Real-Time Spectrum Access in Heterogeneous Wireless Networks

Competition, Deployment and Pricing

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Licentiate Thesis in Radio Communication Systems
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Abstract

The first decade of twenty-first century has witnessed the spread of innovative wireless technologies: novel wireless network architectures and services, operations in unlicensed bands, advanced mobile devices and smartphones. All these have pondered growing demand for wireless broadband services, so that more spectra are required. Consequently, the advent of flat-rate service pricing for mobile broadband services plus continuous investments in a network infrastructure and shortage of licensed spectrum make it more difficult for current wireless operators (OPs) to financially sustain themselves in a competitive environment.

Since existing, fixed spectrum allocation (FSA), mechanism offers very limited flexibility, dynamic spectrum access from the market point of view is exploited here to support such flexibility. A framework of competitive spectrum access, where available spectrum can be leased based on the outcome of competition between heterogeneous wireless operators in a short-term fashion, is reviewed in this thesis. The main objectives are: (1) to maximize spectrum efficiency by utilizing market mechanisms in a heterogeneous setting, and (2) to identify which conditions and criteria should be applied to allow heterogeneous wireless networks to be viable in the marketplace.

Under the competitive spectrum access framework, we explore three directions to tackle these objectives for a case of a two-operators system. First, we will look at how an inter-operator competition can affect the operator profits under an asymmetry in their networks. Then, we will analyze which deployment strategies in a heterogeneous environment should be utilized. Finally, we will consider which pricing strategies can be applied by competing OPs to sustain themselves. Through analysis and extensive simulations, we show that heterogeneous access architectures and the scalable infrastructure deployment could improve not only spectrum utilization efficiency, but also facilitate viability of spectrum allocation in a competitive environment. As a conclusion, we believe that techno-economical approach used to assess a feasibility of the framework could help in the designing of future wireless systems to efficiently utilize both the infrastructure and the spectrum resource.
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List of Abbreviations

AP Access Point
BS Base Station
CAPEX Capital expenditures
CSA Competitive Spectrum Allocation
DSA Dynamic Spectrum Allocation
ICT Information and Communication Technology
ISPs Internet Service Providers
MVNOs Mobile Virtual Network Operators
OPEX Operational Expenditures
OPs Operators
RRM Radio Resource Management
QoS Quality of Service
SP Service Provider
WLAN Wireless Local Area Network
Part I
Chapter 1

Introduction

This thesis focuses on the main challenges for radio resource management within the context of market mechanisms. In this chapter, we will present the background based on trends in spectrum management regime, multi-operator competition, heterogeneous networks, and best practices on pricing and deployment strategies that could be implemented for such networks under competition and market regime.

1.1 Background

1.1.1 Demand for Mobile Broadband Services

The demand for wireless services continues to grow with the increasing popularity of Internet-enabled handheld devices, mobile applications and social networking [1]. Several forecasts have predicted the expected mobile data traffic levels with the growth in the number of cell sites (see in Figure 1.1) ①.

Traditionally, network operators have overcome the growth of traffic demand by:

1. having more available spectrum
2. increasing the number of cell sites
3. using an advanced technology (i.e., increase in spectrum efficiency)

1.1.2 Shift in Radio Resource Management (RRM)

Radio spectrum is a limited resource used for commercial and public purposes. Up to date spectrum was managed based on the “command and control” [2] approach to allocate and assign to spectrum licenses whilst ensuring an interference-protected spectrum. In order to accomplish this, radio spectrum was divided between different

①Available online on:http://www.ericsson.com
services and technologies. However the use of spectrum became rather inflexible and inefficient due to rigid regulations.

Consequently, the demand for spectrum grew. In order to tackle the inefficiency of spectrum utilization with the “command and control” regime, some candidate-regimes were proposed. Likewise, many governmental agencies and organizations have initiated and established activities toward spectrum liberalization and spectrum trading.

1.1.3 Market Mechanisms in RRM

Spectrum market mechanisms are mainly based on the concept of spectrum property rights with a trading capability. The potential benefits of introducing spectrum markets mechanisms which are widely acknowledged. Those are mainly:

i) maximizing economic efficiency

ii) improving spectrum utilization

More particularly, market mechanisms can be subdivided into: spectrum leasing, spectrum trading and pricing, and auctions (see Figure 1.2). Until now, many

\footnotetext{http://www.ictregulationtoolkit.org/en/Section.2094.html}
1.1. BACKGROUND

![Diagram of DSA market mechanisms]

Figure 1.2: A selection of DSA market mechanisms

countries have utilized auction mechanisms to assign a long-term license for mobile services [4]. From the extensive source of literature [5–8], we know that a practical implementation of the market mechanisms for a real-time spectrum allocation is a challenging task. Although potential candidate-mechanisms for the dynamic spectrum access have already been introduced [2, 9, 10], their implementation is rather conservative and tends to lead to more complexity in reality.

To enable more flexible spectrum usage, as well as to improve spectrum efficiency, dynamic spectrum access (DSA) technology has been proposed as a promising candidate to the current “command and control” regime (see in Figure 1.3) [11–17].

DSA might be implemented through either centralized architecture (e.g., via “coordinated protocol” [18], “spectrum server” [16, 17], and “broker” [19]), or distributed approaches using advanced algorithms to coordinate an efficient spectrum usage [20–23]. While centralized schemes are easier to implement and manage, distributed access is faster and more flexible, yet more complex.

Based on a time scale, one can envisage a following representation of the efficiency by utilizing market mechanisms in resource management, e.g., Figure 1.4.

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3Ofcom is the British spectrum regulator. Information is available in: [http://www.ofcom.org.uk/consult/condocs/sfr](http://www.ofcom.org.uk/consult/condocs/sfr)
The common market practice in spectrum management is a spectrum auction [9,10]. Currently, the implemented auctions do not stimulate an open spectrum access and usage [2]. Moreover, the tradeoff between infrastructure investments and spectrum license fees is difficult to fix and it varies from country to country. More specifically, the existing practice of spectrum auctions is on a license-based bidding process, which is a competition limited to a small number of participants and not allowing open spectrum access after the license has been awarded [24]. Historically, spectrum auctions with their rich practice of design facilitate spectrum allocation to its participants by securing revenue to the spectrum owner, i.e., government, but brings operational delays [2].

The other subgroup, named “short-term leasing”, has a shorter processing time than the spectrum actions. However, it still requires supply and demand matching from both the spectrum owners (brokers) and network operators. Despite its complexity, a real-time allocation based on market mechanism would be the most efficient mechanism and could handle an actual traffic demand.

### 1.1.4 Multi-Operator Competition

Competition in mobile broadband marketplace which is believed to foster innovation, enhancing service quality and lowering prices for consumers, is the main
1.1. BACKGROUND

Objective of policies enforced by many spectrum management agencies, e.g., FCC\(^4\) and Ofcom\(^5\) [2, 25, 26].

Since the industry’s inception, the regulation for mobile services was centered on infrastructure-driven competition [27]. However, in the last decade, there has been a shift towards more services-driven competition, starting in fixed networks but now gaining popularity in mobile networks. While some regulatory bodies impose limits on infrastructure sharing [28–30] to obey competition law \(^6\), the benefits of sharing become undeniable due to technological innovation worldwide. Note that in this thesis, we focus our attention towards the services-driven competition.

The marketplace under consideration reveals two levels of competition that

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\(^{4}\)FCC is The Federal Communications Commission (FCC) which is authorized by the US government since 1934 to regulate all issues within IT and telecommunication field.

\(^{5}\)Ofcom is the communications regulator in the UK, which governs in the TV and radio sectors, fixed line and mobile telecoms, post, and satellites.

\(^{6}\)This law is known as antitrust law in the US. It supports and establishes market competition by prohibiting anti-competitive actions by companies. In Europe, it bears similar regulations. See more details in [31]
could be present for multiple operators in an oligopoly market\(^7\). These two are: competition for resources (spectrum) and competition for demand (users) as shown in Figure 1.5. The dynamic spectrum allocation is governed by a central entity, named “Spectrum Broker”.

\(^7\)An oligopoly is a form of market which is dominated and controlled by a few big sellers.

**Figure 1.5:** A centralized DSA scheme for a multi-operator case

### 1.1.5 Heterogeneity in Wireless Networks

Heterogeneous wireless networks (HetNets) are promised to be the panacea for growing traffic of any mobile network. A mobile network consists of different types
of base stations (BSs): macro, micro, pico, femto, and so forth. Furthermore, variety of deploying different radio access technologies, for instance, radio relays and distributed antenna systems. Apparently, a combination of radio access technologies that have supplementary capacity and coverage capabilities is the main driver to respond for different user demand for high speed mobile broadband access in varying (overlapping) coverage for mobile users [32].

Despite a reduction in infrastructure investment, mobile network operators try decrease their OPEX, e.g., by diminishing overall network power consumption. A solution to this could be to employ the heterogeneity in wireless networks. Deployment of HetNets anticipates a sporadic and uneven character in form of integrating unequal coverage areas and capacity. Spectrum sharing [29, 33] between all these sub-networks will be the challenging task for such operators [34].

Furthermore, a prominent property of wireless access is network coverage, which can be classified as either wide area (WA) or local area (LA) of wireless access. Either way, operators which are already in an operating stage within the same industry structure can take the role of either “bitpipe” or “customized tailor”. Utilizing a diversity in the topology and technology, the combination of wide-area with local-area networks could provide a completely different experience for a user compared with a single network.

The impact of heterogeneity in frequency channels under competitive spectrum allocation, due to different channel propagation characteristics, energy cost was developed to capture this phenomenon was studied in [35].

In this thesis we exploited the heterogeneity in terms of different service coverage provided by multiple competing operators (e.g., Figure 1.5). Chapters 3, 4 and 5 will contain some studies, where we consider service differentiation with various coverage types ranging from wide area to discontinuous local area (hotspot).

1.1.6 Energy Efficiency in Wireless Networks

Historically, radio access technologies are designed to improve spectral efficiency. While energy efficiency in the whole ICT sector has earned attention with recent initiatives [36–40] towards two main drivers: contributing in diminishing the environmental impact of the industry and decreasing OPEX due to energy consumption, e.g., more than 80% of total power consumed by the radio access network [41].

When it comes to the energy efficiency in wireless networks, the challenges to lead the high level energy consumption savings can be addressed on different areas, as follows:

- Equipment level, i.e., optimization of the main component of a wireless network, radio base station [37, 41].

- Network topology level, i.e., optimization of cell size [42].

- Operational level, (i.e., backhauling, air-conditioners, etc.) [43, 44].
1.2 Scope of the Thesis

We envision the scenario of an “always connected” traveling business user. As a starting point, we will discuss the research challenges in the areas of multi-operator competition, coverage, network performance, deployment and pricing of heterogeneous coverage area networks. We use this scenario to motivate our vision of ubiquitous mobile broadband connectivity and to explore the various barriers to realizing this vision.

Despite their implementation complexity, market mechanisms for the real-time spectrum allocation are widely believed to handle a growing traffic demand (instantaneous demand variations) and could bring economic benefits by allowing open spectrum access markets to emerge.

In this thesis, we mainly study how operators should adapt to fast traffic demand variations in open spectrum access markets [45]. The main thesis focus chosen is shown in Figure 1.6. More specifically, we adopt the proposed framework of a centralized DSA scheme (see Figure 1.5) based on two-level competition (i.e., for spectrum and for users).

![Figure 1.6: An illustration of emerging paradigm in spectrum access](image)

Therefore, we will primarily consider the dynamic spectrum allocation for a real-time competition case. We address two main challenges in the context of dynamic spectrum allocation for competitive wireless access networks that can be formulated as follows:
1.3. OVERVIEW OF THESIS CONTRIBUTIONS

- How could operators exploit real-time(fast) spectrum market mechanisms in order to adapt to traffic variations?

- How effective are these market mechanisms in a real-time(fast) heterogeneous environments?

- How does heterogeneity (asymmetry) of wireless networks (energy efficiency, deployment, cost, capacity) affect performance?

1.2.1 Research Approach

We utilize techno-economic assessment methodologies for a multi-operator setting which have been proposed [42, 46, 47]. Relevant cost structures, pricing and deployments strategies are projected for the selected scenarios. Comparisons with a single wireless operator case will represent a conventional system where there is no competition.

A selection of the scenarios used throughout the thesis is predetermined to provide a suitable level of abstraction of the way that the system operates meanwhile maintaining a generic analysis to evaluate system performance. Basically, the research areas have been examined taking into account parameters such as user density, user mobility, energy efficiency, network capacity, spatial and market characteristics and some more. The definition of the performance measures applied will be presented for each investigation respectively.

From a wireless network operator’s point of view, the challenge consists of selecting the more appropriate (single or multi) combinations of radio access technologies (RATs) to deploy in order to support an expected growth of users’ demand at an affordable price. To meet the continuously growing spectrum demand of mobile broadband services, every operator cannot afford to deploy a full coverage in a given area. Thus we take into account this fact by considering the problem in the case of asymmetrical service coverage wireless networks. We also consider the case of two competing operators offer identical service coverage for subscription-free customers.

1.3 Overview of Thesis Contributions

This thesis considers several study areas in pursuit of examining how the market mechanisms can efficiently leverage spectrum whilst maintaining economic viability for heterogeneous wireless networks in a real-time setting. Since the precise problem formulation depends on the specific assumptions for any given scenario, a resource allocation problem has been divided by sub-questions, namely \( Q \). A detailed explanation of the performed investigations is given in the following chapters:
Chapter 2: Business models for Municipal Wireless Networks  In this chapter of the thesis, we discuss the concept of deploying city-wide wireless networks which introduction is promised to bring universal service to inhabitants as a ubiquitous wireless Internet access. The challenges that municipalities face in order to provide the service, especially in urban areas, are reviewed. We will observe business models that are already implemented by a municipality. And, we will identify how the selection of a type of ownership of wireless network together with the network deployment and operation might jeopardize feasibility of a city-wide wireless network. The main contribution of this study was summarized in [48, 49]:

P1 Zhe Yang, Saltanat Khamit, Abbas Mohammed, Peter Larson, “A comparative study on business models of municipal wireless cities in the US and Sweden”, Third IEEE / IFIP International Workshop on Business-driven IT Management (BDIM), Salvador, Brazil, 2008, [48]


Both of these papers are the result of joint work with Zhe Yang and the author of In particular, the joint work contains the analysis of the business models for municipal wireless networks and case studies. Dr. Abbas Mohammed and Peter Larson have contributed with a valuable feedback on the initial stage of both papers.

Chapter 3: Multi-Operator Competition After an extensive analysis of related literature, we have identified two scenarios that are most likely to apply in the context of multi-operator competition. Since we deal with mobile broadband access with higher bandwidth it is not obvious that all operators can afford to provide full coverage. Here we have instead a mixed scenario, in which some wireless operators invest more in an attempt to provide wide area coverage whereas other “hot spot” wireless operators invest less but provide service in small areas. Users may be served by any operator since all operators share their networks explicitly in a cooperative manner, or in a competitive fashion where the user in each session picks the wireless operator that can provide the best service, quality and price. This chapter of the thesis focuses on competition with centralized dynamic access (via “Spectrum Broker”) in real-time spectrum allocation and the competitive scenario. We show whether such a competitive access provisioning scheme is feasible in the sense that it can yield positive profits for a “hot spot” wireless operators. We also present results based on the studies of [50, 51]. More specifically, we address this problem by posing the following research sub-questions:

• Q1: Can the hotspot operator, who has a cheaper and smaller network, be profitable within the presence of a macrocell operator in the market?
• **Q2:** How should spectrum be shared between operators operating in heterogeneous coverage areas under a competitive scenario, provided that the operators are limited in their network capacity?

• **Q3:** How should a hotspot operator opt for spectrum in order to maximize its profit and to sustain itself in the presence of a wide-area operator?

We are interested in identifying whether the proposed competitive framework can be utilized for the heterogeneous coverage area revenue-seeking operators. Additionally, we look at a scenario, where wireless operators are bounded by network capacity. Thus, the effect of network capacity is also examined here. The following conference papers have been written in this context:

**P3** Saltanat M. Khamit, Jens Zander, “Competitive spectrum allocation in heterogeneous coverage areas”, in proceedings of the European Wireless conference, EW2011, Vienna, Austria, 2011 [50]

**P4** Saltanat M. Khamit, “Market-based Spectrum Sharing in Capacity-limited Heterogeneous Wireless Networks”, in proceedings of (IEEE) the Swedish Communication Technologies Workshop (SWE-CTW), Stockholm, Sweden, October 2011 [51]

In the papers P3 and P4, the author of this thesis acted as the lead author. All modeling and performance evaluation were done by the thesis’s author. Dr. Jens Zander contributed with valuable guidance and feedback that have improved the quality of the above papers.

**Chapter 4: Energy-efficient deployment in multi-operator competition**

This part focuses on network deployment strategy while reducing energy footprint of traffic transmission. We consider an open wireless access market with the presence of an incumbent operator and the case of a newcomer operator whose objectives are to attract and retain users in order to maximize its revenue. The challenge in this context is:

• **Q4:** How should wireless operator deploy its network in the presence of competitors ensuring energy-efficient communications?

For an operator which might be uncertain about its network coverage and capacity expansion, lowering its capital (CAPEX) and operational (OPEX) expenditures is a way to do. From the operator point of view, there is a demand to find a financially viable deployment strategy for its network. Some aspects will be examined in this thesis. In this chapter, we propose competitive deployment strategies that facilitate an energy-efficient transmission. These network deployment strategies should provide an insight for real scenarios and help to identify effective network deployment schemes for profit-maximizing wireless operators. The main contribution of this chapter is the following conference paper:

All original ideas, system modeling, performance evaluation, and numerical example were developed by the author of this thesis. Dr. Jens Zander contributed with valuable feedback and guidance that have significantly improved the paper quality.

Chapter 5: Demand-driven pricing in multi-operator competition

Here, we study another solution for the spectrum allocation problem, namely spectrum auction. We are interested in the way pricing for heterogeneous wireless networks affects the overall system performance in competitive environment. Similar to any service-generating industry, pricing plays a significant role in mobile service industry. Therefore a wireless operator should choose the price so that its profits are maximized meanwhile the users remain satisfied with the services. In the price setting process, the wireless operator should take into account two main aspects: user demand and competition between wireless operators. Apparently, the user demand and service price are tightly correlated and dependent on each other. For instance, with a higher price is likely that the demand will go down and vice versa; price oscillation directly influences on the level of revenue of an operator. On the other hand, if the price is low, demand will grow, i.e., it will attract more customers (i.e., the buyers), though gains (e.g., ROI) could be not sufficient to maintain profitability in the marketplace. Therefore, by employing the mentioned above assumptions, we have treated this problem by answering this specific question:

• Q5: Which pricing strategy should competitive operators implement in order to maximize their profits with a heterogeneous demand and under different market shares?

We contribute to this context by identifying a suitable competitive pricing strategy as a tool for wireless operators to maximize their revenues in a competitive wireless access market. This problem was investigated in the following paper:


Pamela Gonzalez-Sanchez acted as the primary author of this paper (P6), while the author of this thesis has contributed with refining original ideas and writing paper. Dr. Jens Zander has been a main advisor and has constantly provided a valuable guidance and feedback in all stages of the paper.
1.4 Thesis Outline

This thesis is organized in two parts. The first part contains Chapters 1 through 6 and it includes an overview of related work. It presents also discussion of the included papers of the respective research sub-areas. More specifically, Chapters 3 and 4 cover the resource allocation from wireless operator’s profit maximization problem, whereas Chapter 5 examines competitive pricing under an auction-based setting. Finally the various findings and main conclusions together with suggestions for further research extensions are given in Chapter 6. The second part includes the papers that are reprinted verbatim from submitted and published conference papers. Note that material not directly related to the thesis problems is given in appendix. This includes an overview of the DSA concept and its taxonomy.
Chapter 2

Business Models For Municipal Wireless Networks

Municipal (Muni) wireless network is a recently established form of city-based wireless network, which provides mainly outdoor broadband wireless access to Internet for public usage. The wireless city is usually regarded as a public-utility service, which not only delivers well connected broadband services in the city at an affordable price but also promotes society interaction, bridges the digital divide and brings sustainable development to support municipalities. The concept is therefore attracting more and more attention from city authorities both in developed and developing countries.

![Figure 2.1: Trends of municipality-driven wireless services in 2006-2007](image)

There are hundreds of cities, which have deployed and have plans to build wireless broadband networks over their territories. Figure 2.1 depicts a trend in
CHAPTER 2. BUSINESS MODELS FOR MUNICIPAL WIRELESS NETWORKS

of wireless internet services covered by city-wide network. City authorities are closely involved in network initiatives and rolling out with various forms and scales at different stages, because it is often argued that inexpensive or even free of charge broadband access network are impossible, or at least time-consuming to be realized only depending on market forces. Generally, private network investors are cautious about protecting investment, which could make the end goal of rolling out a full coverage area with an affordable price to be out of consideration. Therefore, employing a suitable business model of a wireless city becomes an important choice regarding the basis and design of wireless city networks.

2.1 Motivation and Related Work

Wireless local area networks (WLANs) have been a great hope in the extension of broadband infrastructure since their introduction in the market in the beginning of 2000s. Being easy to deploy and operating in unlicensed frequency bands, WLANs provide affordable and ubiquitous internet access for public and private purposes. Employing the obvious benefits of WLANs, many operators have taken part in the extensive development of WLANs by deploying access points to provide affordable or free broadband access to their customers. These initiatives were actively supported on a municipal level. Consequently, they have launched a fast deployment city-based wireless network in North America as well as in Europe.

In particular, promoting a healthy climate for economic development, bringing new opportunities to local businesses and creating an appealing environment for startups and in under-served regions, local municipalities have been driven by this strategic thinking to provide cheap or free broadband connectivity in a geographical area. However, deployment and operation of Muni networks have been a challenge for most of these municipalities.

Most of recent studies on business models for Muni-wireless networks are rather vague and are infeasible used in practice. A proposed classification has been designed out of all potential combinations between two key roles: network ownership and network operation that can each be taken by common sorts of affiliation, such as: public, private and a combination of them(private and/or public).2

In the context of a Muni-wireless network, the sustainability of business models that are conceivable and already used in practice was studied [54, 55]. The most important business role can be defined by owning physical assets and customer resources [56]. The methodology used contains all potential combinations between two key roles, namely a network ownership and a network operation. Each role can be executed by three different types of actors: public, private and group of other actors (private and/or public). Operating the network infrastructure is combined either with network ownership or with service provision. The type of ownership can

\footnote{Internet World Stats. Information is available in \url{http://www.internetworldstats.com/stats.htm}}

\footnote{http://www.metrofi.com}
be classified as follows: private, public, open-site and wholesale, as well as different combinations of them.

Therefore, the research objective in this part of the thesis is to provide an overview of business models based on existing practices of municipal wireless networks. In this study, we look at the scenarios of public wireless network in urban areas. Thus, a municipal (Muni) wireless network, which is an established concept of city-based wireless network, provides mainly outdoor broadband wireless access for public usage.

2.2 Contributions

In this chapter, we first summarize the existing business models of Muni wireless networks implemented worldwide by distinguishing between ownerships of the network infrastructure and service provisioning. This step demonstrates the way to find appropriate rationale and system architecture of Muni-wireless network in our case study. To support our reasoning, we will give an analysis of the chosen business model.

The main contribution to this context is:

- an empirical study that assesses and compares the existing practices in contexts of a business feasibility of the municipal wireless networks.

2.3 A Case of a Municipal (Public) Wireless Network (Paper 1, Paper 2)

We investigated and summarized the existing business models of Muni-wireless networks implemented worldwide by distinguishing between ownerships of the network infrastructure and service provisioning. This step demonstrates the way to find appropriate rationale and system architecture of Muni-wireless network in our case study.

First, the business model of Portland wireless city can be interpreted as an “advertiser-supported” model [56]. The network is supported by a “private-wholesale” type of business relations, where network assets belong to MetroFi, the main network provider. Free Web access services are supported by national and local advertisers. As an alternative, users who prefer an Internet access without advertisement can pay for premium services. The municipality of Portland became the major “anchor tenant” for MetroFi’s wireless network provider. The main advantage of this public network is to allow all municipal employees to have an access to the network with certain functionalities. Figure 2.2 gives an insight of the main actors’ relations, all components in “green” identified by Portland’s authority. However components in “pink” show only the influence of outsourcing wireless operators who provide advertising, consulting, customer helpdesk support, etc.
More specifically, we examined the types of ownership for service provisioning by the following categories:

- **Private owner** is usually a wireless operator who supports and creates services to the network by gaining money from users’ subscriptions and advertisements.

- **Public or Non-Profit owner** is a provider who allows an access to network services by using municipality’s funding or applying for state or philanthropic grants.

- **Wholesale** can consist of a group of private owners who offer and provide services to end users.

The general scheme of the business model classification is obtained by the different variations of the network and service ownership relations, as shown in Figure 2.2.

![Figure 2.2: An illustration of the business model for Muni-wireless network](image)

In our study, we also have chosen the wireless city of Karlskrona, which is a Swedish city on the southeast coast of Sweden with wireless city services established in the middle of 2007. Its business model implemented by a local municipality has been achieved with low investments from external business partners and is depicted in Figure 2.3. It is characterized by an open and fair access to wireless services within affordable price for the city residents. These achievements are all significant challenges for a community or for rural developing regions worldwide in the process of successfully introducing Muni-wireless networks. We collected into the association of different actors involved in the business model implemented by Karlskrona municipality (see in Figure 2.3).
2.4 Conclusions

In this chapter, we have given an overview of business models of wireless cities based on the different ownerships of a network infrastructure and a service provisioning. Generally, the concept of Muni-wireless cities cannot be treated as a pure business case since it has public and non-profit attributes.

For this purpose, we have taken an existing practice, the wireless city of Karlskrona in Sweden as a case study with main drivers, business configurations, pricing and subscription schemes regarding its business model. Based on our analysis of the case study, we come to the following conclusions:

- Municipal initiative is essential. Wireless city can be regarded as a symbol of a city and facilitated local activities. In our case, Karlskrona municipality plays an important role in making the decision of building Muni-wireless city based on local municipal profiles and development strategies.

- A fair and open environment is more efficient for supporting competition among all parties involved. Whether being forced or volunteered to open its network, the Muni-network operator needs to provide opportunities for any ISPs and wireless network operators to be fairly associated into the network. It could be regarded as an emerging intention compared with traditional concept of wireless city, where a single company monopoly occupies most positions in the business model of the wireless city.

Figure 2.3: An illustration of business relationship of Karlskrona’s Muni-wireless network
CHAPTER 2. BUSINESS MODELS FOR MUNICIPAL WIRELESS NETWORKS

- Wireless city services like: a public transportation timetable, a city map, should be free of charge for inhabitants. A flexible and easy subscription plan, competitive pricing schemes and high-speed connection rates could make the wireless city to be the most promising alternative to displace traditional fixed broadband and succeed ubiquitous mobility as a bonus.

- Low investment from a municipality could be achieved through the public-wholesale partnership business model. In Karlskrona, the municipality can be regarded as a lossless actor in the market. It doesn’t need to put much investment funds to the wireless network infrastructure.

Based on our investigations, the business model - public-wholesale based on partnership collaboration is a more suitable solution for developing regions to deploy Muni-wireless network. Unlike the traditional business model, it could maximize user choices, creates a fair competition environment and activate all parties in the business model.
Chapter 3

Competition in Spectrum Access Market

In this chapter, we will analyze whether the proposed competitive spectrum allocation framework can facilitate a beneficial situation for the heterogeneous coverage area revenue-seeking operators. Additionally, we will look at a simple and generic scenario, where two wireless operators are bounded by network coverage and capacity.

3.1 Background and Related Work

In [57] Ileri et al. introduced a *Spectrum Policy Server*, which allocates resource for dynamic spectrum access networks with demand-responsive pricing. The competition is modeled as a non-cooperative game, where spectrum is allocated through an iterative bidding process [57]. However, their work is focusing on optimization of social welfare, which was formulated as a wireless operator’s revenue maximization problem. Similar works to [57] have studied the impact of wireless operator competition under Dynamic Spectrum Access (DSA) as well as by applying game theory techniques [12, 14, 15, 58]. A distributed, market-oriented model with a price based scheme within a multi-operator environment was introduced in a subsequent work [46], where a competition between several operators was formulated for a *homogeneous* (fully overlapping) coverage area.

3.1.1 Contribution

We are interested in identifying whether the proposed competitive framework can facilitate a beneficial situation for the heterogeneous coverage area revenue-seeking operators. We divided the problem into two scenarios, where, in first wireless operators are unlimited by network capacity and later, they are limited by network
capacity. The effect of capacity will be examined in this chapter. We applied Monte Carlo simulation experiments to study the problem.

We present below short descriptions of our contributions from the corresponding papers, which are:

- to evaluate the cost efficiency of the heterogeneous networks, applied to a coverage-limited scenario. [50–52].
- to propose a competitive framework that can optimize spectrum utilization and to examine financial viability of short-range operator for coverage-limited case under different user loads [50, 51].
- to valuate performance of wireless operators with heterogeneous coverage areas (with later association with infrastructure costs) and user preferences under competitive regime [50].
- to examine the framework properties that provides insights into the deployment and pricing strategies with and without capacity constraints [51].

### 3.1.2 Delimitations

Although the research has derived optimal operator’s policies in terms of operator profitability, there are no observations made in terms of user metrics. We have proposed a simple scenario to cope with the generalization difficulty of the optimal policies over conventional systems. Simplistic modeling has been used for the numerical evaluation in Papers 3 through 5. Thus, the obtained results might in reality be different from those real systems have. In order to draw general conclusions about performance, a more complex modeling is needed.

### 3.2 Coverage-limited Case: Low Load (Paper 3)

This investigation considers the competitive scenario and analyzes under which conditions the competitive service provisioning is profitable for a small coverage area operator. Unlike the prior work, this investigation considers a framework for operators with heterogeneous (partially overlapping) coverage area, where operators compete for spectrum to serve users. A portion of spectrum can be leased from a Spectrum Broker (Broker) on a short-term basis. The broker transparently allocates spectrum to the bidding winner, governed by demand responsive pricing. Based on the operator’s heterogeneity (ratio of overlapping coverage area), the broker could exploit the competition by introducing different spectrum pricing policies. This could exceed the user’s expected satisfaction in terms of different service offers. In our model, the competition will be induced in partially overlapping coverage areas, where a user picks the operator who offers the best deal in terms of coverage and price.
3.2. COVERAGE-LIMITED CASE: LOW LOAD (PAPER 3)

3.2.1 System Model

The mobile broadband service is moving towards an open access market [25], which can enforce the shift from technology-based competition to service-based competition. No operator can afford deploy full coverage in the whole country to meet a continuously growing demand for spectrum. Some operators invest more to provide wide coverage area (“macrocell”), other operators invest considerably less to provide service in a relatively small discontinuous areas (“hotspot”). Mobile broadband services could be provided by employing two possible business models [45] (see Figure 3.1).

The Broker would allocate spectrum to an operator who offers the highest QoS for the lowest price to encourage user access. We assume that the Broker’s allocation is a channel per user based and in a form of a short-term leasing. Therefore, a number of available channels is assumed to be shortage free. Note that the hotspot operator may use the same spectrum in both hotspots to serve two users at the same time, due to the reuse factor.

In the first, the operators share their networks explicitly in a cooperative manner. In the second, the wireless operators compete to attract users by providing an anticipated quality of service at the lowest price, which can be defined by user’s preferences.

![Figure 3.1: An illustration of emerging wireless operator’s paradigm](image)

3.2.2 User Model

Acceptance Probability Model

From the users’ point of view, the service offer is evaluated by its price and QoS. The acceptance probability (AP) model, which is borrowed from [57,59], is the measure that characterizes a reaction of user on an offered service from a operator. AP
is a function of user utility $U$ and asked price $p$ from the operator $i$ on channel $c$. The acceptance probability, $A_{k,i}$ can be mathematically expressed as follows:

$$AP_{n,i} = 1 - e^{-\zeta \cdot U_{n,i} \cdot p_{n,i}}$$

(3.1)

where $\varepsilon$ - is a sensitivity parameter of the asked price $p_{n,i}$, $\mu$ is a sensitivity parameter of a user utility $U$, and $\zeta$ is a constant that affects a shape of the $AP_{n,i}$.

Utility

In our model we assumed that all users in the system have their preferences, which can be expressed by two parameters that might be crucial to a user’s preferences:

$$U = \frac{(x/K)^\eta}{1 + (x/K)^\eta}$$

where $K$, $\eta$ - are the constant parameters affecting a utility’s shape, borrowed from [17]; $x$ is an expected QoS, in this case it denotes an achieved bitrate from operator $i$, but can as well represent an expected service time of a user $k$ being within a coverage of operator $i$.

Demand

In this chapter, a user demand follows a non-uniform distribution. The probability density function of the user demand obeys Normal distribution with standard deviation, $\sigma$ and mean value $\mu$ and can be expressed as follows:

$$f(x) = \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}},$$

(3.2)

where $l$ is a user location within the system area $A \in [0, L]$.

3.2.3 Operator Model: Expected Operator Profit

As mentioned, the network profit is the weighted difference of price and cost. Due to the coverage consideration and its interdependence with mobile broadband network hardware, the infrastructure as well as the spectrum costs are critical for any network.

The network operator’s objective is to maximize its profit. The total cost is associated with return on investment (ROI) per unit of bandwidth. In our model we assumed the ROI per user is an investment made in radio access infrastructure and other one time costs, such as site acquisition and electrical wiring. A operator gains when the surplus of asked price to the user $n$ on channel $b$ deducted by the cost per user is greater than zero. The expected profit $\Pi_{n,i}$ is expressed as shown in Eq.3.3:
3.2. COVERAGE-LIMITED CASE: LOW LOAD (PAPER 3)

\[ \Pi_{n,i} = \sum_{n=1}^{K} AP(p_{n,i}, r_{n,i})(p_{n,i} - (F_{n,i} + V_{n,i})) \]  

(3.3)

where \( V_{n,i} \) is a spectrum-unit cost; \( F_{n,i} \) is an infrastructure cost per user \( k \). All prices and costs are measured in monetary units \([m.u.]\).

3.2.4 Results

In this study, we analyzed the competitive spectrum allocation for mobile broadband wireless operators with heterogeneous coverage areas. We examined two cost functions for competing operators and revealed the motivations behind them. This study has captured the effect of user mobility on performance of the system. The preferences of a user in form of sensitivity towards price and QoS parameters is an important factor that could affect the wireless operator’s profitability. We also proposed two price setting models, which can be

**Fixed** (FC), where both operators charge corresponding to their infrastructure cost \( F_i \) and spectrum-unit cost \( V_i \). The total cost is simply structured as: \( C_i = F_i + V_i \).

**Spectrum usage based** (SUB) is based on a differentiation between coverage area properties, which can be captured as follows: \( C_i = F_i + V_i \cdot d_{k,i} \). We expect that this pricing model will lead to higher revenue, and more fairness among users.

Note, that the possibility to use the same spectrum in two hotspots (reuse factor) will be taken into account in both schemes above. It will lead to an update of the procedure earlier described, see in Fig. 3, which basically is a recalculation of the hotspot’s price \( p_{k,i} \).

Figures 3.2a and 3.2b demonstrate how an infrastructure cost of a hotspot operator affects its profitability with the presence of competing macrocell operator. Thus, the lower cost of the hotspot infrastructure leads to a price advantage (increased market share) for the hotspot operator. The hotspot operator would benefit substantially from the price-sensitive and stationary (i.e., low speed) customers. Although the operator competition reduces the expected operator’s profit (in monetary units \([m.u.]\)), this loss depends on a better characterization of the infrastructure cost of both operators, which in turn affects a service price.

This analysis, which includes some parameters that were selected in [50], revealed that the macrocell revenue is quite high, i.e., 300 times higher than hotspot’s one in the high mobility case (\textit{speed} = 2[m/s]). To clarify this situation. We complement the results by utilizing “Fixed” cost function in the low mobility case (i.e., \textit{speed} = 0.1[m/s]) with the results as in Figure 3.3a. Here the focus was to set the
parameters so as the hotspot’s profitability would be comparable to the macrocell’s one.

We combine the previous findings in this section. In particular, a combination of the following cases will be investigated: (i) infrastructure costs of hotspot slightly are much lower than macrocell’s, i.e., $F_{HS} = 10\%$ of $F_{MC}$, see in Figure 3.3b.

The simulation study that has been implemented on heterogeneous system to examine the proposed framework and validate performance of the open spectrum market for heterogeneous wireless networks.
3.2. COVERAGE-LIMITED CASE: LOW LOAD (PAPER 3)

(a) with $\epsilon = 4$ and $\mu = 4$ as in [17] under SUB cost function

(b) price-sensitive users (i.e. $\epsilon = 4$ and $\mu = 1$) under Fixed cost function

Figure 3.2: Expected operator’s profit as a function of increasing infrastructure cost of hotspot $F_{HS}$ with a given infrastructure cost of macrocell operator, $F_{MC} = 1[m.u]$
(a) \( F_{HS} = 50\% \) of \( F_{MC} \) under SUB cost function

(b) \( F_{HS} = 10\% \) of \( F_{MC} \) under both: SUB and Fixed cost functions

Figure 3.3: Expected operator’s profit as a function of speed with price-sensitive, i.e., \( \epsilon = 4 \) and \( \mu = 2 \)
3.3. Capacity-limited Case: High Load (Paper 4)

This investigation is an extension of the study in [51] where the effect of network capacity constraints and a nonuniform demand distribution are taken into consideration.

3.3.1 Motivation

The need for providing high quality mobile broadband access have increased rapidly. With increasing number of users, the system gets congested and this situation negatively affects the system performance. Therefore, a wireless operator, which is subject to its network capacity availability, should choose the optimal capacity for its network to sustain itself in a competitive environment. This situation begs to identify tradeoffs between network coverage, cost and capacity that affect system performance. Another aspect that comes with the growth of traffic demand is an intensified operator’s competition, especially in urban areas, where several operators offer their services to the same users. Obviously, competition leads to different deployment and pricing strategies that operators implement to sustain themselves in the marketplace.

In this study, we continue to exploit the concept of a competitive wireless access [45] market, where users have the choice to be connected to any network depending on user’s preferences. We also consider a system with heterogeneous (partially overlapping) coverage area wireless operators competing to derive financial benefits by selling data services to users. The operators deploy different radio access technology (RAT) networks and differ in terms of coverage and capacity (e.g., the right side of Figure 3.1). Apparently, the wireless access market is divided between two different operators. Under above concerns, we carry out our study whether a short-range operator can be financially viable in the presence of a wide-range operator under a market-based spectrum sharing framework.

We also proposed two schemes for the management and deployment of heterogeneous networks. The first scheme presents operators competing and deploying independently two networks, whereas the second scheme embodies an integrated deployment of networks, which are managed by a single wireless operator so-called monopolist according to the ownership of both networks. Under each scheme, we identify the challenges from both economic and technical points of view. We also provide possible solutions to solve these challenges. The schemes consider the optimal pricing for accessing different networks by accounting the user’s satisfaction of service and efficient spectrum utilization with spatial spectrum reuse by deploying a few short-range, geographically separated, base stations.

3.3.2 Results

In this study, a market-based spectrum sharing scenario, where two wireless network operators (operators) compete for users that maximize their revenue, was
considered. We applied a dynamic spectrum allocation (DSA) mechanism based on the market objectives to cope with the problem of spectrum sharing among these competitive operators with capacity constraints.

In our simulation, a users’ mobility is simply implemented as a random direction model and characterized by a direction of movement with a fixed speed. The bandwidth requirement is 1 channel per user allocation (i.e., $b_{req} = 1$), the reuse factor for the hotspot operator equals to 2 due to the spatial distribution of its network.

Figure 3.4: Expected operator profit as a function of system load under two scenarios: competition and monopoly. The network cost of hotspot, $F_{HS} = \frac{1}{2} F_{MC}$ of macrocell. The capacity of hotspot network, $W_{HS} = 30\%$ of $W_{MC}$ of macrocell

The results obtained in Figures 3.4, 3.5, and 3.6 demonstrate that it would be financially viable for a hotspot operator to target the densely populated areas under this mechanism with the presence of a competitor. However, it is evident that the level of profit depends on network capacity. Therefore, by expanding its capacity, the hotspot operator could generate more revenue with a nonuniform user distribution. Our analysis and numerical study suggest that spectrum shared between competing heterogeneous operators can be beneficially exploited and spectrum portion earned depends on the outcome of competition. Furthermore, we presented two schemes that are focusing on maximizing total operators’ profit for
3.4. CONCLUSIONS

In this chapter, we have studied a market-based spectrum allocation framework for heterogeneous coverage area wireless networks under different scenarios.

3.4.1 Competition in Coverage-limited case

The impact of competition on the system performance was investigated for the coverage-limited scenario under this framework. Thus, the competitive behaviors of mobile broadband wireless operators with heterogeneous (partially overlapping) coverage areas were analyzed. Moreover, the studies have captured the effect of user mobility. The impact of sensitive parameters, namely sensitivity of price and QoS, was investigated. Through numerical results, we demonstrated how infrastructure

Figure 3.5: Total expected profit as a function of system load under two scenarios: competition and monopoly. The network cost of hotspot, $F_{HS} = \frac{1}{2} F_{MC}$ of macrocell. The capacity of hotspot-operator, $W_{HS} = 30\%$ of $W_{MC}$ of macrocell

the macro-hotspot networks. Despite achieving higher profit under the monopoly scheme, spectrum utilization is more efficient and suboptimal under the spatial competition. More details can be found in paper [51].
cost of a hotspot operator affects its profitability with respect to macrocell operator. Thus, the lower cost of the hotspot infrastructure leads to a price advantage (increased market share) for the hotspot operator. The hotspot operator would benefit substantially from the price-sensitive and stationary (i.e., low speed) customers. Although competition reduces expected operator’s profit, this loss depends upon a better characterization of the infrastructure cost of both operators, which in turn affects a service price.

### 3.4.2 Competition in Capacity-limited case

We continued our previous study [50] where two heterogeneous coverage area operators deployed cellular-like (macrocell) and WLAN-like (hotspot) networks respectively. These operators are different not only in terms of coverage areas but also in terms of network capacity. We applied a dynamic spectrum allocation (DSA) mechanism based on the market mechanisms to cope with the problem of spectrum allocation among these operators under capacity constraints.

Simulation results showed that it could be financially viable for the hotspot operator under the above assumptions. It is evident that a profitability level depends
3.4. CONCLUSIONS

on prior investments made by an operator in its network capacity. We believe that by expanding its capacity, the hotspot operator could generate more revenue with high traffic demand zones. Despite achieving higher profit within a monopoly service area, spectrum utilization is more efficient and suboptimal under a spatial competition (i.e., in overlapping areas). The benefits of deploying a capacity-driven network are still sufficient to achieve a competitive advantage over competitors who are deploying a wide coverage area mobile network. Therefore, the competing operators, which previously had heavily invested to capture a sufficient market share by having an advantage in coverage area, could expect a user churn. Meanwhile, with “smart” deployment of short-range (with lower network costs) and high-capacity network, an operator can achieve financial benefits (comparable with coverage-driven operator) by only marketing its services in rather small areas with a high user demand.
Chapter 4

Energy-Efficient deployment strategies

4.1 Background

Herein, we will look at the different deployment strategies and analyze a feasibility of suggested pricing schemes in previous studies [14, 17, 50, 57, 59–61], where competition among providers is a form of the efficient exploration of radio spectrum allocation. A multi-provider competition could emerge under the open spectrum concept [45], where new small (short range coverage) provider strive to offer different types of data services than those of an incumbent (wide range coverage) providers, such that their network and deployment strategies would be adopted in a flexible manner. We will provide a comparative analysis of spectrum allocation problem for heterogeneous wireless networks.

We believe that a competition between heterogeneous coverage wireless providers could also imply an increasing energy efficiency [62] of their networks as a consequence of implementing more progressive deployment strategies to sustain in a common marketplace. We will look particularly at the way to apply some of the cost- and energy-efficient deployment strategies that could be beneficial for both providers.

4.2 Related Work

The studies done by Johansson [42] is an outstanding effort to develop methodological assessments for heterogeneous topologies of wireless networks. A distributive market model developed by [46] has dealt with a competition between providers in a fully overlapping coverage area. Here we continue by looking at the competition between wireless network providers in a partially overlapping coverage area. In this study, we seek for energy-efficient deployment strategies for wireless providers with spatial heterogeneity and can meanwhile ensure a financial viability for the
providers in the market.

Traditionally, the major deployment concern of any provider is a coverage of wireless network. For instance, a cellular provider targets towards an abundant coverage deployment, thus infrastructure deployment (i.e., a base station, RBS) incurs a general part of energy consumption for the provider [63].

4.3 Contribution

Deployment paradigms are popping-up among wireless providers actions towards handling the data-driven capacity crunch and small (local coverage) cells offer a significant means to improve network capacity and cope with all-important traffic issues in hot spots.

In this chapter, our contribution is an evaluation of competitive deployment strategies that facilitate an energy-efficient transmission in a heterogeneous multi-provider environment. This network deployment strategies should provide an insight for real scenarios and help to identify effective network deployment schemes for profit-maximizing wireless providers [52].

4.4 Deployment aspects in Competitive Spectrum Access (CSA) Networks (Paper 5)

In this study, we modify the model of competition between heterogeneous wireless providers of [50]. We will study the cost- and energy-efficient deployment strategies to ensure maximization of competing providers’ profitability. We expect competition to enable new coming providers to launch their services more rapidly. It will eliminate expenses in infrastructure needed in the area where there is no demand for high data services.

4.4.1 System Model and Deployment Strategies

We are motivated by the following scenario when with a growing demand for mobile broadband services a wireless network provider faces the problem of network capacity expansion. Moreover, being in a competitive market place, as mobile services, this problem could be more challenging for the provider. However, the market place is not stagnant and there are new wireless providers (new technology) would like to provide customers with high quality services for a sake of maximizing its own profitability. Obviously, in this situation, the wireless provider must evaluate how to reduce capital expenses (CAPEX), plus to revise the cost per service. To this extent, the network deployment strategy with energy efficiency concerns (e.g., diminishing “energy” bill) could facilitate in lowering the network operation expenses (OPEX) and to balance network coverage versus user traffic.

In this study, we look at how a network cost and energy-efficient deployment could be employed to sustain a newcomer(entrant) in the market with the dom-
4.4. DEPLOYMENT ASPECTS IN COMPETITIVE SPECTRUM ACCESS (CSA) NETWORKS (PAPER 5)

The finance of a full-coverage mobile broadband network provider (incumbent). The competition among the incumbent and entrant providers is also considered and schematically presented in Figure 4.1. These providers have the similar goal of maximizing individual profit. The provider competition is imposed in an overlapping coverage areas. A user can chose a provider that offers the best service with high bitrate at a low price. The competition is modeled as an iterative bidding, where providers submit their service offers in a TDMA-like manner with $N \subseteq \{1, 2\}$ base stations (BS). The BSs have different transmit power levels, service range and heights of BS's antenna due to various RATs employed.

![Figure 4.1: Illustration of deployment of mobile broadband system](image)

Two competitive deployment strategies have been selected. Specifically, “Cost Leadership” and “Differential Pricing” strategy, with an energy consumption constraint are used. To give a clear understanding of the investments required in the service coverage and capacity for the entrant provider, a simple model was used in this investigation. The system performance is evaluated in terms of network size (market share), transmitted power, antenna height and user preference.

**User Model**

Customers, named as users, are allowed to roam among service providers, which offer mobile broadband services. In real networks, user distribution is more likely to be spatially heterogeneous in nature.

**Utility function** All users have their preferences in terms of a service offer, and mathematically can be expressed as follows:

$$U = W \cdot \log_2(1 + \frac{P_{tx}}{N \cdot L})$$  \hspace{1cm} (4.1)

where $W$ is available bandwidth measured in [MHz], $P_{tx}$ is a transmit power mea-
CHAPTER 4. ENERGY-EFFICIENT DEPLOYMENT STRATEGIES

Sured in [W], N is an average noise power on total bandwidth measured in [W] and 
L is a path loss.

Satisfaction function From the users' point of view, a service offer from a ser-
vice provider comprises of its price and QoS (bit rates). We also use here acceptance probability [59] which is the function of user utility U (bit rate) and asked service price p per unit of the spectrum band from provider i. The benefits of adopting the acceptance probability, one of which helps to estimate the user satisfaction level based the combination of price and bit rate (equivalent to quality of service (QoS)) are crucial. The acceptance probability, is presented as follows:

$$AP = 1 - e^{-\frac{\kappa}{p_{k,i}}}e^{\mu_k}$$

where $\varepsilon$ - is a price sensitivity $p_{k,i}$, $\kappa$ and $\mu$ are constant parameters, and $U_{k,i}$ is user utility expressed above in Equation (4.1).

Service Provider Model

Expected Profit The service provider objective is to maximize its profit. The cost is associated with return of investment (ROI) per user k. In our model we assume that the ROI per user is the investment made in network infrastructure, such as radio access part, and other additional costs (i.e., power supply, air conditioner, cooling system and etc.). Therefore, the expected provider's profit $\hat{\Pi}_{k,i}$ is mathematically can be expressed as in Eq. (4.3):

$$\Pi_i = \sum_{k=1}^{K} AP(p, U) \cdot (p_i - Cost_i(P_{tx, tot}))$$

where $p_i$ is an asked price to user k, $(k \in K)$.

Infrastructure costs are proportional to expenses for radio access equipment (e.g. power amplifiers, transmitters, etc.), building antenna towers, and etc.

Competitive Strategies In this section we study the competitive deployment strategies that could be used. We utilize the well-known Porter's generic strategies [64] and apply the following in our model:

- Cost Leader (CL) - a strategy seeking for ways to achieve the least-cost position in the market place. We analyze the effect of incremental CAPEX on the capacity of the network and how it would affect its profitability.
4.4. DEPLOYMENT ASPECTS IN COMPETITIVE SPECTRUM ACCESS (CSA) NETWORKS (PAPER 5)

- **Differential pricing** (DP) - a strategy that is preferred when competitive advantage can be achieved via offering different services in terms of better performance at a similar price. An improvement in performance is to introduce more optimized utilization of resources (capacity and coverage), provided that high quality services is maintained.

4.4.2 Results

We carry out a set of simulations in MATLAB with uniform and Gaussian distribution ($\sigma^2 = 250$) of users. Gaussian distribution is chosen to analyze the effect of non-uniformity of user demand in terms of spatial dimension of the system. A list of simulation parameters used is given in the Table-I.

<table>
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<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
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</thead>
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<td>User population $K$</td>
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<td>Noise power $N$, [dBm]</td>
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<td>$\epsilon$</td>
<td>4</td>
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<tr>
<td>Antenna BS height $h_{tx}$, [m]</td>
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<td>$\mu$</td>
<td>4</td>
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<td>Antenna MS height $h_{ms}$, [m]</td>
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<tr>
<td>System area, $L$, [m$^2$]</td>
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<td>$\zeta$</td>
<td>10</td>
</tr>
</tbody>
</table>

We selected a few cases for the simulation study:

- **CL** - where $C_{Entrant} = \frac{C_{Incumbent}}{2}$ with market share equals to 65% of “Entrant” provider, e.g., it can happen when a newcomer has more cost-efficient deployment strategy and has an advantage in price compared to its competitor (incumbent).

- **DP** - where bit rates are taken in account (it has similarity with “usage-based” pricing), i.e., 35% of the market belongs of “Entrant” provider.

- **FC** - when market divided between two, i.e., 50% of the market captured by “Entrant” provider.

The multi-provider competition proved to be an important aspect to take into consideration. In the presence of a non-uniform demand distribution, it was more likely that a new wireless provider would attempt to deploy a competing network. The competition stimulated a cost efficient radio resource utilization.

In this part, the impact of transmit power $P_{tx}$ on the system performance was considered. The expected provider's profit with change of transmit antenna BS height of the “Entrant” is depicted on Fig. 4.2. The performance under DP-scheme for “Entrant”-SP is dominating all over others, while $h_{tx} = 20$[m] is the same and fixed.

The expected user's bit rate with change in transmit power of the “Entrant” is depicted in Figure 4.3. As we might see, the $P_{tx}$ grows $R_k$ converges faster to
a certain level. Under the above assumptions, the “Entrant” can make profit by focusing towards high data rates services.

In this case, the maximum of expected SP’s profit is when $P_{tx}$ is on the 14 [dBm], which is unexpectedly low value of transmit power under competitive scenario and supports a concept of low-power communication, mainly known as “Green Communication” [62].

This study findings revealed the suboptimal transmit power in Figure 4.2, while the effect of antenna height increase can be observed in Figure 4.4.

This investigation was summarized in Paper 5 [52], where the obtained results from the simulation study has been implemented on heterogeneous system to examine the proposed framework under energy consumption constraint for the open spectrum networks [45].
4.5 Conclusions

In this chapter, we considered how a provider can attract customers in a competitive environment by using appropriate deployment strategies. It was shown that the network costs are crucial in our model. We also examined two competitive deployment strategies ("Cost Leadership" and "Differential Pricing" strategy) with an energy consumption constraint. However, it seems that there was not a significant gap in terms of provider profitability between both providers. The reason of such a situation, that the "Entrant"-provider has a much smaller (high) network according to our model. Meanwhile, there are a big gain with regard to the expected service rate for the "Entrant"-provider. In this competitive market, those users located in the coverage of the "Entrant"-provider, but also they preferred to be served by it due its appealing service offer (higher rates at lower price). In the case when the "Entrant"-provider wishes to match a full coverage of the incumbent, it will need (for instance) aggressively adjust its strategy based on the capital and operational expenditures. This wish can be crucial for the newcomer and as shown by

Figure 4.3: Expected user’s bit rate vs. transmit power with fixed transmit antenna height $h_{tx} = 20$ m with non-uniform user distribution
existing practice of mobile services is not cost-efficient. Therefore, the “Entrant” provider deployed a radio access technology smartly, and focusing primarily on business strategy and energy efficiency aspects, would benefit greatly. For instance, the “Entrant”-SP using a “Cost Leadership” strategy had a price advantage over the “Incumbent”-SP, while using the “Differential Pricing” strategy and having a market share up to 35%, would be viable for the entrant also.
Chapter 5

Pricing in Multi-Operator Competition

As mentioned in Chapter 1, pricing plays one of the important roles in any wireless access system. Through a proper pricing scheme, a wireless operator can offer wireless access services in a competitive environment while achieving the highest revenue.

5.1 Background and Related Work

Pricing in wireless systems has been extensively studied since the early 1990’s, mostly in the context of mobile networks [14,57,59–61]. Our work is fundamentally different, because we consider only the competitive scenario. In this context, pricing aspects are critical. These aspects could facilitate a degree of freedom in terms of service offers with the different QoS in the long run, but their cost is substantial. The prominent changes in the wireless telecommunication market are presented in [65], where the authors gave an overview of evolution in an open wireless market. In our work, some implications can be found within the “state of the art” of [65].

In [66], the authors studied how wireless operators should deploy their networks to balance tradeoff between areas of exclusive coverage (i.e., a monopoly situation) and overlapping areas with a competing operator, such that profit was maximized. Moreover, they examined how competitive sharing and coopetition 1 in a multi-operator system could facilitate financial gains for the operators with partially overlapping service coverage. Thus a different level in coverage overlap for homogeneous networks was studied applying the game theoretic framework and proved to affect a level of an operator profitability.

A competitive spectrum allocation mechanism in wireless networks with heterogeneous coverage was addressed in [50]. The authors investigated whether or not it

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1Coopetition is a relationship that occurs with simultaneous cooperative and competitive interactions among parties in the common marketplace [67].
is profitable for a small SP to deploy its network and compete against another SP who provides a wide service area. Unlike that work, we are interested in an equal service coverage access setting amongst competing operators assuming a nonuniform user distribution and a difference in market share, so that there is no market power for wireless operators.

5.2 Contribution

Pricing in wireless networks has been a widely investigated research problem. In this chapter, we are interested in pricing strategies for heterogeneous wireless network operators which compete for users. Similar to any service-generating industry, pricing plays a crucial role in mobile services industry. Therefore a wireless operator should choose the price so that its profit is maximized meanwhile the users remain satisfied with services. In the price setting process, the wireless operator should take into account two main aspects: user demand and competition between wireless operators. Apparently, the user demand and service price are tightly correlated and dependent on each other. For instance, with the higher price it is likely that the demand will go down and vice versa; price oscillations directly influence on the level of revenue of a provider. On the other hand, if the price is low, demand will grow, i.e, it will attract more users (i.e., the buyers), though gains (e.g., ROI) could be insufficient to maintain profitability in the marketplace.

In this context, our contribution is to identify a competitive pricing strategy as a tool for wireless to maximize their revenue in a competitive wireless access market. Since we deal with a spatial price competition, it is also interesting to examine how each operator pricing strategy in a competitive duopoly market compared with monopolistic strategies are affected by a user demand.

5.3 Competitive Pricing with Heterogeneous User Demand (Paper 6)

5.3.1 System Model

In this study, a scenario where a wireless access market is shared between two different operators, which own their networks is considered. The scenario of interest is shown in Figure 5.1. These operators are covering different service area, since it can be expensive for an operators to afford wide area deployment.

In order to bring closer our model to real scenarios, we assume that the user population obeys a Gaussian distribution (i.e., non-uniformly distributed over a given system area). The p.d.f. of the users’ distribution can be expressed as shown:

\[
f(x) = \frac{1}{\sqrt{2 \cdot \pi \sigma}} \cdot e^{-\frac{(x-\eta)^2}{2\sigma^2}} \tag{5.1}
\]
where $\eta$ is the mean value of the user demand, $\sigma^2$ is the variance as the measure for the width of the user position’ $x$ distribution within the range of system area $[0 - L]$. $L = 3 \times r$, and $r$ is the radius of the cell (coverage). Note, that Equation 1 in [53] should be corrected as follows: $l$ must be replaced by $x$, which is the user position in the system.

Another assumption is that this system is interference-free, even under a partial overlap in coverage of two networks. We considered the downlink communication, i.e., from the base stations (BSs) to the users.

### 5.3.2 Model of Wireless Access Market

The users could get a data service, depending on their location from two different coverage-centric markets, as shown in Figure 5.1. They are named as a **monopoly access market** and an **open access market**. When the users are in the non-overlapping areas (served by a sole operator) is considered as the monopoly market. These operators are identical in service coverage range. Meanwhile the users are within the overlapping coverage of both networks and can be served by several BSs, they experience an open access market. Note, we consider competition among the base stations that maximize their individual expected profit per time unit (e.g., second).

**Utility Function** In this study, a user chooses the BS that provides the best service offer, i.e., with highest estimated utility and it can deny a service if the price asked by the BS is too high. The user maximization problem is introduced in Equation (5.2).
CHAPTER 5. PRICING IN MULTI-OPERATOR COMPETITION

\[ \text{maximize } \hat{U}_{i,j}^m(R_{i,j}^m, \epsilon_m) \]  \hspace{1cm} (5.2)

\[ \forall j \in \{1, \ldots, N\}, m \in \{1,2\}, \]

where \( \hat{U}_{i,j}^m \) is the estimated utility of user to be a decision-taking parameter defined as below:

\[ \hat{U}_{i,j}^m = \frac{R_{i,j}^m}{\epsilon_m}. \]  \hspace{1cm} (5.3)

Here \( R_{i,j}^m \) is the peak data-rate that the user experiences based on its position and \( \epsilon_m \) is the reservation price provided by the BSs.

**Acceptance Probability**  The user willingness to pay for the offered service is modeled through an acceptance probability \([16, 17, 50]\) and defined as follows:

\[ A_{i,j}^m = 1 - e^{-C(\hat{U}_{i,j}^m)^\mu(s_{i,j}^m)^\zeta}, \]  \hspace{1cm} (5.4)

where the \( C, \mu \) and \( \zeta \) are positive constant parameters, and \( s_{i,j}^m \) represents the price that the user pays during each auction cycle, and it is equivalent to the bid that this user submits to the BS, (see Equation 5.2). After the first stage (auction 1), if the user starts transmitting, it should remain connected to this base station until the file transfer is completed.

**Base Stations BSs Objective: Profit Maximization**  The BS’s interest, instead, is to maximization its profit by serving as many users as possible. In order to formulate the problem we define the variable \( a_{i,j}^m \in \{1,0\} \) such that \( a_{i,j}^m = 1 \) if user \( j \) chooses \( SP_m \) and \( a_{i,j}^m = 0 \) otherwise.

One constraint that should be considered is that for any user \( j \) a maximum of one \( SP \) should be assigned (as defined in Equation 5.5):

\[ \sum_{m}^{2} a_{i,j}^m \leq 1 \]  \hspace{1cm} (5.5)

The demand-based profit maximization problem for the BSs is formulated by maximizing the sum of all submitted bids by users that accept to enter the game in each auction cycle \( j \) and is defined as follow:

\[ \text{maximize } \sum_{j=1}^{N}(s_{i,j}^m A_{i,j}^m). \]  \hspace{1cm} (5.6)
5.4. **RESULTS**

The summation of all the users that choose BS $m$ forms the generated demand which accepts the service with a probability $A_{i,j}^m$.

### 5.4 Results

Here we have studied a demand-based profit maximization strategy where a competitive pricing game has been used. Figure 5.2 shows the average profit per BSs when both broadcast the same reservation price, $\epsilon_1 = \epsilon_2$. It can be observed that both BSs obtain the same profit and that higher profit values may be generated under lower market share.

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**Figure 5.2:** *Expected BS profit per second as a function of the reservation price when $\epsilon_1 = \epsilon_2$*

Basically results showed that the competing wireless operators tend to aggressively drop the service price to capture a larger number of users in the highly populated area, meanwhile user throughput dramatically fails with a growing number of service transactions (congested system). Our analysis reveals that the operators may retain the demand and hence increase their profits by establishing a reservation price close to a market-oriented one.
5.5 Conclusions

In this chapter, we studied an action-based spectrum allocation mechanism which is conceptually different compared with previous Chapters 3 and 4. Moreover, we have exploited a game-theoretic (by means of simulations) framework to formulate and model a market. More specifically, we studied what kind of pricing strategies maximizes an operator profit meanwhile is responsive to user demand fluctuations can be efficient for an operator under competition.

For this, we have considered a system that consists of two homogeneous networks with overlap in service coverage areas, which results in a different market share in the common marketplace. The main operating objective of the proposed mechanism is coupled with maximization of an individual operator profit, and maximization of the user’s utility (i.e., attaining higher data-rate at lower price). Simulation results revealed that the operators tend to aggressively drop the service price to capture a larger market share in the highly populated area. Meanwhile user throughput dramatically fails with a growing number of service transactions (congested system). Our analysis demonstrates that the operators may retain the demand and hence increase their profits by establishing a reservation price close to a market-oriented one.

From our findings, we believe that a knowledge of which pricing strategies are viable in order to sustain in the open wireless access market is crucial for any operator. Under the above assumptions, we could identify the suboptimal size of market share that facilitates equal profitability of both operators which is proportional to the user demand variations.
Chapter 6

Conclusions

This chapter concludes the discussion of the first part of the thesis. A general summary is presented in Section 6.1 with associated thesis subject studies, while Section 6.2 contains a few directions for further research.

6.1 Concluding Remarks

In this thesis, the main theme has been a real-time spectrum allocation for future wireless services in a competitive case. We envisioned that the spectrum would be allocated based on the market mechanisms on real-time (actual demand) basis between heterogeneous coverage networks that compete on two levels: spectrum and users. We focused on several methods in this context. These solutions were: 1 - adopting DSA framework for the case of heterogeneous coverage networks; 2 - accommodating pricing and deployment strategies that maximize revenue for wireless operators.

This thesis has mainly focused on the development and behavior of multi-operator competition under market spectrum allocation mechanisms in heterogeneous setting. The introductory Chapter 1 was excluded from the discussion of the main subject of the thesis. Since, it did not contain new research material.

Chapter 2 dealt with business models for Municipal (Muni) wireless cities in the US and Sweden. However, it appeared from a small comparative analysis that in practice sustainability of such Muni networks with the varying degree of ownership was crucial with respect to practical interest. Therefore, two main conclusions resulted from Chapter 2. First, one should carefully define the degree of ownership of the Muni-networks. Estimators and assessment procedures for these parameters should be robust. Second, statements about the robustness of statistical information should be as detailed as possible.

In Chapter 3, the competitive multi-operator spectrum access problem has been addressed. First we studied how operators could exploit spectrum market mechanisms in order to adapt to real-time (fast) traffic variations. We considered a
simple modeling of a centralized dynamic spectrum allocation based on a real-time market mechanism. More specifically, the proposed framework revealed interesting trends about the interactions between spectrum allocation and pricing for users, a choice of technology by an operator and spectrum costs charged by a spectrum broker. First, the effect of multi-operator competition on the system performance (operator’s profitability) was investigated for a coverage-limited scenario. Thus, the competitive behaviors of mobile broadband wireless operators with heterogeneous (partially overlapping) coverage areas were analyzed. The importance of cost functions for competing operators was identified throughout the study. More specifically, the impact of user mobility, price’s and QoS’s sensitivities have been investigated with respect to the system performance. The findings obtained demonstrated how the infrastructure cost of hotspot operator leads to its competitive price advantage (i.e., an increase in market share) compared to a macrocell operator.

Then, we continued our previous study [50] where two heterogeneous coverage area operators deployed cellular-like (macrocell) and WLAN-like (hotspot) networks respectively. However, the operators were different not only in terms of service coverage, but also in terms of network capacity. To cope with the problem of spectrum allocation between HetNets operators under capacity constraints, a centralized dynamic spectrum allocation (DSA) based on market terms was also utilized. By expanding its capacity, a hotspot operator could generate more revenue within highly traffic demand density zone. Spectrum utilization was more efficient and suboptimal in overlapping areas (competition), though profit was higher within a macrocell’s (monopoly) service area. The benefits of deploying a capacity-driven network were still sufficient to achieve a competitive advantage over its competitors which target towards a wide coverage network. Therefore, the competing operators, which previously had heavily invested to capture a sufficient market share by having advantage in coverage area, could expect a user churn. Meanwhile, with “smart” deployment of short-range (with lower network costs) and high network capacity an operator could achieve financial benefits (comparable with coverage-driven operator) by only marketing its services in rather small areas with high user demand.

Chapter 4 has been following a study on how competitive service providers can deploy networks to attract more users, which would in return generate more revenue for them. We were motivated by the current fact that in order to attract customers in a highly deployed environment, it was crucial for a new service provider (SP) to offer better services than the rest in the market by utilizing cost-efficient deployment. This deployment meant that the network should be easy to deploy and the spectrum efficiency utilization should be higher so as to keep the costs (OPEX and CAPEX) of a network low. The multi-provider competition proved to be an important aspect to take into consideration. In the presence of a non-uniform demand distribution, it was more likely that a new provider would attempt to deploy a competing network. The competition stimulated a cost efficient radio resource utilization. In this study, two competitive deployment strategies with an energy consumption limit were proposed. Moreover, this study revealed close to optimal
6.2. DIRECTIONS FOR FUTURE RESEARCH

transmit power, antenna height and network size for a newcomer SP under given assumptions. The findings of the study revealed which deployment strategy the newcomer SP could select in order to be viable with a certain market share in the presence of a dominant SP (i.e., deploying a whole coverage area network). We believe that the obtained results could be exploited by service providers to identify potentials of the proposed deployment strategies and to focus their businesses for cost and energy efficient communication.

Finally Chapter 5 covered a study on an action-based spectrum allocation (i.e., which is different compared with Chapters 3 and 4). Moreover, we have exploited a game-theoretic framework to formulate and model an open access market. More particularly, we studied what kind of a pricing strategy can be efficient for an operator under competitive scenario. In order to achieve this, we have considered a system that consists of two given networks with overlap in service coverage areas, meaning a different market share in the common marketplace. The main operating objective of the proposed mechanism was coupled with the maximization of an individual operator profit and the maximization of user utility (i.e., attaining higher data-rate at lower price). Attained simulations revealed that the operators tend to aggressively drop the service price to capture a larger market share in the highly populated area. Meanwhile user throughput dramatically fails with a growing number of service transactions (congested system). Our analysis demonstrated that the operators may retain the demand and hence increase their profits by establishing a reservation price close to a market-oriented one. We believe that the operators could learn and further apply an optimal pricing strategy in order to be financially viable in the open wireless access market. Under our assumptions and the above observations, the optimal size of market share could be gained based on the behavior of the user demand. This would be beneficial for both users and operators.

6.2 Directions for Future Research

In light of the findings obtained in this thesis, we plan to conduct future research which will be mainly focused on circumventing practical limitations of the centralized spectrum allocation algorithm when applied to more realistic scenarios. Such research lines can be summarized as follows:

- Further studies may of course span for a case with a greater number of operators. Also it is an interesting topic to find out whether these performance measures can, in some way, also be used in a context of robust estimators.

- Prospective works would be to apply non-uniform user distributions, and to study how the operators should set their price in a cooperative scenario.

- Although we have touched in Chapter 4, we intent to explore more on the energy efficient deployment for competitive and cooperative scenarios in future.
• Pricing games evaluated for the scenario of Chapter 5 would be interesting and worth further investigation for heterogeneous settings.
Bibliography


Appendix
Overview of DSA

The term dynamic spectrum allocation can potentially cover a range of different subject areas. Several established research fields are related to DSA, such as dynamic channel allocation (DCA), flexible frequency assignment, unlicensed spectrum access, spectrum coexistence and so forth.

If we are considering only a single radio network, the concept of DCA is very close to that of DSA. DCA shares the radio resources among the base stations of a radio access network (RAN), and many different schemes have been suggested in this widely researched field (citation). The area of frequency assignment has also been studied for many years (citation). The idea behind frequency assignment is to develop techniques for finding the optimum assignment of frequencies to radio access nodes (e.g., base stations) in order to meet interference and coexistence constraints. However, we are more interested in methods that allow different radio systems with differing characteristics (e.g., broadcast / multicast / unicast, different overlapping cell sizes, various supportable services / data rates) to dynamically share a set of radio resources between the networks in a composite radio environment scenario. Figure 6.1 demonstrates how the concept of DSA can be categorized with regard to usage and method types.

![Figure 6.1: A taxonomy of Dynamic Spectrum Access (DSA) concept.](image-url)
Part II

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