenuation due to propagation from region R_l to R_k. According to the Okumura-Hata propagation model for urban (medium city) environment [35], parameter $\varepsilon_{k\leftarrow l}$ can be calculated as

$$\varepsilon_{k\leftarrow l}^{[dB]} = -A^{[dB]}\left(d_{k,l}^{[km]}\right) = -130.52 - 35.22 \cdot \lg\left(d_{k,l}^{[km]}\right) \tag{A.1}$$

where attenuation A depends on the distance $d_{k,l}^{[km]}$ between regions R_k and R_l. The distance between two regions is interpreted as the smallest distance between the region borders. Note, that for neighbouring sectors $\varepsilon_{k\leftarrow l}$ is approximately one and (A.1) can be used only in case of bigger distances (non-neighbouring regions). For neighbouring regions we can calculate ε the following way: let us assume that the closest tower is 300m from the border (calculating with average cell radius); now we would like to achieve that on the other side of the border (i.e. 301m from the tower) this tower does not cause harmful interference. So we have to consider the attenuation differences ($0.988 = 10^{(-A(0.301)-A(0.3))/10}$) for the calculation of ε.

The value of the radio technology coupling parameters η can be determined by detailed simulations. This parameter aims at describing the "extent of coexistence"of different radio technologies. Its value is influenced by a number of characteristics of the used technology (e.g., signal processing technology, synchronization, advance knowledge, etc.).

A.2 Interference Tolerance Parameters

The maximum spectral density at the region border (s^{max}) can be calculated as

$$s^{max[dBm/kHz]} = P_{max}^{[dBm]} - 10 \cdot \lg B_r^{[kHz]}, \tag{A.2}$$

where

$$P_{max}^{[dBm]} = P_T^{[dBm]} + G^{[dBi]} - A\left(r_{typ}^{[km]}\right). \tag{A.3}$$

The maximal tolerable interference power (I_{max}) for an NSP can be determined from its $SINR_{min}$ parameter as

$$I_{max}^{[dBm]} = P_{max}^{[dBm]} - SINR_{min}^{[dB]}. \tag{A.4}$$

Thus, the average interference tolerance parameter β is given by

$$\beta^{dBm/kHz} = I^{[dBm]} - 10 \cdot \lg B^{[kHz]}. \tag{A.5}$$

We set parameter α higher than β by 2dB uniformly for all NSPs in the illustrative example simulation in Section 3.2.5, i.e.,

$$\alpha^{[dBm/kHz]} = \beta^{[dBm/kHz]} + 2dB. \tag{A.6}$$

For the simulations discussed in Section 5.2 we used the $\alpha^{[dBm/kHz]} = \beta^{[dBm/kHz]}$ settings.

Appendix B

Multi-Bids of Providers for the Realistic Scenario

This appendix contains the multi-bids of the providers used in the realistic simulation scenario of Section 5.3. The UWB provider requests 20 MHz of spectrum continuously, and for them offers a price of 40. The DVB-T provider's bids are 8 MHz from 0 a.m. to 6 p.m. and offers a price of 300; and 8 MHz basic plus 4 MHz extra from 6 p.m. to 12 p.m. and offers a price of 360 for the basic and 520 for the basic and extra spectrum.

The multi-bids of providers GSM-1, GSM-2, UMTS-1 and UMTS-2 are shown in tables B.1-B.4, respectively.

GSM-1	R_0, R_3, R_4	R_1, R_2	R_5, R_6
t_0	$\{(2,12),(4,16)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_1	$\{(2,12),(4,16)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_2	$\{(2,12),(4,16)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_3	$\{(4,24),(6,28)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_4	$\{(4,24),(6,32),(8,36)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_5	$\{(4,24),(8,40),(10,44)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_6	$\{(4,24),(8,40),(10,44)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_7	$\{(4,24),(6,32),(8,36)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_8	$\{(4,24),(6,28)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_9	$\{(2,12),(4,16)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_{10}	$\{(2,12),(4,16)\}$	$\{(4,24),(6,28)\}$	$\emptyset$
t_{11}	$\{(2,12),(4,16)\}$	$\{(4,24),(6,28)\}$	$\emptyset$

Table B.1: Multi-bids of GSM-1 provider.

GSM-2	R_0, R_3, R_4	R_1, R_2	R_5, R_6
t_0	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(4,24),(6,32),(7,34)\}$
t_1	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(2,12),(3,14)\}$
t_2	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(2,12),(3,14)\}$
t_3	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(2,12),(4,20),(5,22)\}$
t_4	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(2,12),(4,20),(5,22)\}$
t_5	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(2,12),(4,20),(5,22)\}$
t_6	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(2,12),(4,20),(5,22)\}$
t_7	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(2,12),(4,20),(5,22)\}$
t_8	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(4,24),(6,32),(7,34)\}$
t_9	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(4,24),(8,40),(9,42)\}$
t_{10}	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(4,24),(8,40),(9,42)\}$
t_{11}	$\{(4,24),(6,28)\}$	$\emptyset$	$\{(6,36),(8,44),(9,46)\}$

Table B.2: Multi-bids of GSM-2 provider.

UMTS-1	R_0, R_3, R_4	R_1, R_2	R_5, R_6
t_0	$\{(2,10),(4,12)\}$	$\{(8,40),(12,52),(14,54)\}$	$\{(5,25)\}$
t_1	$\{(2,10),(4,12)\}$	$\{(4,20),(6,22)\}$	$\{(5,25)\}$
t_2	$\{(2,10),(4,12)\}$	$\{(4,20),(6,22)\}$	$\{(5,25)\}$
t_3	$\{(4,20),(6,22)\}$	$\{(4,20),(8,32),(10,34)\}$	$\{(5,25)\}$
t_4	$\{(4,20),(6,26),(8,28)\}$	$\{(4,20),(8,32),(10,34)\}$	$\{(5,25)\}$
t_5	$\{(4,20),(8,32),(10,34)\}$	$\{(4,20),(8,32),(10,34)\}$	$\{(5,25)\}$
t_6	$\{(4,20),(8,32),(10,34)\}$	$\{(4,20),(8,32),(10,34)\}$	$\{(5,25)\}$
t_7	$\{(4,20),(6,26),(8,28)\}$	$\{(4,20),(8,32),(10,34)\}$	$\{(5,25)\}$
t_8	$\{(4,20),(6,22)\}$	$\{(8,40),(12,52),(14,54)\}$	$\{(5,25)\}$
t_9	$\{(2,10),(4,12)\}$	$\{(8,40),(16,64),(18,66)\}$	$\{(5,25)\}$
t_{10}	$\{(2,10),(4,12)\}$	$\{(8,40),(16,64),(18,66)\}$	$\{(5,25)\}$
t_{11}	$\{(2,10),(4,12)\}$	$\{(12,60),(16,72),(18,74)\}$	$\{(5,25)\}$

Table B.3: Multi-bids of UMTS-1 provider.

UMTS-2	R_0, R_3, R_4	R_1, R_2	R_5, R_6
t_0	$\{(5,25),(10,30)\}$	$\{(10,50),(15,65)\}$	$\{(10,50),(15,65)\}$
t_1	$\{(5,25),(10,30)\}$	$\{(5,25),(10,30)\}$	$\{(5,25),(10,30)\}$
t_2	$\{(5,25),(10,30)\}$	$\{(5,25),(10,30)\}$	$\{(5,25),(10,30)\}$
t_3	$\{(10,50),(15,55)\}$	$\{(5,25),(10,40)\}$	$\{(5,25),(10,40)\}$
t_4	$\{(10,50),(15,65),(20,70)\}$	$\{(5,25),(10,40)\}$	$\{(5,25),(10,40)\}$
t_5	$\{(10,50),(20,80),(25,85)\}$	$\{(5,25),(10,40)\}$	$\{(5,25),(10,40)\}$
t_6	$\{(10,50),(20,80),(25,85)\}$	$\{(5,25),(10,40)\}$	$\{(5,25),(10,40)\}$
t_7	$\{(10,50),(15,65),(20,70)\}$	$\{(5,25),(10,40)\}$	$\{(5,25),(10,40)\}$
t_8	$\{(10,50),(15,55)\}$	$\{(10,50),(15,65)\}$	$\{(10,50),(15,65)\}$
t_9	$\{(5,25),(10,30)\}$	$\{(10,50),(20,80),(25,85)\}$	$\{(10,50),(20,80),(25,85)\}$
t_{10}	$\{(5,25),(10,30)\}$	$\{(10,50),(20,80),(25,85)\}$	$\{(10,50),(20,80),(25,85)\}$
t_{11}	$\{(5,25),(10,30)\}$	$\{(15,75),(20,90),(25,95)\}$	$\{(15,75),(20,90),(25,95)\}$

Table B.4: Multi-bids of UMTS-2 provider.

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