Resource Sharing and Network Deployment Games

In Open Wireless Access Markets

DINA PAMELA GONZALEZ-SANCHEZ

KTH Information and Communication Technology

Licentiate Thesis in
Communication Systems
Stockholm, Sweden 2011

KTH Information and
Communication Technology

Resource Sharing and Network Deployment Games

In Open Wireless Access Markets

DINA PAMELA GONZALEZ-SANCHEZ

Licentiate Thesis in
Communication Systems
Stockholm, Sweden 2011

TRITA–ICT–COS–1107
ISSN 1653–6347
ISRN KTH/COS/R--11/07--SE

KTH Communication Systems
SE-100 44 Stockholm
SWEDEN

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges till offentlig granskning för avläggande av teknologie licentiatexamen i radiosystemteknik tisdagen den 04 October 2011 klockan 10.00 i sal C1, Electrum 1, Kungliga Tekniska Högskolan, Isafjordsgatan 26, Kista.

Tryck: Universitetsservice US AB

Abstract

The most recent problem that wireless service providers (SPs) face nowadays is related to the introduction of the new market rules i.e., flat rate pricing policies.While SPs have deployed additional infrastructure in order to provide higher data rates to increasing numbers of customers the flat rate pricing policies have lead to decreased profits by the SPs. These flat rate revenue streams in combination with rapidly growing costs associated with conventional access deployment have resulted in what is usually referred to as the “revenue gap”. Efficient utilization of radio resources has became the key enabler to satisfy both the service provider (the operator) and the users. This points out to the need for better radio resource management (RRM). The challenge is to design mechanisms that allocate resources on a dynamic basis (i.e., dynamic spectrum access (DSA) and management, power control, cooperation enforcement, etc.) in order to either reduce or close the revenue gap *without* negatively impacting users' performance. Efficient utilization of radio resources is one solution to this problem, as it would allow SPs to support high data rates while providing wide area coverage at relatively low cost.

In this thesis, we study competitive games among revenue seeking SPs and the impact on their revenues and on the user' performance. We analyze the problem described above from two perspectives. First, we focus on a particular system where limited available spectrum resources are allocated among the SPs dynamically by a Spectrum Broker. We study the effect of channel heterogeneity (frequency channels that differ in propagation conditions and interference levels) on the performance of the system in terms of spectrum utilization, SP's profit, and energy consumption. In the second part, we analyze several different competitive network deployment games. We focus on a scenario where wireless networks (different SPs) with limited available bandwidth cope with the problem of how to maximize their network revenue. Noncooperative games between users and SPs are investigated and an open wireless access market is introduced based on network deployment strategies.

Based on the results of the studies that were performed, we observe that although there are considerable approaches (in literature) supporting that competitive schemes are good strategies for load balancing, the output of our study reflects that competition for spectrum resources based on users request (real-time allocation) leads to dead race when the over load case is considered. A negative impact in SPs' profits is observed and might thus not be the most effective solution if revenue-seeking SPs are considered. However, under the specific assumptions for the analysis in Chapter 2, it has been shown that the spectrum utilization could be substantially improved if the channel heterogeneity is

taken into account when devising spectrum access schemes. Regarding deployment strategies, providing partially overlapping coverage in a competitive fashion is an option for SPs to maximize their profits. Results indicate that the fraction of coverage overlap affects both the quality of service experienced by the users and the profitability of the access providers. However, a suitable percent of overlapping service areas by the two networks may be beneficial to all in the system. We can also infer that a prior analysis based on the strategies used by the opponent SPs should be implemented by a newcomer SP before entering the wireless market. When an incumbent places its network properly according to the demand, it is less likely for an entrant to be self-sustained in the market.

Acknowledgements

The LORD Jesus Christ has blessed me with the opportunity to grow not only professionally but also spiritually during the journey of getting a Licentiate degree. I thank HIM for all in all! My sincere gratitude goes to Professor Jens Zander, my advisor, for giving me the opportunity to join the COS group and for his guidance and encouragement during these studies. I really appreciate all our discussions which helped me grow and inspired me with new ideas. May the LORD bless you. Special thanks to everybody in my church KLIPPAN for their prayers. They have been like a family to me in Sweden during the last few years.

I am thankful to Dr. Klas Johansson (Ericsson) for reviewing my Licentiate proposal and for all valuable comments that helped improve this thesis. To Professor Seong-Lyun Kim for reviewing a preliminary version of this thesis. I am very thankful to Dr. Claes Tidestav (Ericsson) for accepting the role as opponent on my defense. Many thanks to Professor Gerald Maguire for his valuable feedback in some of the work included in this thesis.

I would like to take this opportunity to thank my colleagues at the Communication System department and let you all know how I have enjoyed working with you these past few years: Dr. Östen Mäkitalo, Dr. Pietro Lungaro, Dr. Ki Won Sung, Dr. Jan Markendahl, Professor Claes Beckman, Professor Ben Slimane, Jan-Olof Åkerlund, Anders Västberg, Göran Andersson, Saltanat Khamit, Tafzeel ur Rehman, Ali Özyagzi, Evanny Obregon, Lei Shi, Do Ho Kang, Sibel Tombaz, and Serveh Shalmashi. Also to former colleagues: Dr. Luca Stabellini, Dr. Bogdan Timus, Dr. Aurelian Bria, Dr. Ömer Ileri, and Dr. Johan Hultell. For all the support in administrative issues and technical matters I thank Adriana Flores (from Nicaragua), Anna Barkered, Irina Radulescu, Ulla Eriksson, Robin Gehrke and Richard Andersson.

I am grateful for the experience, good talks, and challenges I got from my colleagues in Nicaragua: Dr. Marvin Arias, Dr. Marvin Sánchez, Oscar Somarriba, Dr. Leonel Plazaola, Marco Munguia, Pablo Vásquez, Johnny Flores, Anayanci López, Norman Vargas and Apolinar Picado. In general, I would like to thank anyone who has worked at the department of Communication Systems COS/KTH in Sweden and at the National University of Engineering (UNI) in Nicaragua, for providing a fun and warm work environment.

Special thanks to my friends for sharing good moments and for caring for me:

Karolina Björsund, Anna Palbom, Islam Al-yafawi, Luis Guillermo Martinez, Miurel Tercero, Raul Rodriguez, Aaron Josué Quiróz, and Cristobal Viedma. To my fiancé, Pethrus Gärdborn, for his love and care. I am indebted to my family for their unconditional love and support, specially to my wonderful mother Maria Felix Sanchez for all her prayers and encouragement. She has always been there for me, always.

The financial support from the Swedish International Development cooperation Agency (SIDA) and the National University of Engineering (UNI) is gratefully acknowledged. This was a cooperation between the department of Communication System COS/KTH in Sweden and UNI in Managua, Nicaragua.

Pamela Gonzalez Sanchez
Kista, September 2011

Contents

List of Tables

List of Figures

List of Abbreviations

AC	Alternate Current
AP	Access Point
APs	Access Points
BR	Best Response
BS	Base Station
BSs	Base Stations
$CAPEX$	Capital Expenditures
$COCORA$	Conference on Advances in Cognitive Radio
$CoRR$	Computing Research Repository
$CROWNCOM$	Conference on Cognitive Radio Oriented Wireless Networks and Communications
dB	Decibel
DC	Direct Current
DSA	Dynamic Spectrum Access
$DySPAN$	Dynamic Spectrum Access Networks
EW	European Wireless
GHz	Gigahertz
$IEEE$	Institute of Electrical and Electronics Engineers
ICC	International Communication Conference
$ICMCS$	International Conference on Multimedia Computing and Systems
$ICUMT$	International Congress on Ultra Modern Telecommunications

KTH	Kungliga Tekniska Högskolan
QoS	Quality-of-Service
MHz	Megahertz
MODyS	MultiOperator Dynamic Spectrum Access
MVNO	Mobile Virtual Network Operators
NEP	Nash Equilibrium Point
NOMS	Network Operations and Management Symposium
OPEX	Operating Expenditures
PIMRC	Personal, Indoor and Mobile Radio Communications
RAN	Radio Access Network
RAT	Radio Access Technology
RRM	Radio Resource Management
SIDA	Swedish International Development Cooperation Agency
SNR	Signal-to-Noise Ratio
SP	Service Provider
SPs	Service Providers
TDMA	Time Division Multiple Access
UK	United Kingdom
UNI	Universidad Nacional de Ingenieria
USA	United Stated of America
VTC	Vehicular Technology Conference
WiCOM	Wireless Communications, Networking and Mobile Computing
3*G*	Third Generation

List of Notation

Notation (and default units) used in Chapter 2:

$C_{Cost(j)}$	Channel cost or cost of frequency j
Co	Constant based on the SNR_{th}, noise power and speed of light
$d_{r,i}$	Distance between the base station of provider r and the user i
f_j	Frequency j
K	Energy Cost in *monetary units/power units*
SP_r	Service Provider r
$P_{(r,i,j)}$	Power required by service provider r to reach user i on channel j
$U_{(r,i,j)}$	Utility of service provider r when serving user i on channel j
x_{user}	Fixed price that each user pays to the SP for the service

Notation used in Chapter 3:

$A_{i,j}^m$	Acceptance probability of user j in auction i at base station m
β	Location of the pick of the demand
c, μ, ζ	Positive constants to shape the acceptance probability function
D_0	Potentially offered load in megabits/BS/second
ϵ	Reservation price
ϵ_{max}	Maximum reservation price
ϵ_m	Reservation price established by base station m
ϵ_m^*	Best response associated with base station m

ϵ_{min}	Minimum reservation price, fixed cost incurred by the SP
λ	Package arrival intensity
l	Users' location
L	Longitude of the system area
N	Number of users in the system
q	Size of the file to be downloaded
R	Cell radius
$R_{i,j}$	Data-rate experience by user j in auction i
$R_{z,j}$	Data-rate experience by user j in auction z (last round)
σ	Level of market share
σ^2	The measure of the width of the user distribution
$s_{i,j}$	Bid in *monetary units* that user j places in auction i
$S_{i,-j}$	Bids of all the opponent users, represented also as $s_{i,k} + \epsilon$
$s_{i,j}^m$	Bid that user j places in auction i at base station m
T_A	Auction cycle equal to 1 second
$U_{i,j}$	Utility of user j during auction i, value for money
$\hat{U}_{i,j}^m$	Estimated utility by user j during auction i at base station m
$x_{i,j}$	Portion of transmission time for user j in auction i
x_1	Coverage of base station 1
x_2	Coverage of base station 2
z	Last auction round

Part I

Chapter 1

Introduction

1.1 Background

Wide area mobile communication systems were primarily designed to provide cost efficient wide area coverage for users with moderate bandwidth demands. The high demand for these services, combined with decreasing terminal prices and reasonable infrastructure investment requirements for operators created a very successful evolution environment in the beginning of the 20^{th} century [2]. However, this combination of factors is not longer true. The rapidly increasing demand for high-speed wireless data services has lead to bursts of high bandwidth demands from users in wide area wireless networks. Additionally with the large numbers of users, many of whom want and use high speed services, the total traffic load increases while revenue has flattened out as shown in Figure 1.1.

The lack of additional spectrum and the introduction of new market rules, i.e., flat rate pricing policies, have prompted SPs to deploy additional infrastructure, i.e., more base stations (BSs), in order to provide higher data rates, which in turn negatively affects their profits. The flat rate revenue streams in combination with the rapidly growing costs associated with conventional access deployment is usually referred to as the *"revenue gap"*, as shown in Figure 1.1. This rapid development of mobile broadband access services have vastly increased the interest in wireless solutions which combine high-capacity with low-cost [3].

Efficient utilization of radio resources[1], i.e., infrastructure, energy and spectrum, has always been a tool for service providers to improve the performance of their networks and lower their operational costs[2]. This problem has attracted research

[1] Generally referring to efficiency of utilization of a radio channel (i.e., choosing the appropriate time slot, frequency band, dynamic channel allocation) and transmit power.

[2] The operational costs include all of the annual costs of operating the network, including electrical power, personnel, taxes, etc.

interest in the last few years and new approaches have been introduced where resources are allocated dynamically (by means of Dynamic Spectrum Access (DSA) and management, power control, cooperative enforcement, etc.) striving for better RRM in order to reduce the revenue gap.

Sufficient availability of radio spectrum allows service providers to reduce their investment costs [4, 5]. Therefore, efficient radio spectrum management plays an important role in order to support high data rates while offering wide area coverage at relatively low cost. Unfortunately, spectrum is not yet properly managed and the implementation of DSA mechanisms require large investments in software, signaling, coordination, etc, hence well devised network deployment strategies are an important and interesting aspect of providing a practical solution to the problem of the revenue gap.

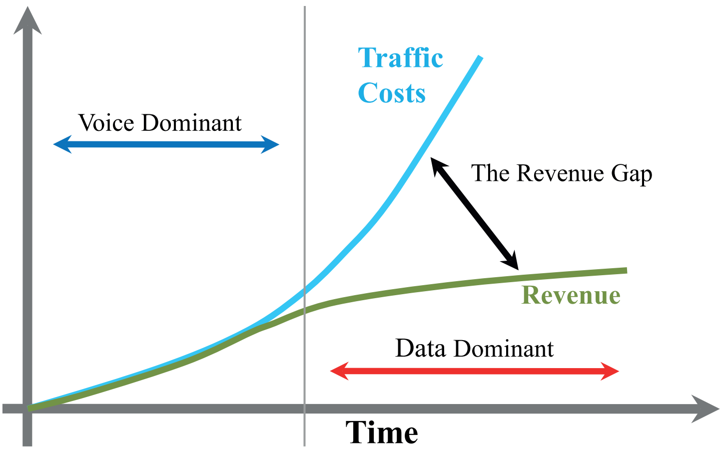

Figure 1.1: The Revenue Gap

Sharing resources is a promising way to efficiently utilize radio resources and hence lower network costs. In the following subsection an overview of the benefits of radio resource *sharing* is given.

1.1.1 Resource Sharing

The benefits that can be obtained by sharing network resources are: cost-oriented (i.e., lower CAPEX[3] and OPEX[4]), customer-oriented (i.e., higher capacity, more coverage, end-user better quality of service (QoS) in terms of achievable throughput), regulatory reasons (i.e., satisfying licensing agreements), environmental benefits (i.e., reduced number of sites, power consumption), etc.

In this thesis we focus on the cost reduction benefit and consider, specifically, two ways of sharing; *infrastructure* and *spectrum sharing*. The first method refers to the use of common networks or parts of networks, different types of roaming [6], deployment based on different technologies, offloading to local networks, sharing a common geographic region, mutual service provisioning (as a business model), and others strategies [3]. Spectrum sharing schemes, on the other hand, allow several operators to share frequency carriers from a common pool [7]. This enables them to serve on-demand traffic while minimizing their investment risks due to reduced CAPEX – since the number of base station sites can be reduced substantially [3].

- Spectrum Sharing: Due to the current static way of allocating the frequency spectrum, the amount of identified available resource is not large sufficient to support large bandwidth allocations for many operators. Therefore, it is of paramount importance for future mobile cellular systems to share the frequency spectrum [8]. Dynamic mechanisms, aiming to put spectrum to its best use on a short-term time-scale, have been widely proposed in literature [9–13]. Such models, tailored for future systems, are designed to allow sharing either on a competitive or cooperative fashion and in both temporal and spatial domains.

  Competitive spectrum sharing is usually done by service providers who share a block of spectrum in a competitive fashion aiming to selfishly maximize their individual utilities. In cooperative spectrum sharing, on the other hand, a group of wireless operators agree to share the available spectrum and together maximize *the system utility*. An example of this is the secondary spectrum access model where the primary and secondary users (systems) collaborate and coordinate by agreeing on terms and conditions of sharing (i.e., by establishing what frequencies, when to share, and prices).

  In thesis, we have partially studied competitive spectrum sharing; where SPs accesses the spectrum in a competitive fashion. It has been debated that com-

[3]The CAPital EXpenditures represent expenses to upgrade the physical network or equipment. This type of outlay is made by service providers to maintain or increase the quality of their networks and services.

[4]The Operating EXpenses represent ongoing costs for running the network, supporting business, and other costs required to keep the system operating.

petitive spectrum access[5] puts frequency spectrum to its best use. Allocating spectrum licenses among several wireless SPs creates competitive scenarios[6] and a rapidly growing wireless industry [20,21]. It has been clear that *competition* drives SPs to participate in auction mechanisms to get cellular spectrum licenses, makes them willing to pay high prices in order to assure *exclusivity*[7], and keeps new entrants out of the wireless market. This also allows the SPs to provide higher data-rates without being forced to deploy more base stations.

- Infrastructure Sharing: From an economic point of view and because wireless networks are often composed of a mixture of radio access technologies (RATs), *infrastructure sharing* is a possible cooperative alternative which offers high speed data access in a cost efficient manner [22]. The starting point is usually the sharing of passive infrastructure i.e., towers, shelters, air conditioning and cooling systems, AC and DC power supplies, and diesel generators. Sharing leased lines and microwaves links also help optimize access transmission[8]. The sharing of network infrastructure presents economic options for coverage and capacity growth for new entrants as well as network consolidation through cost optimization and technology upgrades for incumbent operators [1,23].

  Infrastructure sharing can be categorized in three dimensions; *business model*, *geographic model*, and *technology model*, as presented in [1] and illustrated in Table 1.1.

  The business dimension focus on the parties involved and their contractual relationships. The second dimension considers in the different technology models. While the third dimension considers the operators' geographic market share, addressing their in coverage area and if they overlap or share this coverage area depending upon their business model and technology choices.

  This thesis contains some studies of the geographic model where we analyze the behavior of the system under different regimes; ranging from the full split

[5]This type of competition is carried out among service providers with the spectrum broker as a mediator. Examples of similar approaches based on competitive spectrum allocation via a spectrum broker can be found in [14–17]

[6]This competition is at the level of the consumer of wireless services, "the end user" and it is beneficial since this creates opportunities for them to get better services; specifically higher data-rates at lower costs [18,19].

[7]The SP could potentially limit competition at the level of wireless users by purchasing additional spectrum that would otherwise go to an entrant (Newcomer SP). This may represent a danger by limiting dynamic evolution of service if competition with other SPs is necessary to speed up buildout and development of new technologies [20].

[8]The case of UK operators, Orange and Vodafone [1].

Table 1.1: The three dimensions of infrastructure sharing [1]

Dimensions	Scope
Business Model	- Unilateral Service Provisioning - Mutual Service Provisioning - Joint Venture - 3^{rd} Party Network Provider
Technology Model	- Site Sharing - Access Transmission Sharing - Active Radio Access Networks (RAN) Sharing - 3G Multi-Operator Core Network - Roaming Based Sharing
Geographic Model	- Full Split - Common Shared Region - Unilateral Shared Region - Full Sharing

case through some common shared region until reaching the full sharing case (see Chapter 3).

The sharing of wireless infrastructure, however, raises the question of how resources and revenues should be divided when multiple subsystems, managed by potentially competing actors, are involved in delivering the access service. An alternative would be to share the infrastructure implicitly by establishing an open wireless access market wherein networks not only compete for users on a long-term time-scale, but also on a much shorter time-base. This could be realized with an architecture where autonomous trade-agents, that reside in terminals and BSs, manage the resources through negotiations [24–27]. In our studies we have used such a scheme, which is explained in detail later in Section 3.3 of the thesis.

In this thesis, we focus on competitive scenarios and investigate their impact on SPs' revenue and users' performance. Approaches to dynamic spectrum sharing and network deployment strategies have been studied in several particular forms, specifically

- **Auction Mechanisms** have been tailored for allocating transmission rights on a short term basis in order to provide efficient allocation of scarce resources. In our study, we first address spectrum auction as a competitive mechanism for spectrum sharing. Since their introduction in 1994, spectrum auctions have been remarkably successful in assigning and pricing spectrum. Assigning spectrum licenses to private for-profit companies throughout most of the world, including developed and developing countries, has led to the rapid development of wireless telecommunications. Indeed, wireless communications has become a factor in economic development [20, 28].

- **Noncooperative Approaches** have been adopted to solve many protocol design issues in wireless networks[9]. In a multi-user network, services are provided to multiple users in which each user is assumed to be rational enough to achieve their individual highest performance. Therefore, game theoretic formulations can be used, and a stable solution for the players can be obtained through equilibrium analysis [29]. In a resource management game, multiple players (i.e., users and network service providers) are assumed to act rationally to achieve their objectives. The solution to the game can be obtained by maximizing the network service providers' profits while satisfying the users [30].

1.2 Problem Formulation

In most systems for wireless communications, efficient utilization of scarce resources (*i.e., frequency spectrum, energy consumption, etc.*) has became the key enabler to satisfy both the service provider[10], (SP, the operator), and the users. A provider of wireless communication services wants efficient utilization of the system since the provider derives more revenue by providing services to more users. The user in turn wants a good quality-of-service (QoS) at a reasonable cost [22]. Although, new pricing rules[11] have been established in the wireless market, pricing benefits to the users, SPs have been affected negatively by a decrease in their revenues. The challenge is to design mechanisms that allocate radio resources efficiently aiming to close the revenue gap without hurting users' performance.

More efficient utilization of existing resources and low cost deployment are key solutions investigated in this thesis in the form of competitive games:

1. Open Spectrum sharing aims to investigate how this paradigm affects the utilization of available frequency spectrum resources as well as the impact

[9] These methods are mostly known and proposed as *game theoretic approaches*. In our specific case, the game theoretic analysis has been carried out via mean of simulation and the Nash equilibrium point has been calculated only for some sample scenarios.

[10] Providing higher revenues which compensates the costs of service provisioning.

[11] Referring to the flat rate pricing

of this spectrum sharing on SPs' utility[12] and users' performance. In this section, we address the following research question.

- How the propagation conditions in the frequency channels[13] may impact the performance of the system in terms of energy expenditure while providing services?

We study a particular system where limited available spectrum resources are allocated among the SPs[14] dynamically as short-term allocations, through auction mechanisms via a Spectrum Broker.

2. Network deployment strategies are sought that lower investment costs, increases SPs' profits, and provides high user satisfaction. Scenarios with spatially heterogeneous user distribution are examined. We first consider the case when users are uniformly distributed across the service area. Following this, the case of highly populated areas with increasing demand for wireless services, i.e.,"hot-spots", is modeled considering this as a driving force for entrant SPs to deploy wireless access networks in a duopoly market. It is worthy mentioning that incumbent SPs are "always" able to deploy new base stations (BSs) - if this would yield higher profits for them. We are interested in analyzing the case when incumbent SPs are not willing to extend their service offering areas by deploying more BSs. Studies addressing the consequences of this decision are presented. The following research statements are studied.

   - How the service provider's revenue is affected by the level of competition (which is later referred to as the level of overlap) and the traffic load variations in the system? We also investigate whether the users' quality of service, QoS, available data rate, and cost per Megabyte is affected by these two parameters.
   - Which pricing strategy should the SPs implement in order to maximize their profits in a competitive environment with a heterogeneous demand and under different market shares?
   - Through simulation analysis we intend to investigate and establish, whether or not, it is suitable for the Newcomer SP to deploy a network in a duopoly market according to the location of an Incumbent SP, and if so, where it should be placed.

[12] One can also refer to service providers' revenue.

[13] This is also referred as *channel heterogeneity* later in this thesis.

[14] In this scenario we have assumed that the service providers offer subscription-based services and that the users who have subscribed to a service cannot change their subscription until their contract ends.

1.3 Overview of the Thesis Contributions

The key contributions of the thesis in each of the chapters are summarized next, including previously published material on the research ideas and obtained results.

Chapter 2

Chapter 2 focuses on competitive spectrum sharing for heterogeneous channels[15]. This heterogeneity with regard to the frequency channels affects the profitability of the SPs due to the fact that the difference in channel characteristics influences the energy expenditure required to serve the end user. Therefore, a sub-problem of optimizing the energy consumption emerges. This sub-problem has been addressed in:

- **Paper 1:** M. Tercero, Pamela Gonzalez-Sanchez, Ömer Ileri, and Jens Zander "Distributed Dynamic Spectrum Access with Energy Constraint for Heterogeneous Channels", in proceedings of the fifth international conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom), Cannes, France, June 2010.

More specifically, Paper 1 studies a competitive scheme that can be used to optimize spectrum utilization and power consumption via optimally utilizing the heterogeneity of the channels in a distributed manner. The paper defines the different distributed spectrum access algorithms used in our model and provides a comparative analysis with the reference mechanisms which provide lower and upper bounds in terms of spectrum utilization. Results obtained from the simulation of the methods that have been studied are presented.

In this paper, all the authors contributed in devising the problem formulation. The modeling, simulation, and writing process were done by the author of this thesis and Miurel Tercero Vargas. Professor Jens Zander and Ömer Ileri provided valuable insight regarding the direction of the paper.

Chapter 3

Chapter 3 presents an analysis based on network deployment strategies under competitive settings. The effect of competition and market shares on the SPs' profitability and on the users' performance has been studied for some specific sample scenarios. We focus on the case where wireless networks (with different SPs) with

[15]Channels are considered heterogeneous (different) in terms of propagation characteristics, therefore, requiring different transmission power levels.

limited available bandwidth cope with the problem of how to maximize their network revenues[16]. Noncooperative games between users and SPs are investigated and an open wireless access market is introduced based on the different network deployment strategies. We first analyze the system performance in terms of service provider's revenue, users' quality of service, QoS, available data rate, and cost per Megabyte, assuming that the user traffic is uniformly distributed across the coverage area.

An explanation and detailed results of this analysis are included in:

- **Paper 2:** Pamela Gonzalez-Sanchez and Jens Zander. "Deployment Strategies in Competitive Wireless Access Networks", in proceedings of the first international Conference on Advances in Cognitive Radio (COCORA), Budapest, Hungary, April 2011.[Best Paper Award]

Next, we consider a more realistic situation where the user traffic is nonuniformly distributed and the demand is directly influenced by the price of the resources. We investigate demand-based revenue maximization in competitive network deployment games. The contribution in this case is given by a demand-based pricing strategy as a tool for service providers to maximize their revenues in a competitive wireless access market. The description of results and conclusion of this study is included in:

- **Paper 3:** Pamela Gonzalez-Sanchez, Saltanat M. Khamit, and Jens Zander, "Competitive Pricing with Demand Heterogeneity in Open Wireless Access Markets", in proceedings of the third International IEEE Congress on Ultra Modern Telecommunications and Control Systems (ICUMT), Budapest, Hungary, October 2011.

The last study on network deployment strategies in competitive scenarios is based on nonuniform traffic distributions. We consider an open wireless access market with an Incumbent SP and a Newcomer SP. The objective of both SPs is to attract and retain users in order to maximize their profits. A detailed explanation and results are included in:

- **Paper 4:** Pamela Gonzalez-Sanchez and Jens Zander, "Competitive Access-point Deployment in Mobile Broadband Systems", in proceedings of the tenth

[16] Here we analyze SP's profit rather than revenue. This shift in metric occurs in the papers 3 and 4.

Scandinavian Workshop on Wireless Ad-hoc Networks (ADHOC'11), Stockholm, Sweden, May 2011.

Paper 4 addresses the main problem that a Newcomer SP faces when entering the wireless market, i.e., to determine a feasible location for its BS (or access-point, AP) in order to capture most of the population (customers) and thus be sustainable in the market. We analyze whether or not it is profitable for the Newcomer SP to deploy its own network and if so, where the BSs should be placed. This will be formulated as a simple competitive network deployment strategy that provides insight for real scenarios and contributes to improving future network deployment models of revenue-seeking service providers.

Papers 2, 3, and 4, are results of research discussions between the author of this thesis and Professor Jens Zander. The modeling, simulation, and writing of these papers were performed by the author of this thesis. Professor Jens Zander provided valuable insight and comments concerning the direction of all the papers. Saltanat M. Khamit contributed in the writing process to Paper 3.

1.4 Thesis Outline

This thesis is organized in two parts. The first one, contains the contents from Chapters 2 through 4. Chapter 2 and 3 briefly summarize the studies that have been performed, including a short related literature review highlighting the specific research areas we have considered.

In Chapter 2, we motivate why *competitive spectrum sharing* has been considered in this research. The specific scenario under investigation is also explained and finally some results are introduced followed by a short discussion.

Chapter 3 presents studies of network deployment strategies for revenue seeking service providers under competitive settings. It contains details of the basic assumptions we have considered, the resource allocation mechanism that has been used, the open wireless access model, and three different scenarios that have been investigated.

Chapter 4 contains concluding remarks and suggests some ideas for possible future research ideas. The second part consists of *verbatim* copies of all the papers included in this thesis.

Chapter 2

Competitive Spectrum Sharing

The currently enforced spectrum management mechanisms for cellular networks mostly rely on static allocation of frequency channels across SPs. In this allocation method an SP gets dedicated usage rights for a specific band for a long term. Such static allocation mechanisms guarantee interference-free operation and exclusive rights to offer mobile services. Debates concerning higher flexibility for the spectrum licenses have became more common of late and the necessity to make changes in the regulatory scheme is becoming evident [31].

Research suggests that static spectrum allocation methods are inefficient in terms of spectrum utilization for dynamic traffic, especially when the demand changes drastically over the time [32]. Therefore, dynamic spectrum access mechanisms (DSA), such as real-time allocations of spectrum, would be useful to balance demand and supply. In this chapter we study dynamic mechanisms in the specific form of *competitive frequency spectrum sharing* among wireless networks that offer mobile services based upon a subscription.

2.1 Related Literature

The rapidly growing demand for wireless communication services and the technological development have created a spectrum shortage. This apparent paradox is commonly referred as *spectrum scarcity*. Several authors argue that spectrum *per se* is not scarce - rather, it is inefficiently managed, in ways that restrict users' options to exploit this resource efficiently [33]. In light of this, there is a need for more efficient use of available spectrum resources. For this reason the development of new schemes for dynamic spectrum sharing, aiming to avoid the inefficiencies inherent in traditional licensing, have recently attracted significant interest.

Most of the earlier contributions concerning DSA schemes concentrated on scenarios where the frequency channels are considered as identical resources *(i.e., homogeneous channels)*, since all of the channels are assumed to be equal in terms of propagation characteristics [14, 34–36]. In such scenarios, DSA mechanisms are often implemented in the form of auctions where the prices for the different channels do not differ. In these auctions the auctioneer keeps increasing the unit cost for the channels until the total bandwidth demand is less than the total bandwidth supply. Only a few of the previous studies on DSA schemes [37–39] have considered *heterogeneous* channel settings, assuming that the channels have the same bandwidth but have different propagation characteristics. Therefore, the users experience different transmission ranges, and thus different frequencies are more or less suitable for different user locations. These studies focus on the description of how channel heterogeneity can be addressed in the context of DSA. However, these studies do not evaluate the effect of energy cost on efficient spectrum utilization.

Khamit and Zander [40] proposed a competitive spectrum allocation mechanism for wireless networks in which heterogeneous coverage was addressed. The authors investigated whether or not it is profitable for a small SP to deploy its own network and to compete against another SP who provides a wide service area. A DSA mechanism was implemented but, the channels were assumed to be homogeneous channels.

2.2 Why Spectrum Sharing?

Measurements of the spectrum usage have demonstrated that with static spectrum sharing[1] this resource is idle[2] most of the time and that new techniques for access and sharing of the spectrum resources are needed in order to increase its utilization. Spectrum sharing techniques allow SPs to effectively get larger "chunks" of spectrum (see Figure 2.1) and different frequency bands can be more efficiently utilized (trunking gains), thus enabling higher peak data rates to the end users.

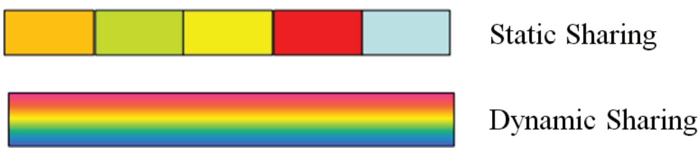

Figure 2.1: Schematic representation of two different methods for spectrum sharing.

The challenge that emerges in this context is to establish how to dynamically share the spectrum so that interference is minimized and spectrum is efficiently utilized, while SPs' revenues are maximized. This valuable resource can be managed

[1]This refers to the current way of spectrum management.
[2]Spectrum not being utilized at any time and place.

in two independent manners: as *cooperative sharing* where agreements between SPs must be established and *competitive sharing* where a coordinator of the competition may be needed. In competitive sharing access schemes all transactions and strategies are controlled – thus fairness in revenue generation and users' performance can be assured. In this Chapter, we investigate the later case, i.e., competitive sharing.

2.3 Distributed Spectrum Access with Energy Constraint for Heterogeneous Channels (Paper 1)

In this section we look at the scenario where SPs share a pool of limited spectrum resources in a competitive manner. We analyze the behavior of the system for "overload" situation, considering a high (but manageable) load which is greater than the available supply. Two main aspects are here considered; *channel heterogeneity* – which implies *energy constraint* – and we investigate the impact on the system performance.

- **Channel Heterogeneity**: Channels are assumed to be heterogeneous based on the fact that they are located in widely separated frequency bands and would show differences in transmission ranges meaning that they differ in propagation conditions and hence in inference levels. Our aim is to identify, under certain basic assumptions, how much spectrum utilization can be increased by accounting for the heterogeneity of the frequency channels.

- **Energy-constrained Wireless Networks**: as widely known, resource management has always been a tool for SPs to improve the performance of their networks. Consequently transmission power is an important resource to be managed efficiently. Energy-constrained wireless systems have been analyzed given the increased awareness about the excessive energy consumption of the communication systems[3]. It is likely that the energy consumption will become a major concern even for down-link transmissions in infrastructure systems [41]. Consequently, the propagation characteristics of available channels should be considered in spectrum allocation decision-making. On light of this, we also analyze the effect of energy-constrained wireless networks on the system's performance under competitive settings.

The basic competitive sharing scenario under investigation is addressed in Figure 2.2. We investigate the impact of frequency channels in different bands, *heterogeneity*, with different spectrum prices and we also analyze different Power cost required to provide the service.

[3] We can observe how the "green radio" paradigm has recently become a major concern.

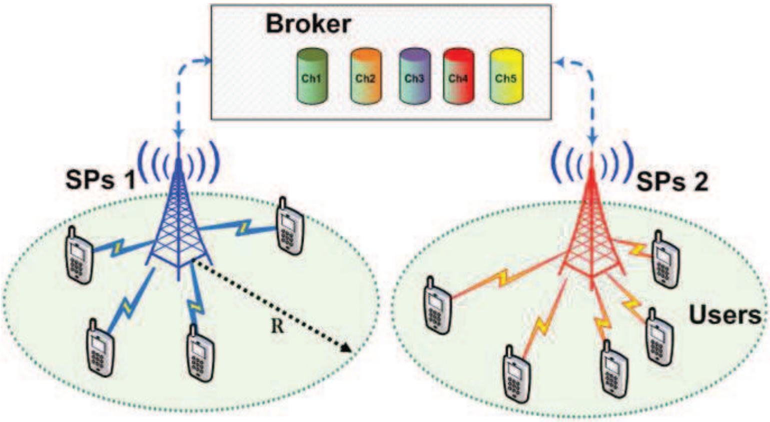

Figure 2.2: Wireless Network Structure - a competitive sharing scenario.

The SPs compete against each other in a dynamic fashion in order to get some frequency channels from the spectrum manager entity (introduced in the literature as the *Spectrum Broker* [14, 16]) and being able to serve their subscribed users while selfishly try to maximize their revenues, *network utility*[4]. Users are assumed to have a fixed subscription and they have the option to connect only to the SP they belong to. We explore *"channel heterogeneity"*, which is a unique feature of cognitive radio networks, where channels present different characteristics [37].

Two distributed DSA mechanisms which take into account the propagation characteristics and power requirements of different channels; *Sequential* and *Concurrent spectrum access* have been studied. The objective is to provide different means of propagation-aware DSA mechanisms[5], so that we might be able to understand which competitive schemes should be used to optimize spectrum utilization and power consumption as well as how the heterogeneity of the channels should be optimally utilized. Two regimes of interest are considered, the first one is when the transmission energy cost[6] is low, potentially related to a wireless network with large coverage area, and the second one when transmitting represents high cost corresponding to a wireless network with a poor coverage.

We model the transmit power that a given service provider r (SP_r) requires to reach user i using the channel j (frequency f_j), as stated in the following:

$$P_{(r,i,j)} = Co.(d_{r,i})^{\alpha}.(f_j)^2, \tag{2.1}$$

[4]In wireless systems network utility can be also referred to the throughput of the system.

[5]Referring to mechanisms that take into account the heterogeneity of the channels when making decisions regarding spectrum allocation. This allows to apply discriminatory pricing strategies.

[6]This refers to the monetary cost of each unit of energy required to transmit.

where Co is a constant computed from the SNR threshold, noise power and the speed of light, $d_{r,i}$ is the distance between the base station of the SP_r and the user i. Note, the dependence of $P_{(r,i,j)}$ on the propagation characteristic of channel j that is being utilized and the user location.

An important outcome from the auction process is the SPs revenue that has been introduced as the utility function, $U_{(r,i,j)}$, which is used as a decision-taking element by the SPs. Based on this the service is provided to those users that show positive utility[7], ($U_{(r,i,j)} > 0$), and is defined as follows:

$$U_{(r,i,j)} = x_{user} - C_{cost(j)} - K.P_{(r,i,j)}, \tag{2.2}$$

here x_{user} is the fixed price that each user pays to the SP for the service, $C_{cost(j)}$ is the channel cost that keeps varying during the auctioning phase (in monetary units) and K is the energy cost per session in *monetary unit/power unit.*

2.4 Results and Discussion

The main findings of this study are illustrated in Figures 2.3 and 2.4 and can be summarized as follows: The results from concurrent scheme show that by auctioning the channels based on their propagation conditions a considerable gain is provided in terms of spectrum utilization. Considering a low value of energy cost[8] is considered the sequential and concurrent mechanisms present almost the same performance as the Centralized in terms of channel occupancy, allocating the maximum possible number of channels. By assuming that the value of energy cost increases[9] a greater difference between sequential and concurrent schemes can be observed, showing that the concurrent access almost approaches the upper bound[10].

The maximum utility that a SP can perceive by serving a user is obtained from the Centralized mechanism – as it was expected – since the channel price is considered zero, see Fig.2.4. However, when the channel price is taken into account in the distributed mechanisms, sequential and the concurrent access, the last one gives higher utility. Furthermore, it can be observed that for low energy cost values an overload situation leads to "death race" between SPs. The channel cost, C_{cost}, and subsequent to this fact the SP utility starts to decrement radically after five users.

[7]The users have QoS requirement in the form of received SNR threshold value. We also assume that each SP's base station employs power control so that the transmit power at a given channel is the minimum power sufficient for achieving the required SNR value at the designated end user.

[8]For the simulation analysis a low value of energy cost is modeled with $K = 10$.

[9]High values of energy cost are represented with $K = 1000$.

[10]Presenting almost the same performance as that obtained with a Centralized allocation.

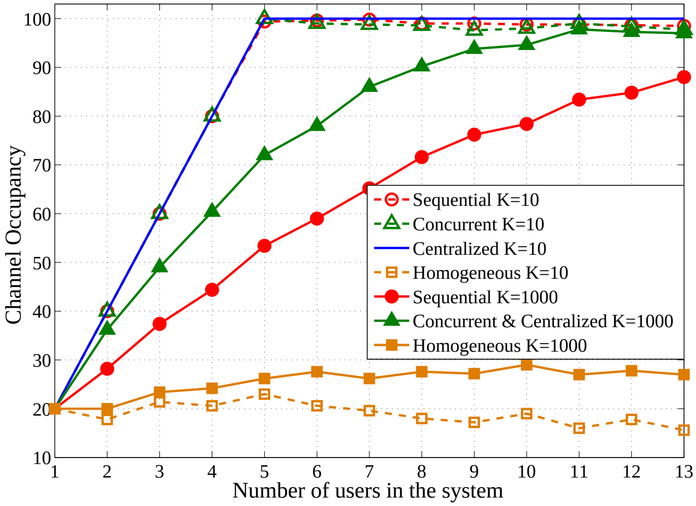

Figure 2.3: Channel Occupancy as a function of the number of users in the System.

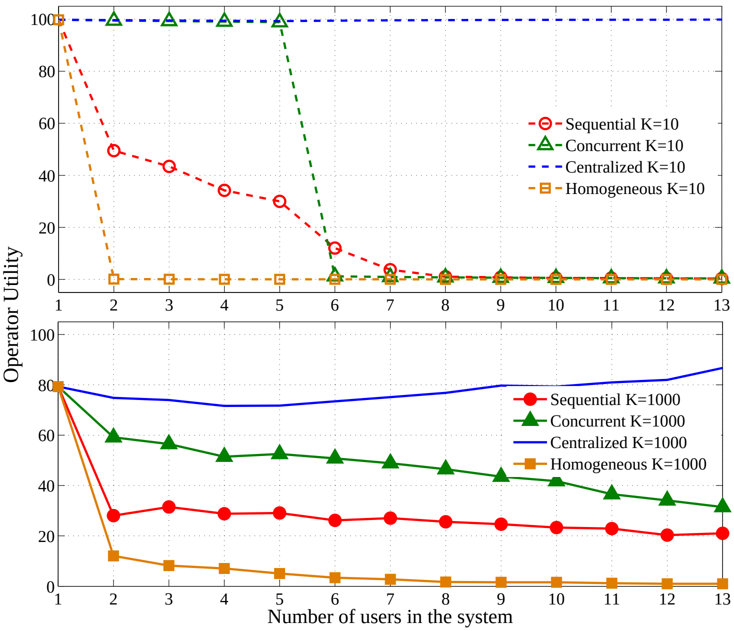

Figure 2.4: Service provider utility as a function of the number of users in the System.

2.5 Summary

Paper 1

Based on the simulation results, it can be concluded that the channel heterogeneity proves to be an important fact to be taken into account in order to improve the spectrum occupancy. In terms of profitability for the SPs some other cooperation strategies may be more efficient leading to better profits. There is an effect, obviously observed in auction mechanisms, that points to SPs willing to pay high prices for spectrum licenses with the objective to increase their market share aiming to keep entrants out of the wireless competition. To avoid this situation it has been assumed that the SPs offer subscribed services and bidding for a frequency channel that will not be used may only cause negative impact in their utilities.

In energy-constrained wireless network the SPs have to be aware of the power expenditure when choosing the $user - channel$ pairs. The sequential access mechanism presents higher power consumption per each served user due to the fact that all the channels are auctioned one by one consecutively and the SPs do not know whether or not the next channel is better. Under this condition, the concurrent access scheme proves to be the better option for dynamic spectrum access. Extended explanation and results are presented in [42].

Chapter 3

Network Deployment Strategies in Open Wireless Access Markets

The rapid increase of mobile internet traffic has put the spotlight on how the future wireless broadband access systems should be deployed and operated at significant lower costs per transmitted bit than today. Closing the "revenue gap" caused by the "lethal" combination of flat rate revenue streams and the rapidly growing costs associated with conventional access deployment is on top of the priority list of most wireless mobile service providers.

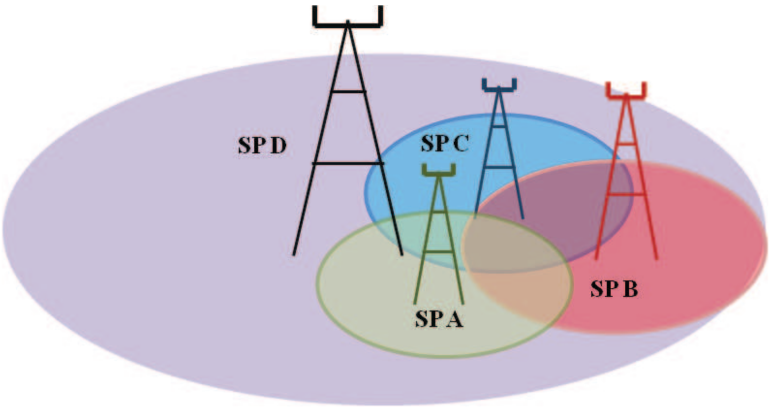

Figure 3.1: Service providers - choose their target areas and QoS offerings

Based on the technological development and business models, the trend in wireless access markets is pointing to a market with "plenty" of SPs utilizing numerous technologies and competing for users (see representation in Figure 3.1). Network deployment strategies that allow SPs cooperate and compete at the same time while maximizing their profits should be devised. On light of this, competitive sharing mechanisms ("coopetition") – where competing SPs cooperate by chosen their target service areas trying to avoid complete overlap with their competitor – are investigated in this Section.

The rest of this Chapter is organized as follows: Section 3.1 contains related literature in order to specify the research area considered in this chapter. Section 3.2 describes the dynamic resource allocation mechanism applied in all the investigated scenarios. In Section 3.3 a competitive sharing mechanism that allows SPs to identify a suitable coverage overlap among their network in order to maximize revenues is investigated. Section 3.4 addresses different competitive games based on network deployment strategies for profit maximization using a simulation approach.

3.1 Related Literature

The traditional way of infrastructure deployment has been that every operator provides his own access system in all locations, i.e., achieving "full" coverage by himself. This has been possible in most mobile phone systems due to the relatively low costs and high profit margins. As the increasing data rates require a much denser (and more expensive) network of base stations, full coverage is no longer an option to most operators. Instead *Infrastructure sharing*, where providers share infrastructure in low user density areas is one possible alternative to offer better coverage and QoS in a cost efficient manner [26, 43]. The sharing of wireless infrastructure, however, raises the question of how resources and revenues should be divided when multiple subsystems, managed by potentially competing actors, are involved in delivering the access service. An alternative would be to share the infrastructure implicitly by establishing an open wireless access market wherein networks not only compete for users on a long-term time-scale, but also on a much shorter time-base. This could be realized with an architecture where autonomous trade-agents, that reside in terminals and access points (APs), manage the resources through negotiations [24–27, 44].

In [24], the authors developed a framework for studying demand-responsive pricing in contexts where access points (APs) – with fully overlapping coverage – compete for users. They show that an open access market results in better services at lower price which in the long term also yields more satisfied customers compared to a scenario where APs cooperate. A market-based framework for decentralized RRM in environments populated by multiple, possibly heterogeneous APs, was introduced in [26]. The problem addressed for the user is to determine how much resources to purchase from different APs in order to maximize its utility ("value for money").

In competitive multi-user networks, services are provided to users assumed to be rational, choosing strategies in order to maximize their own utility. In such a game formulation of the resource management problem, the system performance can be expressed in terms of the Nash equilibrium, or solution of such a game, when none of the users can further improve their utility. [29, 30].

3.2 Resource Allocation Mechanism

In this study we use a game theoretic approach and the proportionally fair divisible auction mechanism introduced in [24, 26, 45–47]. The resources to be allocated among users is transmission time which is divided via employing the aforementioned auction mechanism.

In a proportional share fair allocation scheme each user is characterized by a parameter that expresses the relative amount of the resource that it should receive. Hereafter, the bid that the user submits to the BS is used to express the user's share. In this work a dynamic system has been modeled in which users are assumed to dynamically join and leave the competition (game). Therefore, the portion of the resource depends on both the number of users that enter the game and the level of competition at different times. This mechanism allows flexibility, since the users can decide when to join or leave the competition, and ensures fairness which follows from the fact that the users always get a share of the resource proportionally to their bids (as expressed in Equation 3.1).

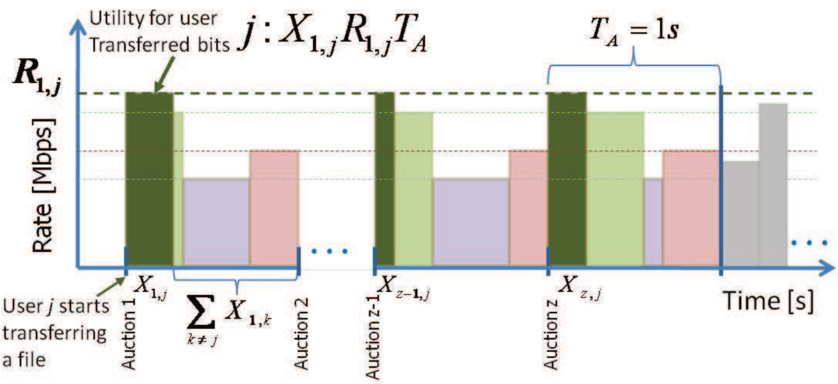

Figure 3.2: Representation of the auction procedure associated with a file transfer. In this example trade-agent j initiates a file transfer in auction 1.

We model a file download service, specifically, the download time in a wireless TDMA system with N selfish competing users and m BSs with overlapping coverage areas. The BSs are assumed to be identical in transmit power, system bandwidth, minimum received signal to noise ratio requirement, etc. We assume that the resource is infinitesimally divisible and that the cost associated with the file transfer depends on the total time-duration and the monetary expenditure required for the complete file download. As it is shown in Figure 3.2, the transmission time is allocated in several auctions.

We implement a trade-agent-based model for the auction bidding process.The trade-agents are entities located in the BSs, who act selfishly on behalf of their users. The main objective of each trade-agent is to maximize its user's utility (here computed as *value for money*). The portion of the transmission time allocated to user j can be expressed as follows:

$$x_{i,j}(s) \quad = \quad \frac{s_{i,j}}{s_{i,j} + S_{i,-j}} \in [0,1), \tag{3.1}$$

where $s_{i,j}$ denotes the bid in *monetary units* that user j places during auction i in order to get a portion of the available transmission time $x_{i,j}$ for a file transfer. $S_{i,-j}$ represents the strategies (bids) of all the opponent trade-agents and it is equal to $\sum_{k \neq j} s_{i,k} + \epsilon$ where the reservation price $\epsilon \in (\epsilon_{min}, \epsilon_{max})$. The reservation price is a nonzero price floor below which the resource will not be sold. Note that by definition the price floor must be nonzero as if it were zero, then there would be no price floor.

Assuming that the peak data-rate of a single user j on whose behalf the trade-agent j is acting, remains unchanged during the entire file transfer and that this applies for all the users, i.e. $R_{i,j}{=}R_{z,j}\ \forall\ i,z$, the total demand associated with the other trade-agents, thus $\sum_{k \neq j} s_{i,k}{=}\sum_{k \neq j} s_{z,k}\ \forall\ i,z$. Note that z is the last round of the auction as represented in 3.2. Due to these assumptions, each trade-agent will place identical bids in all the auctions.

3.3 Deployment Strategies in Competitive Wireless Access Networks (Paper 2)

In this section we study how competitive sharing ("coopetition"), where various access providers provide partially overlapping coverage in a competitive fashion, can generate additional gains to the SPs. Basically, we analyze how the the balance between areas of exclusive coverage (as shown in Figure 3.3) – where each SP has a monopoly situation – and overlap areas with provider competition, affects the profitability of the access providers. We use a game theoretic approach and the proportionally fair auction mechanism, described above (Figure 3.2). We seek to answer the following research questions: How is the operator revenue affected by the level of overlap? and further: Is the user QoS in terms of available data rate and cost per Megabyte affected by the overlap?

The scenarios studied can be illustrated as in Figure 3.3, where $s^{m}_{i,j}$ denotes the bid, that user j places in auction i at BS m (Note that we have assumed a purely time division multiplexed link). The link $user-SP$ indicates the link provided by the SP who dominates the market in this area (i.e., the access providers who provide coverage) and it is to this BS that users should send a positive bid in order to be served.

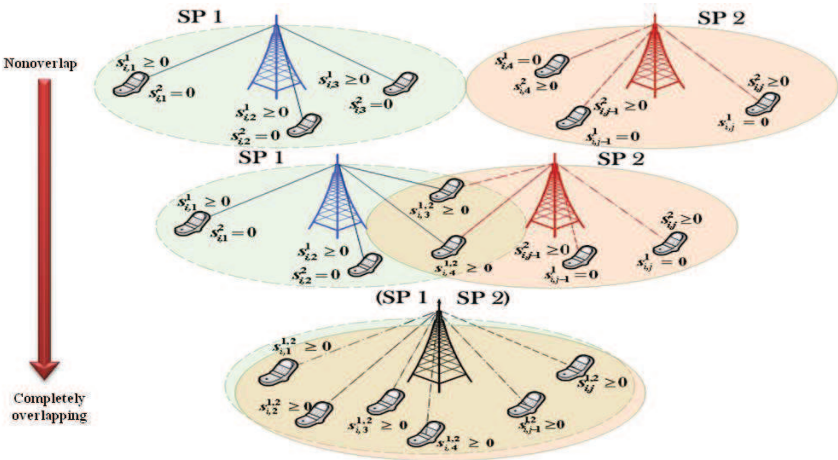

Figure 3.3: Basic scenario - Illustration of a wireless network architecture with different percentages of overlapping, which represents a system under different levels of competition

The user's performance (QoS) is quantified through the average user throughput and monetary expenditure per transferred Megabyte. The users compete against each other for resources - while trying to maximize their utility function in order to transfer a file. This game is expressed in Equation (3.2). For our analysis, we assume that the file size is finite (and identical), $q = 1$ Megabyte.

$$\begin{aligned} \varphi(s_{-j}) &= \arg\max_{s_j} U_{i,j}(s_j, S_{-j}) \\ &\forall \quad j \in \{1, ..., N\}, m \in \{1, 2\}. \end{aligned} \tag{3.2}$$

In the above equation $U_{i,j}(s_j, S_{-j})$ is related to the throughput, $x_{i,j}R_{i,j}$, associated with user j and is defined as:

$$U_{i,j} = \sum_{m=1}^{2} \max\Big[0,\ x_{i,j}R_{i,j}^{m} - s_{i,j}^{m}\Big]. \tag{3.3}$$

Deriving the first order solution (i.e., as a linear equation) of Equation (3.3) with respect to $s_{i,j}^{m}$ we can obtain the best response (BR) which describes how trade-agent j should react to the strategies (optimal bid that the trade-agent should submit the BSs) of all the other trade-agents in order to maximize its user's utility. This would be expressed as follows:

$$s_{i,j}^{m} = \sqrt{R_{i,j}^{m}(\sum_{k\neq j} s_{i,k}^{m} + \epsilon_m)} - \sum_{k\neq j} s_{i,k}^{m} + \epsilon_m. \tag{3.4}$$

Since the peak transfer rate for all of the users is the same over all auctions, and they all have to transfer the same size file, then giving each user the whole channel (i.e., all of the time slots) enables this user to complete and leave the system, hence leaving all of the remaining resources for the *remaining* users.

A second game takes place and it is defined as *open wireless access market*, when BSs compete for users and selfishly, try to maximize their own expected revenue per second, as defined in Equation (3.5).

$$\phi_m(\epsilon_{-m}) = \arg\max_{\epsilon_m} \Phi(\epsilon_m, \epsilon_{-m}), \tag{3.5}$$

$$\epsilon_m^{*} = \phi_m(\epsilon_{-m}^{*}) \quad \forall m \in M, \tag{3.6}$$

where $\phi_m(\epsilon_{-m})$ represents the best response (BR) function associated with BS m. Equation (3.6) describes the NEP which is the solution to the competitive game among BSs.

We focus in finding the Nash Equilibrium Point (NEP) for the reservation price of the resource, ϵ, considering the two games (competition among users for resources and among BSs for users) in the competition area for different levels of coverage overlap. This NEP is related to the Best Response from the trade-agents. In the monopolist area (non-overlapping coverage) only competition among users is observed. By obtaining the NEP we are able to analyze the BS's expected revenue with different levels of competition. These results enable us to predict the users' performance (in terms of throughput and monetary expenditure per transferred file).

The stability and uniqueness of the NEP for the games have been calculated through iterations via mean of simulation. Further details on these results and the pathloss model as well as the peak data-rate version used in our scenario can be found in [48].

Results and Discussion

The average revenue associated with the BS game for different levels of coverage overlap can be observed in Figure 3.4. As the overlapping area by the two wireless networks increases so does the level of competition and more users experience an *open access market*. The reservation price for the resource decreases as a consequence of the competition leading to lower BS's revenue.

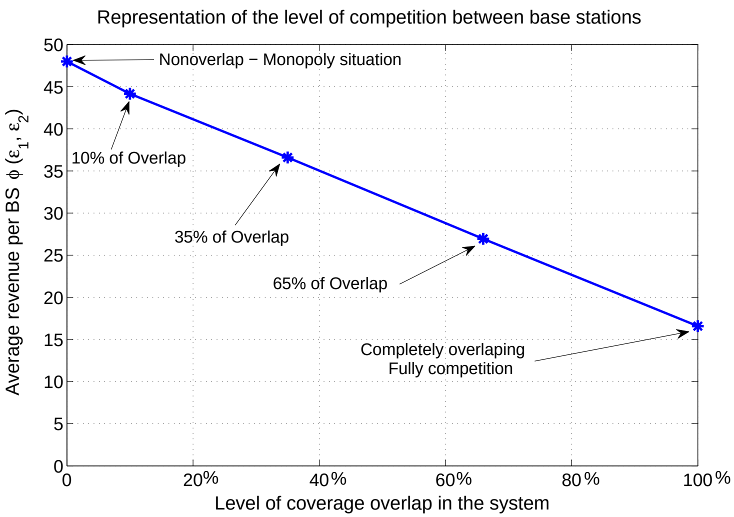

Figure 3.4: Average revenue per base station and time slot associated with the BS game under different percentages of overlapping coverage

Figures 3.5 shows that the experienced user's QoS is affected for low demand density. However, we can notice that for load density higher than 3.2 Megabits/second (λ=0.4 files/s) the degradation is slightly smaller leading to less impact on the user's experienced QoS and providing a great gain (more than 50%) in the BS's revenue.

It has been shown that as the BSs overlap less in coverage, the level of competition decreases and the BSs can charge the users in the non overlapping areas a higher price, and for low load, the user experienced throughput degrades considerably. For

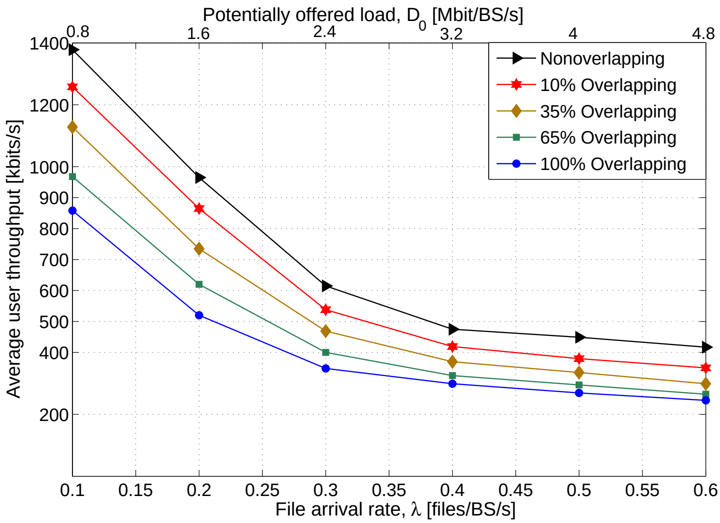

Figure 3.5: Average throughput experienced by users for different percentages of overlapping coverage as a function of the potentially offered load.

load density of 3.2 Megabits/second, and higher, the gain in throughput may be smaller giving less impact in the user's experienced quality of service (See Figure 3.5). On the other hand, our simulations indicate that a win-win situation for both users and BSs can be achieved with a suitable overlap coverage by two networks.

According to our results a proper percent of overlap might be approximately 35% depending on the interest or objective function of all the involved parties. Figure 3.4 represents the behavior of the revenue per BS on each auction round, where on average 0.4 files/s arrive to each BS, each file is of size q = 8 Megabits. We acknowledge the fact that the system's performance was analyzed by considering only two wireless networks in order to get insight on to which extent competition can be beneficial for both providers and users. Explanation and detailed results of this analysis are included in [48].

3.4 Competitive Games for Revenue Maximization with Heterogeneous Demand (Paper 3, Paper 4)

In order to maximize network revenue and be competitive in the market profit-seeking SPs shall utilize their resources efficiently and price their services properly based on the demand responsiveness. Pricing strategies play an important role in the network performance since these directly influence user demand. Clearly, uncertainty in traffic demand implies risk in revenue generation for SPs. In this section we analyze the price-demand relationship and based on this we aim to propose a pricing strategy as a tool for service providers to maximize their revenue.

3.4.1 System Model

We analyze a scenario where two wireless networks are deployed in a densely populated area with nonuniformly distributed users. We model the user population with a Gaussian distribution and its probability density can be expressed as below:

$$f(l) = \frac{1}{\sqrt{2 \cdot \pi\sigma}} \cdot e^{\frac{-(l-\beta)^2}{2\sigma^2}}, \tag{3.7}$$

where β is the mean (location of the peak of the demand), σ^2 is the variance (the measure of the width of the distribution) for the user position l within the system area [0 - L] where $L = 3 * R$. Here R is the cell radius defined in Table 1 in [49].

We assume an interference-free system and that the two networks, belonging to different SPs, overlap partially in coverage. We focus on communication in the downlink direction, i.e., from the BSs to the mobiles.

Wireless Access Market - Model

The users experience two location-based wireless markets: *monopoly access market* and *open access market* as illustrated in Figure 3.7. The monopoly market is observed while users are located in the non-overlapping areas, since there is only one BS providing access to its network. When the users are within the overlapping coverage by the two networks, they experience an open access market. A competitive game takes place among the BSs, who selfishly, try to maximize their own expected profit per second, as defined in Equation (3.11).

The users are able to pick the BS that offers the highest peak data-rate at the lowest price (highest *estimated utility*). Each BS broadcasts its reservation price among the users located within its coverage area. Note, that a price differentiation is used by the BSs, meaning that the users in the monopoly coverage area might experience higher costs in the absence of any competition.

As explained in [48], we model a file download in a TDMA system and apply a trade-agent based mechanism for the bidding process.

Resources are allocated using a proportional fair auction mechanism (this method is explained in detail in [48]) and based on their bids users will get a portion of transmission time defined by Equation (3.1) in Section 3.2.

Note that ϵ_{min}, the price floor in Equation (3.1), is a representation of the fixed cost incurred by the SP, $\epsilon_{min} = Cost$. For this study we have assumed a fixed cost $\epsilon_{min} = 2$, which has been previously considered in [14].

User Model

- **Utility Function**

In this analysis, we assume that a user picks the BS that provides the highest *estimated utility* and it is given the choice to not enter the system if the price established by the BS is too high. The user maximization problem is introduced in Equation (3.8).

$$\begin{aligned} &maximize \quad \hat{U}^m_{i,j}(R^m_j, \epsilon_m) \\ &\forall j \in \{1, ..., N\}, m \in \{1, 2\}, \end{aligned} \tag{3.8}$$

where $\hat{U}^m_{i,j}$ is the user's estimated utility which is used as the decision-taking parameter defined as bellow:

$$\hat{U}^m_{i,j} = \frac{R^m_{i,j}}{\epsilon_m}. \tag{3.9}$$

Here $R^m_{i,j}$ is the peak data-rate that the user experiences based on its location and ϵ_m is the reservation price broadcasted by the BSs.

- **Acceptance Probability**

Let us define x_1 as the coverage of BS_1 and x_2 as that of BS_2. Then, it is clear that user j located at $x_1 \cap x_2$, (see Figure 3.6) will therefore prefer, initially, BS_1 if and only if $\hat{U}^1_{i,j} > \hat{U}^2_{i,j}$ during auction 1.

Once the user has decided which BS provides the best service, its satisfaction and so the wiliness to pay for the offered service can be measured with an acceptance probability defined as follows:

$$A^m_{i,j} = 1 - e^{-c(\hat{U}^m_{i,j})^{\mu}(s^m_{i,j})^{\zeta}}, \tag{3.10}$$

where the c, μ and ζ are appropriate positive constants that determine the level of sensitivity to the offered price and QoS, and the shape of the function. Here

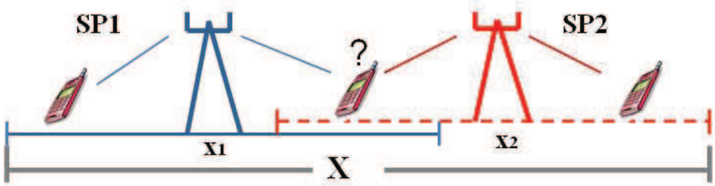

Figure 3.6: Base stations location - linear geographical region

$s^m_{i,j}$ 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 3.1). This acceptance probability model is a modified version of the one used in [14, 16, 40]. 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 - Profit Maximization

The BS's interest, instead, is to maximization its profit by serving as many users as possible. The demand-based profit maximization problem for the BSs is formulated by maximizing the sum of all submitted bids by the users that accept to enter the game in each auction cycle i and is defined as follow:

$$maximize \sum_{j=1}^{N} \left(s^m_{i,j} . A^m_{i,j} \right). \tag{3.11}$$

The summation of all the users that choose BS m formes the generated demand which accepts the service with a probability $A^m_{i,j}$. The average revenue per BS, the monetary expenditure and average user throughput, all as a function of the resource price, have been used to measure the system performance.

3.4.2 Pricing Game with Heterogeneous Demand in Open Access Markets (Paper 3)

In this paper we, basically, study the case where N competing users are non-uniformly distributed across the coverage area, $x \in [0, L]$, which is shared by two base stations BSs (we assumed that the BSs belong to different SPs). This scenario is represented in Figure 3.7.

These two networks are deployed with areas of exclusive coverage (monopoly situation) and partially overlapping area (competition for users). We are interested

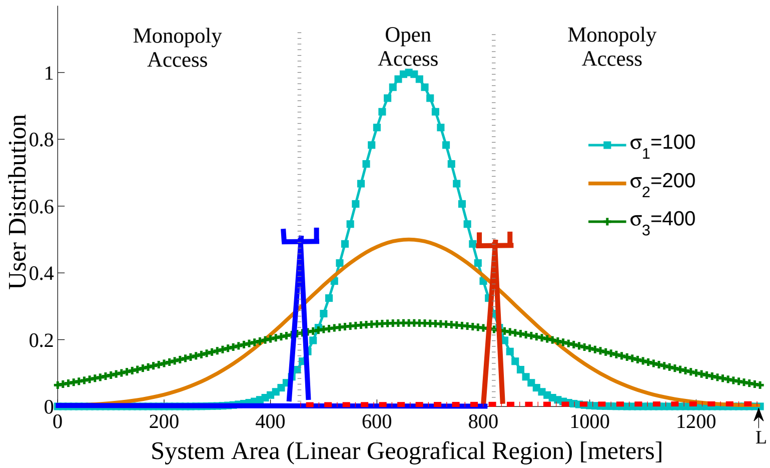

Figure 3.7: Network Deployment - Given Scenario1

to answer the following research question: Which pricing strategy should the SPs implement in order to maximize their profits in a competitive environment with a heterogeneous demand and under different market shares?

Figure 3.7 shows that the users experience two location-based markets: *monopolistic wireless access market* and *open wireless access market*. The monopoly market is observed while users are in the nonoverlapping areas, since only one BS is providing access to the offered services. When the users fall in the competition area, overlapping coverage by the two networks, they are able to choose the BSs that provides the highest peak data-rate and the lowest price.

Results and Discussion

The system is analyzed under different levels of market share (inversely proportional to $\sigma = 100, 200, 400$).

Base Station's Profit:
Figure 3.8 shows the average profit per BS for $\sigma = 100$.This graph indicates that there is a max-min behavior on the generated profit. For certain price values, only one BS is able to maximize the utility of its network meanwhile the other BS gets the minimum possible. When both BSs applied the same price to the resource, an equilibrium point in profit is observed. When one decides to deviate from the equilibrium the opponent BS maximizes its profit and the one that deviates obtain the minimum possible value.

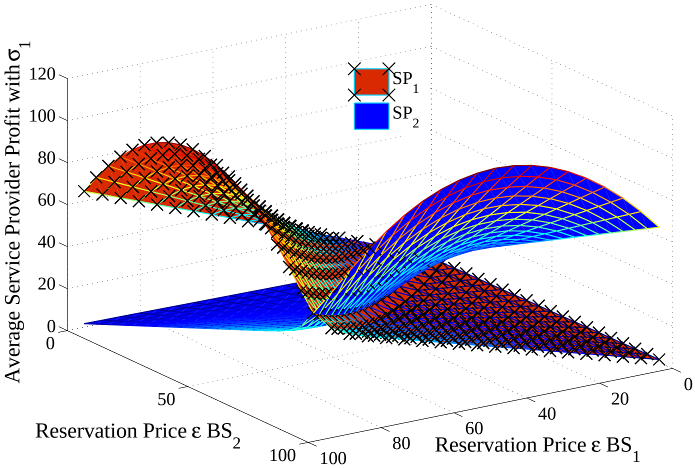

Figure 3.8: Average profit per BS per second in the System based on a demand-responsive pricing mechanism considering the case of a "high competitive" regime, with market share $\sigma = 100$.

Figure 3.9 shows the average profit per BSs when both SPs operate at the equilibrium broadcasting 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.

User Performance:
Since the users are given the choice to not enter the system if the reservation price of the resource is too high, we show in Figure 3.10 how they respond to the price established by the BSs. We demonstrate that with a higher level of market share (small σ) the users accept the service with high probability when the reservation price is relatively low. For high price values the users become more sensitive and the probability of accepting the service drops drastically.

In [49], extended explanations on the quality of service, QoS, experienced by users in terms of average throughput per second and monetary expenditure per transferred Megabyte can be found. It has been observed that for high level of market share, $\sigma = 100$, (i.e., when almost all the users fall in the competition area), the users get the lowest throughput. This fact can be explained considering that when the broadcasted reservation price is low, all competing users want to transmit and submit a positive bid.

Considering that fairness is guaranteed in the system, all of the users that submit a bid will get a small portion of transmission time. This is due to the fact

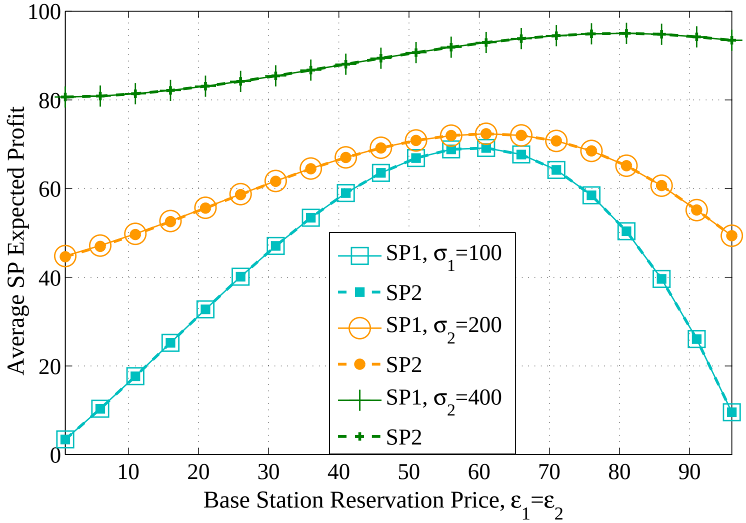

Figure 3.9: Expected BS profit per second as a function of the reservation price when $\epsilon_1 = \epsilon_2$.

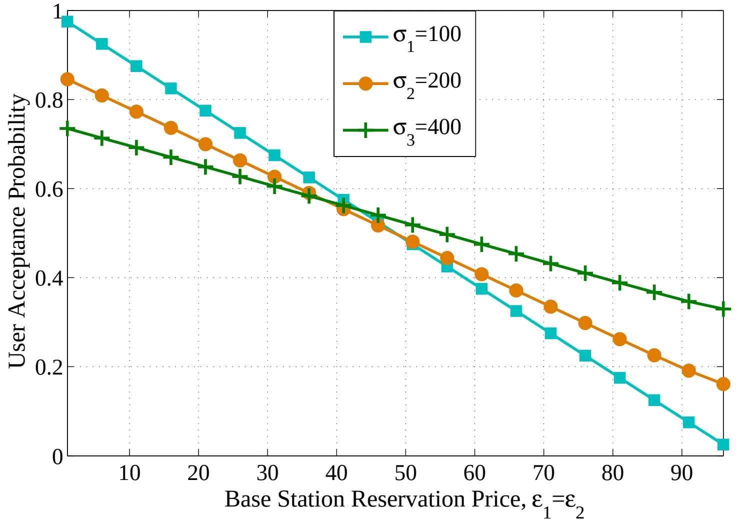

Figure 3.10: The user responsiveness in the system, denoted by the *Acceptance Probability* as a function of the reservation price during each auction cycle. We observe how the probability that the user accepts the service from a SP varies under different market shares, σ.

that the time slot is divided among all competing users, the more users actively bid for the resource the shorter time and lower throughput they will get. On the other hand, it is also observed (as expected), that competition lower prices, but this does not necessarily mean that it is optimal for the user performance. The shorter transmission time a user gets the longer it takes to download a file. The waiting time accumulates and the user might withdraw its bid in an auction, this negative consequence is, however, out of the scope of this thesis.

3.4.3 Competitive Access-point Deployment in Mobile Broadband Systems(Paper 4)

Here, we investigate network deployment strategies and aim to propose a feasible approach for revenue-seeking service providers regarding favorable access-point placement in competitive scenarios. We assume that an entrant SP is willing to deploy a wireless network and be competitive in a market that is already monopolized by an existing network as illustrated in Figure 3.11.

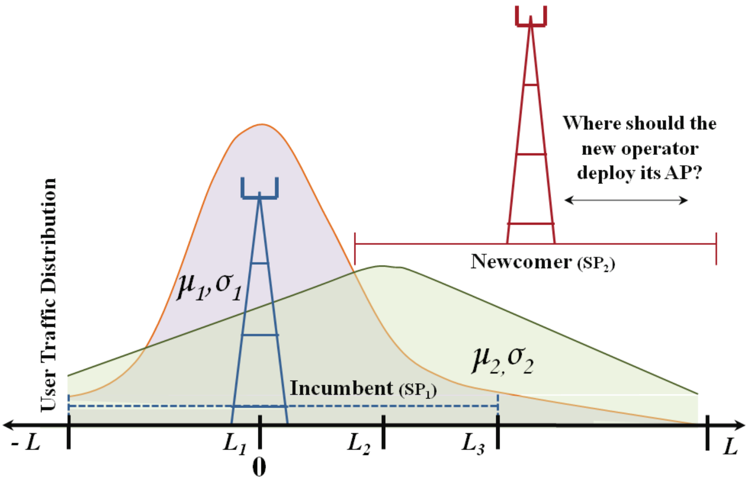

Figure 3.11: Illustration of a basic scenario when a newcomer SPs gets into the wireless market - Scenario2

An open wireless access market is observed when both BSs overlap in coverage. Clearly, new SPs will have to compete against the market rules of the incumbent wireless SPs, and optimum schemes should be developed to break through the marketplace.

Results and Discussion

A short summary of the simulation analysis is addressed in the following.

1. AP Profit Maximization

We consider the case when the incumbent has monopolized the market establishing a high price for the resource. A fixed price is assumed for the Incumbent, varying the reservation price of the Newcomer in order to determine the value that maximizes its profit. We investigate how the system behaves under different market shares, see illustration in Figure 3.11. The optimal price for the Newcomer was calculated only for $\sigma_1 = 100$ which presents a highly competitive scenario, meanwhile, $\sigma_2 = 500$ corresponds to a less competitive environment. Graphical representation and detailed explanation can be found in [50].

The simulation analysis shows that there is a price that maximizes the Newcomer's profit independently of its location for any given price established by the Incumbent. However, as already known, it is observed that the Incumbent is the one directing the course of the market, by establishing the price of the services and that the Newcomer should first study the strategies of its competitor. Once we have defined the optimal price of the Newcomer SP given the price of the Incumbent we carry out the competitive AP location game to estimate the suitable positioning of the Newcomer's AP. We also clarify that when μ_1 and σ_1 are taken into account the whole demand is inside the coverage area whereas with settings of μ_2 and σ_2 part of the users get in outage stage, out of coverage.

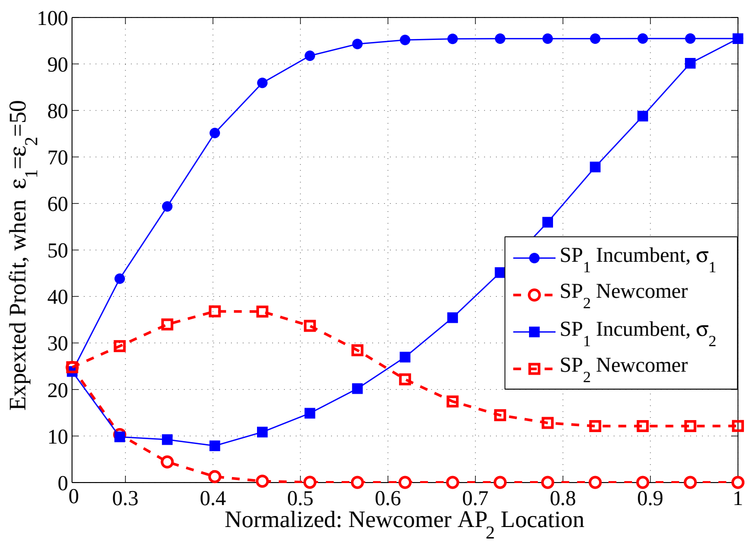

Figure 3.12: Expected profit per AP per second (time slot) as a function of the Newcomer's AP location. The Newcomer SP gets into the market pricing the services equally to the Incumbent.

In Figure 3.12 we observe the system's performance when the Newcomer enters the wireless market with an equal pricing strategy (imposing the the same price as the Incumbent). We have assumed a high price for the service $\epsilon_1 = \epsilon_2 = 50$ considering that the users have been given the choice to not enter the game if the established prices are too high. It can be observed that when the Incumbent is properly located according to the demand, the Newcomer should deploy its network co-located to the Incumbent. However the full competition setting provides but very low profits for both SPs. For the case when the Incumbent is not properly located (μ_2, σ_2), the Newcomer gets higher profits.

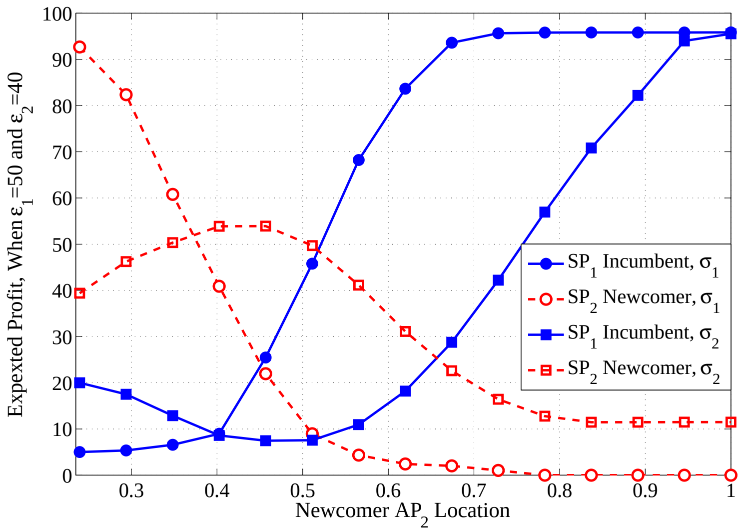

Figure 3.13: Expected profit per AP per second (time slot) as a function of the Newcomer's AP location. The Newcomer SP gets into the market with a lower price for the services.

Figure 3.13 shows that lowering the price for the service, compared to the Incumbent, seems to be a good strategy for the Newcomer to generate higher profits. Note that our assumption is that there is no reaction from the Incumbent to the strategy of the Newcomer. We acknowledge that this is not the case in real competitive scenarios and that an incumbent SP will always react to the strategies of its competitor leading thus to a price war, which in the end will affect negatively both SPs' profitability.

3.5 Summary

Paper 2

In this section a competitive sharing scheme ("coopetition") where two access providers provide partially overlapping coverage in a competitive fashion as an option to maximize their revenue has been analyzed. Specifically, the following research statement has been addressed: *how the balance between areas of exclusive coverage and overlap areas with provider competition affects the profitability of the access providers.*

Access providers with symmetric wireless networks that overlap partially in coverage compete with each other by selecting a reservation price. Based on the results it can be noticed that the fraction of coverage overlap does play an important role for both the performance of the system and the profitability of the access providers. As the level of overlap increases the revenue that each base station gets decreases significantly. In addition, the user's experienced throughput degrades considerably but only for low demand density (This is due to the fact that the price of the resource is low, then, all the users behave (compete) aggressively for the resource) meanwhile the cost per transferred Megabyte is affected in a low scale. Further, we conclude that a win-win situation for both users and access providers can be achieved with a suitable coverage overlap by two networks.

Paper 3

In this work, we studied a demand-based profit maximization strategy where a competitive pricing game has been used. An open wireless access market (with different size of market share) has been addressed, where two given networks overlap in service areas. Simulation results show that the competing service providers tend to aggressively drop a service price to capture a larger number of users in the highly populated area, while user throughput dramatically fails with a growth in service transactions (congested system). Our analysis reveals that the SPs may retain the demand and hence increase their profits by establishing a reservation price close to a market-oriented one. We believe that the SPs could learn and further adapt which pricing settings are viable in order to be competitive and sustainable in an open wireless access market. Under our assumptions and based on these observations we conclude that the optimal size of market share could be gained based on the behavior of the user demand and be beneficial for both users and SPs.

Paper 4

A prior analysis based on the strategies used by the Incumbent should be implemented by the Newcomer before entering the wireless market. When the Incumbent is properly located, according to the demand and both SPs have the same service price, there are less probability for an Entrant to be self-sustained in the market.

Decreasing the service price seems to be a good strategy to attract the demand, but considering real scenarios, an Incumbent will also decrease its price and this may end up in a price war leading to a negative impact in their profitability. On the other hand, when the Incumbent is not properly located, the case of μ_2 and σ_2, the Entrant is more like to succeed.

Chapter 4

Conclusion

4.1 Concluding Remarks

Nowadays, in wireless communication systems users are used to have high speed connections which are traduced, sometimes, as high quality of service (QoS). The high expectations of users have created an increasing capacity demand and the problem of "revenue gap" has emerged. Since the current way for spectrum allocation has limited the spectrum usage, apparently, there is not enough available spectrum for wireless communication. Dynamic spectrum access mechanisms have emerged with possible promising solutions to make efficient spectrum usage and thus devising attractive business models for the service providers and increasing user satisfaction. However, research studies and current network deployment models show, evidently, that additional spectrum is not the sole solution to achieving ubiquitous broadband wireless access. In order to overcome this problem awareness on different possible solutions to this issue has to be created. In addition to dynamic methods for spectrum access network deployment strategies have the potential to improve users satisfaction and increase SPs profit if well devised.

In the first part of the thesis we considered competitive wireless spectrum access and studied two main algorithms that take into account the fact that the frequency channels are different in propagation conditions. Since this is an important characteristic, which is closely related to the levels of power transmission, energy-constrained system have been also assumed. Although there are considerable approaches (in literature) supporting that competitive schemes are good strategies for load balancing, the output of our study reflects that competition for spectrum resources based on users request (real-time allocation) leads to dead race when the over load case is considered. A negative impact in SPs' profits is observed and might thus not be the most effective solution if revenue-seeking SPs are considered. Therefore, some other strategies either in a cooperative or competitive manner or a combination of both should be implemented.

In auction mechanisms it is often observed that SPs are willing to pay high prices for spectrum licenses. This is due to their objective to increase their market share aiming to keep entrants out of the wireless competition. On the other hand, under the specific assumptions for the analysis in Chapter 2, it has been shown that the spectrum utilization could be substantially improved if the channel heterogeneity is taken into account when devising spectrum access schemes.

In the second part we focused our attention on network deployment strategies addressing competitive sharing schemes ("coopetition") where two access providers cooperate with each other by providing partially overlapping coverage in a competitive fashion as an option to maximize profit. Access providers with symmetric wireless networks that overlap partially in coverage compete with each other by selecting a reservation price for the resource. We have modeled different market shares and a heterogeneous demand aiming to establish whether it is suitable for an entrant SP to deploy a wireless network and if so, under which conditions. Results on the first studied scenario indicate that the fraction of coverage overlap affects both the quality of service experienced by the users and the profitability of the access providers. However, a suitable percent of overlapping service areas by the two networks may be beneficial to all in the system. We believe that the additional investment costs of network deployment might be compensated by the gain obtained in revenues with this strategy, nevertheless, this issue is out of the scope of this thesis.

By applying a competitive pricing game we show that wireless service providers tend to drop the service price aggressively in order to attract the demand, which in turn affects their profitability. Meanwhile, the users throughput degrades considering that they actively bid when the prices go down and the transmission time slot is divided among a larger number of users through the proportionally fair auction. We believe that the SPs could learn and further adapt which pricing settings are viable in order to be competitive and sustainable in an open wireless access market capturing a near optimal size of market share that generates high profits.

From the performed studies we can infer that a prior analysis based on the strategies used by the opponent SPs should be implemented by any SP before entering the wireless market. When an incumbent is properly located according to the demand it is less likely for an entrant to be self-sustained in the market. Decreasing the service price seems to be a good strategy to attract the demand, but considering real scenarios, any incumbent will as well drop the service price and this might lead to a price war with negative impact in their profitability. On the other hand, when an incumbent is not properly located an entrant has higher probabilities to succeed.

4.2 Future Work

This section outlines possible directions for future work. As mentioned in the previous section, well structured and studied network deployment strategies have a great potential to improve the system performance of wireless networks. Allowing the wireless service providers to achieve cost-efficient service provisioning in mobile broadband systems. We consider that our work represents a small contribution to the tremendous amount work that can still be done on this area. In the following we state some additional issues that may lead to interesting results.

- Cooperative strategies where service providers buy capacity from existing SPs in the form of Spectrum trading. These SPs may operate as mobile virtual network operators (MVNOP) and yet compete in service provisioning with the existing SPs.
- Competitive pricing games in interference-limited systems would be interesting to investigate. Investigating if there exists an optimal price that maximizes users utility and provider's profit in competitive settings and under which conditions this could be possible. The result of this analysis may provide guidelines that might be used to select the scheme that better suits a specific scenario..
- Investigating network deployment strategies for revenue maximization and interference mitigation among heterogeneous wireless access networks.

Bibliography

[1] T. Frisanco, P. Tafertshofer, P. Lurin, and R. Ang, "Infrastructure sharing and shared operations for mobile network operators from a deployment and operations view," in *Proceedings of The Network Operations and Management IEEE Symposium, NOMS*, April 2008.

[2] J. Zander, "On the cost structure of future wideband wireless access," in *Proceedings of The* 47^{th} *IEEE Vehicular Technology Conference, VTC-Spring*, May 1997.

[3] J. Markendahl, "Mobile network operators and cooperation a tele-economic study of infrastructure sharing and mobile payment services," Ph.D. dissertation, Kungliga Tekniska Högskolan KTH, Sweden, 2011.

[4] HiQ Data AB, "Potential value of additional spectrum for an UMTS operator," April 2004. [Online]. Available: http://www.pts.se/upload/Documents/SE/UMTS_Value_of_extra_spectrum_D_april_2004.pdf

[5] J. Harno, T. Smura, K. Ratna, A. Hoikkanen, I. Welling, O.-P. Pohjola, Thor Gunnar Eskedal, R. Venturin, Borgar Torre Olsen, D. Katsianis, T. Rokkas, and Dirk van Hugo, "Final techno-economic results on mobile services and technologies beyond 3g. technical report, ECOSYS deliverable 19," September 2006. [Online]. Available: http://www.optcomm.di.uoa.gr/ecosys/deliverables/ECOSYS_Del19_v1.0.pdf

[6] J. Hultell and K. Johansson, "An estimation of the achievable user throughput with national roaming," in *Submitted to The* 63^{rd} *IEEE Vehicular Telecommunication Conference, VTC-Spring*, May 2006.

[7] M. D. Maran Kumar Pereirzrsamy, Jijun Luol and C. Hartmann, "An approach for inter-operator spectrum sharing for 3g systems and beyond," in *Proceedings of The* 15^{th} *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, September 2004.

[8] M. Bennis, "Spectrum sharing for future mobile cellular systems," Ph.D. dissertation, University of Oulu, Finland, 2009.

[9] S. Geirhofer, L. Tong, and B. M. Sadler, "Dynamic spectrum access in wlan channels: empirical model and its stochastic analysis," in *Proceedings of The first international workshop on Technology and policy for accessing spectrum, TAPAS*, 2006.

[10] R. Zarookian, "Feasibility of spectrum sharing between airborne weather radar and wireless local area networks," Ph.D. dissertation, Virginia Polytechnic Institute and State University, USA, 2007.

[11] S. Sengupta and M. Chatterjee, "Designing auction mechanisms for dynamic spectrum access," *Mobile Network Applications Journal*, 2008. [Online]. Available: http://www.cs.ucf.edu/~mainak/papers/SpectrumAuction.pdf

[12] J. Perez-Romero, X. Gelabert, O. Sallent, and R. Agustin, "A novel framework for the characterization of dynamic spectrum access scenarios," in *Proceedings of The* 19^{th} *IEEE International Symposium Personal, Indoor and Mobile Radio Communications, PIMRC*, September 2008.

[13] X. Chen and J. Huang, "Evolutionary game and learning for dynamic spectrum access," *CoRR*, vol. abs/1103.1026, 2011.

[14] O. Ileri, D. Samardzija, and N. Mandayam, "Demand responsive pricing and competitive spectrum allocation via a spectrum server," in *Proceedings of The* 17^{th} *IEEE Real-Time Systems Symposium*, November 2005.

[15] M. M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, "Dimsumnet: New directions in wireless networking using coordinated dynamic spectrum access," in *Proceedings of The IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, WoWMoM*, June 2005.

[16] O. Ileri, D. Samardzija, and N. B. Mandayam, "Dynamic spectrum access models: Toward an engineering perspective in the spectrum debate," *Communication Magazine, IEEE*, vol. 46, no. 1, January 2008.

[17] J. Bae, E. Beigman, R. Berry, M. L. Honig, and R. Vohra, "Approaches to spectrum sharing," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 7, September 2008.

[18] F. Berggren, O. Queseth, J. Zander, B. Asp, C. Jonsson, P. Stenumgaard *et al.*, "Dynamic spectrum access, phase 1 scenarios and research challenges," *Technical report, Royal Institute of Technology, TRITA-S3-RST-0407, Stockholm*, September 2004.

[19] K. Johansson, "Cost effective deployment strategies for heterogeneous wireless networks," Ph.D. dissertation, Kungliga Tekniska Högskolan KTH, Sweden, 2007.

[20] P. C. Cramton, E. Kwerel, G. L. Rosston, and A. Skrzypacz, "Using spectrum auctions to enhance competition in wireless services," *Journal of Law and Economics, Forthcoming; Stanford Law and Economics Olin Working Paper No. 406*, February 2011. [Online]. Available: http://ssrn.com/abstract=1757140

[21] T. W. Hazlett and R. E. Muñoz, "A welfare analysis of spectrum allocation policies," *The RAND Journal of Economics*, vol. 40, no. 3, July 2009. [Online]. Available: http://onlinelibrary.wiley.com/doi/10.1111/j.1756-2171.2009.00072.x/references

[22] J. Zander and S.-L. Kim, *Radio Resource Management for Wireless Networks.* Norwood, MA, USA: Artech House, Inc., 2001.

[23] D.-E. Meddoura, T. Rasheedb, and Y. Gourhanta, "On the role of infrastructure sharing for mobile network operators in emerging markets," *Computer Networks Journal Recent Advances in Network Convergence*, vol. 55, no. 7, May 2011. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128611000776

[24] M. Blomgren and J. Hultell, "Demand-responsive pricing in open wireless access markets," in *Proceedings of The IEEE Vehicular Technology Conference VTC-Spring*, Dublin, Ireland, April 2007.

[25] R. T. Maheswaran and T. Baçar, "Nash equilibrium and decentralized negotiation in auctioning divisible resources," *Group Decision and Negotiation Journal*, vol. 12, no. 5.

[26] M. Blomgren and J. Hultell, "Decentralized market-based radio resource management in multi-network environments," in *Proceedings of The* 65^{th} *IEEE Vehicular Technology Conference, VTC-Spring*, Dublin, Ireland, April 2007.

[27] R. T. Maheswaran and T. Baçar, "Coalition formation in proportionally fair divisible auctions," in *Proceedings of The second international joint conference on Autonomous agents and multiagent systems*, Melbourne, Australia, 2003. [Online]. Available: http://doi.acm.org/10.1145/860575.860580

[28] P. Cramton, "How best to auction natural resources," *Handbook of Oil, Gas And Mineral Taxation*, 2009. [Online]. Available: http://ideas.repec.org/p/pcc/pccumd/09anr.html

[29] D. Fudenberg and J. Tirole, *Game Theory.* MIT, Press, August 1991.

[30] D. Niyato and E. Hossain, "Radio resource management games in wireless networks: an approach to bandwidth allocation and admission control for polling service in ieee 802.16," *Wireless Communications, IEEE Journal*, vol. 14, no. 1, March 2007.

[31] J. Peha, “Approaches to spectrum sharing,” *Communications Magazine, IEEE*, vol. 43, no. 2, February 2005.

[32] M. Pattal and J. Zeng, “Spectrum management reforms: A step towards a flexible spectrum management,” in *Proceedings of The* 4^{th} *International Conference on Wireless Communications, Networking and Mobile Computing, WiCOM*, October 2008.

[33] F. Minervini, “Emerging technologies and access to spectrum resources: the case of short-range systems,” *Communications and Strategies Journal*, September 2007. [Online]. Available: http://mpra.ub.uni-muenchen.de/6786/1/MPRA_paper_6786.pdf

[34] S. Sengupta, M. Chatterjee, and S. Ganguly, “An economic framework for spectrum allocation and service pricing with competitive wireless service providers,” in *Proceedings of The 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, April 2007.

[35] S. Sengupta and M. Chatterjee, “Sequential and concurrent auction mechanisms for dynamic spectrum access,” in *Proceedings of The* 2^{nd} *International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom*, August 2007.

[36] G. Sorabh, B. Chiranjeeb, C. Lili, Z. Haitao, and S. Subhash, “Toward real-time dynamic spectrum auctions,” *Computer Networks*, vol. 52, no. 4, March 2008. [Online]. Available: http://portal.acm.org/citation.cfm?id=1343121.1343364

[37] M. Ma and D. H. K. Tsang, “Impact of channel heterogeneity on spectrum sharing in cognitive radio networks,” in *Proceedings of The IEEE International Conference on Communications, ICC*, May 2008.

[38] J. Sun and E. Modiano, “Wireless channel allocation using an auction algorithm,” *IEEE Journal on selected areas in Communication*, vol. 24, no. 5, 2006.

[39] V. Brik, E. Rozner, S. Banerjee, and P. Bahl, “Dsap: a protocol for coordinated spectrum access,” in *Proceedings of The* 1^{st} *IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, November 2005.

[40] S. M. Khamit and J. Zander, “Competitive spectrum allocation in heterogeneous coverage areas,” in *Proceedings of The the European Wireless, EW*, Vienna, Austria, April 2011.

[41] Kungliga Tekniska Högskolan, “Research project: Green radio-investigating energy consumption of wireless networks,” *Technical Report, Available: http://www.wireless.kth.se/projects/GREEN/index.php*, 2009.

[42] M. Tercero, P. Gonzalez-Sanchez, O. Ileri, and J. Zander, "Distributed dynamic spectrum access with energy constraint for heterogeneous channels," in *Proceedings of The* 5^{th} *International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom*, Cannes-France, June 2010.

[43] J. Markendahl, Östen Mäkitalo, J. Werding, and B. G. Mölleryd, "Business innovation strategies to reduce the revenue gap for wireless broadband services," *Communications and Strategies Journal*, vol. 1, no. 75, 2009. [Online]. Available: http://econpapers.repec.org/RePEc:idt:journl:cs7502

[44] A. Tonmukayakul, "An agent-based model for secondary use of radio spectrum," Ph.D. dissertation, University of Pittsburgh, USA, 2007.

[45] I. Stoica, H. Abdel-Wahab, K. Jeffay, S. Baruah, J. Gehrke, and C. Plaxton, "A proportional share resource allocation algorithm for real-time, time-shared systems," in *Proceedings of The* 17^{th} *IEEE Real-Time Systems Symposium*, December 1996.

[46] I. S. Hussein, H. Abdel-wahab, and K. Jeffay, "On the duality between resource reservation and proportional share resource allocation," in *Proceedings of Multimedia Computing and Networking*, 1997.

[47] L. Abeni, G. Lipari, and G. Buttazzo, "Constant bandwidth vs proportional share resource allocation," in *Proceedings of The IEEE International Conference on Multimedia Computing and Systems*, 1999. [Online]. Available: http://portal.acm.org/citation.cfm?id=839287.841966

[48] P. Gonzalez-Sanchez and J. Zander, "Deployment strategies in competitive wireless access networks," in *Proceedings of The International Conference on Advances in Cognitive Radio, COCORA*, Budapest, Hungary, April 2011, [Best Paper Award].

[49] P. Gonzalez-Sanchez, S. M. Khamit, and J. Zander, "Competitive pricing with heterogeneous demand in open wireless access market," in *Proceedings of The* 3^{rd} *International IEEE Congress on Ultra Modern Telecommunuication and Control Systems, ICUMT*, Budapest, Hungary, October 2011.

[50] P. Gonzalez-Sanchez and J. Zander, "Competitive access-point deployment in mobile broadband systems," in *Proceedings of The* 10^{th} *Scandinavian Workshop on Wireless Ad-hoc Networks, ADHOC*, Stockholm, Sweden, May 2011.

Part II

Paper Reprints

Paper I: Distributed Spectrum Access with Energy Constraint for Heterogeneous Channels

Miurel Tercero, Pamela Gonzalez-Sanchez, Ömer Ileri, and Jens Zander
In proceedings of the 5^{th} international conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), Cannes, France, June 2010.

Distributed Spectrum Access with Energy Constraint for Heterogeneous Channels

Miurel Tercero [1,2], Pamela González Sánchez [1,2], Ömer Ileri [3], Jens Zander [1]
[1]The Royal Institute of Technology KTH, Radio Communication Systems, SE-164 40 Kista, Sweden
[2]National University of Engineering (UNI), P.O. Box 5595, Managua, Nicaragua
[3]The Scientific and Technological Research Council of Turkey (TÜBİTAK)
Emails: mitv@kth.se, dpgs@kth.se, omer.ileri@uekae.tubitak.gov.tr, jenz@kth.se

***Abstract*—The demand for wireless communications services has increased the amount of spectrum resources required, promoting research interest in dynamic spectrum allocation schemes. There exist many promising solutions to allocate spectrum on a dynamic basis in order to get an efficient spectrum usage. One particular form is auction mechanism, tailored for allocating transmission rights on a short term basis to provide efficient allocation of scarce resources. However, most existing approaches are focused on homogeneous settings where all channels are treated as if they have the same propagation characteristics. In this work we consider two distributed auction schemes; *sequential and concurrent*, based on sequential ascending and combinatorial bidding, respectively, taking into account the propagation conditions of the channels (heterogeneous settings). The performance of these schemes is compared to two reference cases: (i) distributed homogeneous channels allocation (channel-agnostic case), and (ii) the centralized allocation scheme. Experimental results suggest that auction mechanisms which take into account the channel characteristics improve spectrum utilization under energy constraint. For wireless cellular networks with high unit energy cost (low coverage) concurrent access gives a better utilization of the spectrum and energy resources with higher service providers utility.**

I. Introduction

The rapid pace of technological development recently creates a need for more efficient use of available spectrum resources. The currently enforced spectrum management mechanisms mostly rely on static allocation of frequency bands across consumers (operators), in which a service provider (SP) gets usage rights for a specific band with long term dedication. Such static allocation mechanisms guarantee interference-free operation for the SP. Recent studies, on the other hand, suggest that static spectrum allocation methods are indeed inefficient in terms of spectrum utilization [1], especially when the demand drastically changes over the time. Then dynamic access mechanisms are needed in order to balance the demand with the supply.

Therefore, developing new schemes for dynamic spectrum access (DSA), aiming to avoid inefficiencies in the traditional licensing, has attracted significant interest recently. Fig.1 shows a schematic comparison for the trends of spectrum allocation mechanisms, characterized by two dimensions; performance and complexity. The complexity of a dynamic spectrum access system is likely to increase as the systems require more coordination, resulting in greater overhead due to control signalling. Such increased complexity, however, is likely to bring improvements in spectrum utilization efficiency.

Most of the earlier contributions on DSA schemes are concentrated on scenarios where the channels are considered as identical resources *(channel agnostic)*, since all of them are assumed to have the same propagation characteristics, [2]–[5]. In such scenarios, DSA mechanisms are often implemented in the form of auctions where the prices for the different channels do not differ. Rather the auctioneer keeps increasing the unit cost for the channels until the total bandwidth demand is less than the total bandwidth supply.

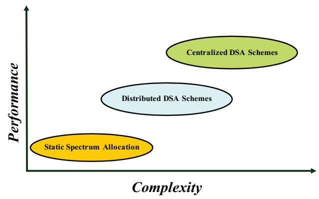

Fig. 1. Schematic comparison of different spectrum allocation mechanisms from two dimensions (performance,complexity)

Given the increased awareness about the excessive energy consumption of the communication systems, the "green radio" paradigm has recently started to emerge. It is likely that the energy consumption will become a major concern even for down-link transmissions in infrastructure systems [6]. Consequently, the propagation characteristics of available channels should be considered in making spectrum allocation decisions.

In this work, we consider two distributed DSA mechanisms that take into account the different propagation characteristics and power requirements of different channels; *Sequential* and *Concurrent spectrum access*. Similar schemes have also been investigated in [4], where the author has instead considered a channel-agnostic setting where the SPs determine their bids for the channels without any consideration of the propagation conditions.

The novelty of our work is to provide different means of propagation-aware DSA mechanisms (heterogenous channels) and show how they compare to each other with changing number of users for different energy cost levels. More specifically, we consider two regimes of interest, the first one is when the transmission energy cost (the monetary cost of each unit of energy required to transmit) is low, potentially resulting in a wireless network with large coverage area, and the second one when transmitting represents high cost corresponding to a wireless network which has poor coverage.

Only a few of the previous studies on DSA schemes [7]–[9] have considered *heterogeneous* channel settings, making the assumption that the channels have the same bandwidth

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9242
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9242

but different propagation characteristics. Therefore, the users experience different transmission ranges, and thus different frequencies are suitable for different user locations. These studies focus on the description of how channel heterogeneity can be addressed on DSA. However, they do not evaluate the effect of energy cost on spectrum utilization efficiency.

We compare the performance of the considered two schemes to the centralized allocation scheme and the distributed homogeneous channels scheme which provide the upper and lower bound regarding to spectrum utilization, respectively.

The rest of the paper is organized as follows. In Section II we present the system model describing the basic assumptions and the operator revenue function used in our approaches. The auction mechanisms and the algorithms applied for the spectrum access schemes are described in detail in Section III. In Section IV we present the simulation results and finally, Section V summarizes the conclusion of this work.

II. System Model

A. Basic assumptions

We consider a cellular system scenario as illustrated in Fig.2, where users are randomly located with uniform distribution on a flat circular geographical region with cell radius R. There are two service providers (SPs), each with one base station and their own predefined set of users $i = \{1, 2, ..., I\}$, and a broker who represents the regulatory body responsible for spectrum allocation, with a set of available channels $j = \{1, 2, ..., J\}$. The users want to get service and they can be served only by the operator that they belong to. The broker charges the operators for their channel usage, and it is responsible to gradually increase the channel prices (either in the form of sequential or combinatorial auctions), till there is no contention by the service providers for any of the channels.

The system is session based where a session is defined as the time duration for which the link gains in the system are constant or moderately changing. In our model we consider a simple distance based link gain model, therefore in the context of this study, a session is initiated each time there is a change in the location of any one of the users in the system. Note, however, that the concepts and mechanisms discussed in this paper are applicable in settings where link gains are time-varying, by considering the mean link gains over certain time intervals instead of taking the exact instantaneous link gain for a given user. The auction mechanisms are initiated at the beginning of each session and are finalized when all the channels are auctioned. The determined channel allocations are then valid for the rest of the session till a new session is initiated.

For the sake of simplicity, only downlink transmission is considered in this work. At the beginning of each session, the SPs consider the set of available channels and the corresponding link gains to their users over these channels. SPs are motivated to maximize their profit by choosing the most suitable $user - channel$ combinations in the system, considering the cost for using the channel, as well the energy consumption that depends on the propagation characteristics of the channels. The auctions result in an interference-free system where each channel is occupied by at most one SP-user pair at any time instance.

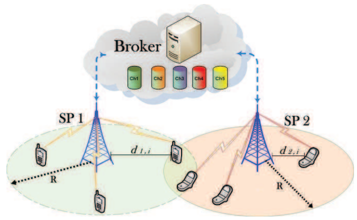

Fig. 2. Wireless Network Structure

B. Channel Model

The free space propagation model is used to deduce the required power transmission for a given service provider r (SP_r) in order to reach the single user i using the channel j (frequency f_j), as shown in Eq.(1).

$$P_{(r,i,j)} = Co.\,(d_{r,i})^{\alpha}\,.\,(f_j)^2 \tag{1}$$

Where Co is a constant computed from the SNR threshold, noise power and the speed of light, $d_{r,i}$ is the distance between the base station of the SP_r and the user i. Note, the dependence of $P_{(r,i,j)}$ on the propagation characteristic of channel j that is being utilized and the user location.

C. User Perspective

The users have quality of service (QoS) requirement in the form of received signal to noise (SNR) threshold value. We also assume that each SP base stations employ power control so that the transmit power at a given channel is the minimum power sufficient for achieving the required SNR values at the designated end user.

D. Service Provider Perspective (Revenue function)

An important parameter in our algorithm that addresses the result from the auction process is the revenue (utility) function $U_{(r,i,j)}$. This represents the profit that the considered provider SP_r achieves by serving user i on channel j. In our model a revenue function is considered as shown in Eq.(2), which is used as a decision-taking element by the SPs, thus the service is provided to those users which promote positive utility ($U_{(r,i,j)} > 0$). The utility that a SP_r perceives by serving the user i in the channel j is defined as follows:

$$U_{(r,i,j)} = x_{user} - C_{cost(j)} - K.P_{(r,i,j)} \tag{2}$$

Where x_{user} is a fixed price that each user pays to the SPs for the service, $C_{cost(j)}$ is the channel cost that keeps varying during the auctioning phase (in monetary units) and K is the energy cost per session in *monetary unit/power unit* . It can be viewed that high values of K (expensive energy) relates to situations where SPs have limited coverage due to excessive expense of transmission, then the SPs are restricted to serve the nearer users. Meanwhile low values of K (inexpensive energy) represents scenarios where SPs have relatively high coverage.

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9242
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9242

E. Performance Measures

In order to evaluate the performance of the system the following parameters are considered:
1. Channel Occupancy[%] is the total number of channels allocated to the SPs in the system as a result of the auctioning phase expressed in percentage. The channel occupancy is 100% when all the channels are assigned.
2. Normalized Power consumption per active user is the average power that each base station expends to serve a single user, achieving the SNR threshold. The expended power depends on the propagation characteristic of selected channels and the location of the users.
3. Service Provider Utility[%] represents the SPs' average profit per each served user in the system.

III. Mechanism Description

A. Broker-SP Interaction

The broker mediates the SP competition for the available channels. We consider two different auction mechanisms, sequential ascending for the distributed sequential access scheme and combinatorial iterative for the distributed concurrent access scheme. In order to solve the possible channel conflicts between the SPs the broker keeps setting (increasing or decreasing) the price for the channels for which there is contention until the conflicts are solved. The auction proceeds either in a simultaneous manner, as in distributed concurrent access scheme, or on a channel-by-channel basis, as in distributed sequential access scheme.

B. Distributed Sequential and Concurrent Access schemes

In this study we consider a two SPs setting. Note, however, that the mechanisms considered here are applicable to settings in which there are more SPs. As soon as the auction process is over, each SP is assigned a set of different channels, then the SPs start a session with their respective users. In the following we describe the two distributed schemes which are compared with the homogeneous and the centralized schemes.

Distributed Sequential Access scheme: In this scheme the spectrum access is based on sequential ascending auction. The broker offers the channels one by one on an individual basis. The competition is executed for one channel without any information about the likely price for the following channels.

Particularly in this model, the sequential access provides an inefficient channel allocation because the SPs can win the "wrong" channel at very high cost. Such phenomena is also mentioned in [10], which points out the fact that SPs are aware of this risk and they tend to respond by bidding more conservatively. Thus, the order in which the available channels are offered would make a difference. In this mechanism the channels are auctioned starting with the lowest frequency in ascending order in carrier frequency. We believe it is intuitive to start auctioning the channels with the greatest demand which are the channels with better propagation conditions (lower frequency) meaning that less power is required.

The auction is coordination-based where the broker is increasing the price ($\Delta 1$), for a specific channel as long as both SPs are still interested in acquiring the channel. The process is executed till the price gets high enough so that only one of the SPs is still interested in the channel, and a consensus on spectrum allocation decision is reached, but there exist the risk that none of SPs get the channel.

The winner SP is charged with the prevailing price for the obtained channel and it can start a session transmission ($SP-user$) with its user. Note also that for any given channel, while making their bids the SPs select the remaining user which would require the minimum energy, in order to achieve the greatest possible revenue as expressed in Eq.(2).

In every iteration, each SP communicates the indicator variable a_r to the broker, when $a_r = 1$ SPr is still interested in the channel, and $a_r = 0$ represents the lack of interest. The algorithm that performs this scheme is summarized as below.

Algorithm - Distributed Sequential Scheme

for j=1:J
  $C_{cost}(j)$=0
  $a_1 = 1$ and $a_2 = 1$
  while $a_1 = 1$ and $a_2 = 1$
    $C_{cost}(j)$=$C_{cost}(j)$+ $\Delta 1$;
    SP_r determines user (i) that Max Eq(2)
    SP_1 and SP_2 send a_1 and a_2 to Broker
  end (while)
Start session on channel j
end for

Distributed Concurrent Access scheme; The spectrum access is carried out by iterative combinatorial auction. The SPs are bidding for a package of different channels. The SPs compute the best *user-channel* combinations based on channels propagations characteristics, the location of their users and the channel costs as declared by the broker. In order to formulate the problem we define the combinatorial variable $a_{(r,i,j)} \in \{1,0\}$, such that $a_{(r,i,j)} = 1$ if channel j is assigned to user i for SP_r and $a_{(r,i,j)} = 0$ otherwise, thus SP_r finds the maximum revenue from the whole system by:

$$Max \sum_{i,j}^{I,J} a_{(r,i,j)} U_{(r,i,j)}. \quad (3)$$

Two constraints that should be considered are that for any user i a maximum of one channel should be assigned and any channel j cannot be allocated to more than one user (as defined in Eq(4) and Eq(5), respectively).

$$\sum_{r,j}^{R,J} a_{(r,i,j)} \leq 1 \quad (4)$$

$$\sum_{i}^{I} a_{(r,i,j)} \leq 1 \quad (5)$$

The auction is implemented in multiple rounds where in each round each SP_r computes its preferences and submits a channel request list $\overline{a_{(r,j)}}$ to the Broker. This channel list does not include user index since this is a concern for SPs only. At the end of each iteration, the broker determines the channels for which there is contention ($\overline{a_{(1,j)}} \bigcap \overline{a_{(2,j)}}$), increases the price for them at $\Delta 1$ while the prices for the channels that are not demanded are decreased by $\Delta 2$ to make

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9242
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9242

them attractive for the SPs. The algorithm for Distributed Concurrent Access scheme is described as below.

Algorithm - Distributed Concurrent Scheme

C_{cost}=0
Initially $\overline{a_{(1,j)}} \bigcap \overline{a_{(2,j)}} \neq$ null: Ch-Conflict
while1 Ch-Conflict
  C_{cost}(Ch-Conflict)=C_{cost}(Ch-Conflict)+ $\Delta 1$;
  C_{cost}(Ch-Free)=C_{cost}(Ch-Free)- $\Delta 2$;
  EachSP_r determine (i, j) pairs that Max Eq(3)
  SP_1 and SP_2 send $\overline{a_{(1,j)}}$ and $\overline{a_{(2,j)}}$ to Broker
end (while1)
Start session on all channels

C. Reference Mechanisms

Distributed Homogeneous Access Scheme: It is an auction-based homogeneous channels allocation mechanism that is modeled as a special case of the concurrent scheme with the variation that all channels are priced for the same amount meaning that the price is increased for all the channels at $\Delta 1$. In this sense the set of channels are auctioned as homogeneous resources even though the energy consumption in all the channels is different. Note that such an algorithm is representative of schemes where the auctioneer keeps increasing prices for all the channels as long as there is contention in any one of the available channels. The algorithm for Distributed Homogeneous Access scheme is described as follows.

Algorithm - Distributed Homogeneous Scheme

C_{cost}=0
Initially $\overline{a_{(1,j)}} \bigcap \overline{a_{(2,j)}} \neq$ null: Ch-Conflict
while1 Ch-Conflict
  C_{cost}(All-Channels)=C_{cost}(All-Channels)+ $\Delta 1$;
  Each SP_r determine (i, j) pairs that Max Eq(3)
  SP_1 and SP_2 send $\overline{a_{(1,j)}}$ and $\overline{a_{(2,j)}}$ to Broker
end (while1)
Start session on all channels

Centralized Access Scheme; The decision-making process is led by the spectrum broker who is responsible for allocating spectrum resources among the SPs. It is a full knowledge system which gives the upper bound in spectrum utilization. The broker determines the optimum *SP-user-channel* associations that maximizes the total income of the SPs meaning that the total energy expenditure in the system is the minimum value. Moreover, here the channel cost is zero and the allocation process is implemented with no SP competition. In this scheme the SPs communicate the link gain vector for their end users, $\overline{g_i^r}$ to the broker. A basic algorithm has been developed and is described as follows:

Algorithm - Centralized Scheme

SP_1 and SP_2 send $\overline{g_i^r}$ to Broker
Broker determines the (SP_r, i, j) triplets for both operators, such that total revenue of both operators are maximized
Start session on all channels

It is relevant to mention that this is a hypothetic dynamic scheme, given that the allocation is not static. However, this scheme has the shortcoming regarding truthful information reporting by the SPs to the Broker. It is possible that the SP reacts selfishly and reports a suitable link gain vector in order to get the resources of interest. Moreover the system requires a high complexity design, high setup delays, and suffers single point of failure and non scalability. In this situation the distributed schemes are better options.

IV. Numerical Results

A. Simulation Settings

In this section we present the numerical experiments that we conducted in a two SPs setting where each SP has a maximum of seven users. The system has five available channels with carrier frequencies as indicated in Table I, which summarizes the simulation parameters.

TABLE I
SIMULATION PARAMETER VALUE

PARAMETERS	VALUES
Propagation exponent, α	2
Users distribution	Uniform
Energy Cost, K [monetary unit/power unit]	[10,1000]
User Payment, P_{user} [monetary unit]	5
Channel Price, $C_{cost(j)}$ [monetary unit]	[0-5]
Number of Channels	5
Number of SPs	2
Carrier Frequencies [GHz]	0.6, 1.3, 1.7 1.9, 2.5

B. Simulation Results

1. Channel Occupancy; From Fig.3 the main findings can be summarized as follows: The results from concurrent scheme show that by auctioning the channels based on their propagation conditions (discriminatory pricing is applied) a considerable gain is provided in terms of spectrum occupancy. When low value of energy cost (K=10) is considered sequential and concurrent mechanisms present almost the same performance as the Centralized in terms of channel occupancy, allocating the maximum possible number of channels. By assuming that the value of energy cost increases (K=1000) a greater difference between sequential and concurrent schemes can be observed, showing that the concurrent access almost approaches the upper bound (the centralized allocation).

2. Normalized Power Consumption per active user; Fig.4 shows that the power consumption in the homogeneous scheme is the lowest in the system since the channel occupancy is the minimum compared to other schemes. The power consumption that the sequential access mechanism expends per each served user is the highest since all the channels are auctioned one by one consecutively and SPs do not know whether or not the next channel is better.

In general the power expenditure tends to decrease as a function of the distance between the base station and the served users, $d_{r,i}$. As there are more users in the system, the probability that the served users get nearer to the base station increases and so the power consumption gets lower.

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9242
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9242

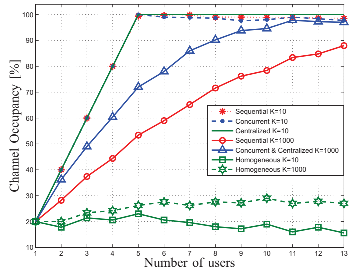

Fig. 3. Channel Occupancy in the System versus number of users

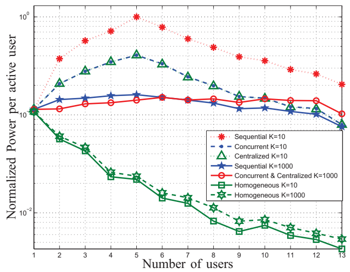

Fig. 4. Power expended per each served user in the System

3. Service Provider Utility; The maximum utility that a SP can perceive by serving a user is obtained from the Centralized mechanism as it was expected since the channel price is considered zero, see Fig.5. However, when the channel price is taken into account in the distributed mechanisms, the concurrent access gives higher utility.

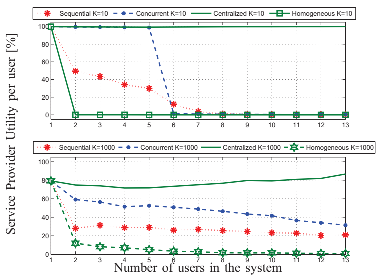

Fig. 5. Service provider utility per served user in the System

Furthermore, for low energy cost (K=10) in the concurrent and sequential access the channel cost, C_{cost}, increments as a function of the number of users in overload situation. Subsequent to this fact the SPs utility starts to decrement radically after five users. From this graph we may conclude that the strategy used in distributed sequential scheme is not that efficient, and some other cooperation strategy may lead to better profits.

V. Conclusion

We considered two distributed DSA schemes, based on auction methods with energy constraint for heterogeneous channels settings. The channel heterogeneity proves to be an important fact to take into account in order to improve the spectrum occupancy. Based on the energy constraint the SPs have to be aware of the power expenditure when choosing the user-channel pairs. In the case of low unit energy cost K (good coverage) the performance of the sequential and concurrent access schemes approaches the upper bound (centralized access) regarding to spectrum utilization. Furthermore, when the unit energy cost is high (limited in coverage) the sequential access gives higher power consumption and lower SPs' utility due to inefficient channels allocation. Hence, we summarize that when it comes to the case of wireless network with energy constraint the concurrent access scheme is the better option for DSA.

Acknowledgment

The authors would like to acknowledge the Swedish International Development Agency (Sida), who has supported in part this work.

References

[1] M. Pattal and J. Zeng, "Spectrum management reforms: A step towards a flexible spectrum management," in *Wireless Communications, Networking and Mobile Computing, WiCOM 08, 4th International Conference on*, 2008.
[2] O. Ileri, D. Samardzija, and N. Mandayam, "Demand responsive pricing and competitive spectrum allocation via a spectrum server," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, Nov. 2005.
[3] S. Sengupta, M. Chatterjee, and S. Ganguly, "An economic framework for spectrum allocation and service pricing with competitive wireless service providers," in *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, 2007.
[4] S. Sengupta and M. Chatterjee, "Sequential and concurrent auction mechanisms for dynamic spectrum access," in *Cognitive Radio Oriented Wireless Networks and Communications, 2007. CrownCom 2007. 2nd International Conference on*, Aug. 2007, pp. 448–455.
[5] G. Sorabh, B. Chiranjeeb, C. Lili, Z. Haitao, and S. Subhash, "Toward real-time dynamic spectrum auctions," *Computer Networks*, vol. 52, pp. 879–897, 2008.
[6] Kungliga Tekniska Hgskolan, "Research project: Green radio-investigating energy consumption of wireless networks," *Available: http://www.wireless.kth.se/projects/GREEN/index.php*, 2009.
[7] M. Ma and D. H. K. Tsang, "Impact of channel heterogeneity on spectrum sharing in cognitive radio networks," in *Communications, 2008. ICC '08. IEEE International Conference on*, 2008.
[8] J. Sun and E. Modiano, "Wireless channel allocation using an auction algorithm," *(IEEE) Journal on selected areas in Communication*, vol. 24, no. 5, 2006.
[9] V. Brik, E. Rozner, and S. Banerjee, "Dsap: a protocol for coordinated spectrum access," in *IEEE DySPAN*, 2005, pp. 611–614.
[10] C. Kolboldt, D. Maldoom, and R. Marsden, "The first combinatorial spectrum auction, lessons from the nigerian auction of wireless access licences," in *London W1S - 106 1DN*, 2003.

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9242
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9242

Paper II: Deployment Strategies in Competitive Wireless Access Networks

Pamela Gonzalez-Sanchez, Jens Zander
In proceedings of the 1^{st} international Conference on Advances in Cognitive Radio (COCORA), Budapest, Hungary, April 2011. [Best Paper Award]

COCORA 2011 : The First International Conference on Advances in Cognitive Radio

Deployment Strategies in Competitive Wireless Access Networks

Pamela González Sánchez [1,2], Jens Zander [1]
[1]The Royal Institute of Technology KTH, Radio Communication Systems, 164 40 Kista, Sweden
[2]National University of Engineering UNI, P.O. Box5595, Managua, Nicaragua
Emails: dpgs@kth.se, jenz@kth.se

***Abstract*—The rapid growth of mobile internet traffic has forced wireless service providers to deploy increasingly higher capacity in their wireless broadband access systems. The flat rate revenue streams in combination with the rapidly growing costs associated with conventional access deployment is usually referred to as the "revenue gap". In this context, various schemes for infrastructure sharing to reduce unnecessary duplication of infrastructure present an interesting solution. Besides explicit cooperation, competitive sharing ("coopetition") where various access providers provide partially overlapping coverage is one interesting sharing mechanism. In this paper, we analyze such a scheme and study how the operator should deploy their networks, striking a balance between areas of exclusive coverage, where each provider has a monopoly situation, and overlap areas with provider competition, to achieve maximal profitability. The competition is based on the proportionally fair auction scheme. The users behave selfishly as they bid for the various access providers. The access providers compete with each other by selecting the so called reservation price. Results are expressed in terms of Nash equilibrium solutions, which are numerically derived for some sample scenarios. Results indicate that the fraction of coverage overlap does play an important role for both the performance of the system and the profitability of the service providers. As the level of overlap between the two networks increases the revenue that each base station gets decreases significantly. In addition, the user experienced throughput degrades considerably for low demand but the cost per transferred Megabyte is not greatly affected. Further, we conclude that a win-win situation for both users and access providers can be achieved with a suitable overlap coverage by two networks.**

***Index Terms*—Wireless access markets; coverage overlap; competition; resource allocation; Nash equilibrium**

I. Introduction

A. Overview

The rapid increase of mobile internet traffic has put the spotlight on how the future wireless broadband access systems should be deployed and operated at significant lower costs per transmitted bit than today. The flat rate revenue streams in combination with the rapidly growing costs associated with conventional access deployment is usually referred to as the "revenue gap. Nowadays, closing this "gap" is on top of the priority list of wireless mobile service providers. Low cost deployment and more efficient utilization of existing resources are key solutions to be investigated.

The traditional way of infrastructure deployment has been that every service provider offers his own access system in all locations, i.e., achieving "full" coverage by himself. This has been possible in most mobile phone systems due to the relatively low costs and high profit margins. As the increasing data rates require a much denser (and more expensive) network of base stations, full coverage is no longer an option to most service providers. Instead *Infrastructure sharing*, where providers share infrastructure in low user density areas is one possible alternative to offer better coverage and quality of service (QoS) in a cost efficient manner [1].

The sharing of wireless infrastructure, however, raises the question of how resources and revenues should be divided when multiple subsystems, managed by potentially competing actors, are involved in delivering the access service. An alternative would be to share the infrastructure implicitly by establishing an open wireless access market wherein networks not only compete for users on a long-term time-scale, but also on a much shorter time-base. This could be realized with an architecture where autonomous trade-agents, that reside in terminals and access points (APs) or base stations (BSs), manage the resources through negotiations [2]–[5].

In competitive multi-user networks, services are provided to users that are assumed to be rational, choosing strategies in order to maximize their own utility. This resource management problem can be expressed as a noncooperative game and the system performance can be analyzed in terms of the Nash equilibrium, i.e., a set of optimal bids such that no single user wishes to deviate from its bid given that the bids of the other users remain the same and cannot further improve their utility [6]–[8].

B. Prior Work

In [2], the authors developed a framework for studying demand-responsive pricing in contexts where access points (APs) with fully overlapping coverage compete for users. Resources are partitioned through a proportional fair divisible auction and they investigated if, and when, an open market for wireless access can be self-sustained. They showed that in scenario where access providers (APs) compete an open access market results in better services at lower price, compared to a case where APs cooperate. They utilized an architecture where autonomous trade-agents manage the resources through negotiations.

In [4], a market-based framework for decentralized radio resource management in environments populated by multiple, possibly heterogeneous, APs and the service provided to the users is of file transfers, was introduced. The problem addressed for the user is to determine how much resources it should purchase from the different APs in order to maximize its utility ("value for money").

In [7], Maheswaran et al. introduced a bidding mechanism for allocation of network resources among competing agents, and study it from a game-theoretic perspective. Although they proved the existence and the uniqueness of Nash equilibrium in a decentralized manner, the user's performance (QoS) and service providers' revenue have not been studied.

C. Our problem

In this work we study how competitive sharing ("coopetition"), where various access providers provide partially overlapping coverage in a competitive fashion, can reduce cost.

The scenarios studied can be illustrated as in Figure 1. We analyze how the balance between areas of exclusive coverage, where the provider has a monopoly situation, and overlap areas with provider competition affects the profitability of the access providers. We also analyze how the user's QoS is affected by this level of overlap among networks and by traffic load variation. A game-theoretic approach and the proportionally fair auction mechanism [9]–[11] are used aiming to answer the following questions:

- *How is the operator revenue affected by the level of overlap and the traffic load variations in the system?*
- *Is the user quality of service, QoS, in terms of available data rate and cost per Megabyte affected by these two parameters?*

The rest of the paper is organized as follows. In Section II, we introduce our basic assumptions and describe the wireless architecture-scenario, resource allocation mechanism, and user demand model. Section III gives a thorough overview of the user game. Section IV outlines the service providers' strategy. In Section V we show the numeral results from simulation and in Section VI we present out the conclusion.

II. System Model

The system model with the basic assumptions, a description of the scenario under consideration and the resource allocation mechanism applied in this work are introduced in the following.

A. Basic Assumptions - Scenario

Given the network deployment illustrated in Figure 1, the problem for each BS is to select a reservation price, ϵ, so that its expected revenue is maximized. When the user is in a non-overlapping area, this user can only bid for resources from the single BS that provides coverage of this area. This user faces a monopolistic market, since the BS can charge any price due to the absence of a competitor. Both, in overlapping and nonoverlapping coverage the users may choose not to utilize a specific BS if the price is too high.

Figure 1 illustrates the basic scenario under investigation, where $s^m_{i,j}$ denotes the bid, in *monetary units*, that user j places in auction i at BS m, in order to get a portion of the available transmission time $x_{i,j}$ for a file transfer (Note that we have assumed a purely time division multiplexed link). The link $user{-}SP$ indicates the link provided by access provider who dominates the market in this area (i.e., the access providers who provide coverage) and it is to this BS that users should send a positive bid in order to be served.

We model a file download service, specifically, the download time in a wireless TDMA system with N selfish competing users and m BSs with overlapping coverage areas. The BSs are assumed to be identical in transmit power, system bandwidth, minimum received signal to noise ratio requirement, etc.

The resources that we focus on are downlink transmission slots. These slots are allocated to different users in order to share the downlink throughput among them. Allocation of the resource is done through a proportional fair divisible auction. We assume that the resource is infinitesimally divisible and that the cost associated with the file transfer depends on the total time-duration and the monetary expenditure required for the complete file download.

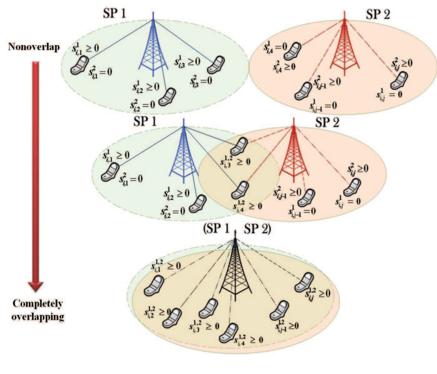

Fig. 1. Basic scenario - Illustration of a wireless network architecture with different percentages of overlap, which represents a system with different levels of competition

As in [2] [4], we investigate a trade-agent-based model for the auction bidding process.The trade-agents are entities located in the BSs, who act selfishly on behalf of their users. The main objective of each trade-agent is to maximize its user's utility (here computed as *value for money*). The portion of the transmission time allocated to user j can be expressed

 ISBN: 978-1-61208-005-5

as follows:

$$x_{i,j}(s) \;=\; \frac{s_{i,j}}{s_{i,j} + S_{i,-j}} \in [0, 1), \qquad (1)$$

where $S_{i,-j}$ represents the strategies (bids) of all the opponents' trade-agents and it is equal to $\sum_{k \neq j} s_{i,k} + \epsilon$ where the reservation price $\epsilon \in [0, \epsilon_{max})$. The reservation price is a nonzero price floor below which the resource will not be sold. Note that by definition the price floor must be nonzero as if it were zero, then there would be no price floor.

Assuming that the peak data-rate of a single user j on whose behalf the trade-agent j is acting, remains unchanged during the entire file transfer and that this applies for all the users, i.e., $R_{i,j}$=$R_{z,j}$ $\forall$ i, z, the total demand associated with the other trade-agents, thus $\sum_{k \neq j} s_{i,k}$=$\sum_{k \neq j} s_{z,k}$ $\forall$ i, z.

Note that z is the last round of the auction. Due to these assumptions, each trade-agent will place identical bids in all the auctions.

B. Resource Allocation Mechanism - Proportionally Fair Divisible Auction

As described in the previous section, the total transmission time is divided via employing a proportional fair divisible auction . In a proportional share allocation scheme each user is characterized by a parameter that expresses the relative share or amount of the resource that it should receive. Hereafter, the bid that the user submits to the BS is used to express the user's share. In this work a dynamic system has been modeled in which users are assumed to dynamically join and leave the competition (game). Therefore, the portion of the resource depends on both the number of users that enter the game and the level of competition at different times. On light of this, this mechanism allows flexibility, since the users can decide when to join or leave the competition, and ensures fairness, which follows from the fact that the users always get a share of the resource proportionally to their bids (as expressed in Equation 1).

The auction process is held by an auctioneer located in the BS (thus since the users' trade-agents are also allocated in the BS all the communication between the trade-agents and the auctioneer is strictly local to the BS). This concept was introduced in [9] and analyzed later in competitive environments for networks with fully overlapping coverage in [2], [4]. We examine the case where the file transfer requires z auctions to complete, i.e., $i = \{1, ..., z\}$ (see Figure 2).

Figure 2 illustrates the auction procedure associated with a file transfer [4]. In this example trade-agent j initiates a file transfer in auction 1.

Since, at the beginning of each allocation cycle, an interrupt is generated in the system, too short a cycle may cause a large overhead in the system, in the long run (i.e., in Operating Systems each allocation cycle is in the order of milliseconds).

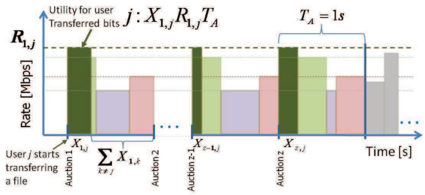

Fig. 2. Illustration of auction procedure associated with a file transfer

On the other hand, a cycle of too long duration (i.e., cycles of one minute) may induce a large delay for the file download, thus, a degradation in the user QoS.

In our analysis, we assume that each auction is carried out every one second [2], [4]. This means that each auction determines the allocation of resources for the time after the conclusion of the auction and that a new auction starts every second. Note that the auction can proceed in parallel with the usage of the link resources for downloading, but this usage is according to the resource allocation determined by the last auction. For simplicity of the analysis, we neglected the overhead that can occur in a real system application.

In a proportional fair resource allocation mechanism, a user knows exactly how much it has to "pay" over any interval of time while this is active, considering that they choose how much they will bid for the resource. The user cannot, however, predict how much service time it will actually receive. This is because the fraction of the resource, and therefore the service time the user will receive, may change at any time depending on the level of competition for the resource [10].

In each auction, user j is allocated a portion $x_{i,j}$ of the total available transmission time during each auction T_A (where $T_A = 1$ second), and depending on its peak data-rate $R_{i,j}$ the agent will be able to transfer a total of $x_{i,j} R_{i,j} T_A$ bits. After participating in z auctions the file transfer is completed and the trade-agent j awaits for a new request from its user to enter the competition again.

C. User Demand Model

A demand function that consists of files with an expected size q in Megabits is considered. Each file arrives to the system of BSs according to a Poisson process characterized by an intensity, λ.

D_0 represents the potentially offered load, which can be defined as D_0=$q\lambda$, and it is assumed that the aggregate demand is perfectly known for all BSs [2].

III. USER GAME - UTILITY MAXIMIZATION

We focus in finding the Nash Equilibrium Point (NEP) for the reservation price of the resource, ϵ, considering the two

 ISBN: 978-1-61208-005-5

games (competition among users for resources and among BSs for users) in the competition area for different levels of coverage overlap. This NEP is related to the Best Response from the trade-agents (acting on behalf of the users). In the monopolist area (non-overlapping coverage) only competition among users is observed.

By obtaining the NEP we are able to analyze the BS's expected revenue with different levels of competition. These results enable us to predict the users' performance (in terms of throughput and monetary expenditure per transferred file).

The users compete against each other for resources - while trying to maximize their utility function in order to transfer a file. This game is expressed later in Equation (2). For our analysis, we assume that the file size is finite (and identical), $q = 1$ Megabyte.

$$\varphi(s_{-j}) = \arg\max_{s_j} U_{i,j}(s_j, S_{-j}) \quad \forall \quad j \in \{1, ..., N\}, m \in \{1, 2\}. \tag{2}$$

In the above equation $U_{i,j}(s_j, s_{-j})$ is related to the throughput, $x_{i,j}R_{i,j}$, associated with user j and is defined as:

$$U_{i,j} = \sum_{m=1}^{2} \max\left[0,\ x_{i,j}R^m_{i,j} - s^m_{i,j}\right]. \tag{3}$$

Deriving the first order solution (i.e., as a linear equation) of Equation (3) with respect to $s^m_{i,j}$ we can obtain the best response (BR), which describes how trade-agent j should react to the strategies (optimal bid that the trade-agent should submit the BSs) of all the other trade-agents in order to maximize its user's utility. This would be expressed as follows:

$$s^m_{i,j} = \sqrt{R^m_{i,j}(\sum_{k\neq j} s^m_{i,k} + \epsilon_m)} - \sum_{k\neq j} s^m_{i,k} + \epsilon_m. \tag{4}$$

Since the peak transfer rate for all of the users is the same over all auctions, and they all have to transfer the same size file, then giving each user the whole channel (i.e., all of the time slots) enables this user to complete and leave the system, hence leaving all of the remaining resources for the *remaining* users.

The monetary expenditure, E^m, incurred by user j is given by the summation of the bids submitted in all the auctions, z_j, required to download the file, as indicated in:

$$E^m_j = \sum_{i=1}^{z_j} s^m_{i,j} \tag{5}$$

IV. Base Station Strategy-Revenue Maximization

A. Open Access Market-Competing BSs

This game take place among BSs, who selfishly, try to maximize their own expected revenue per second, as defined in Equation (6).

$$\phi_m(\epsilon_{-m}) = \arg\max_{\epsilon_m} \Phi(\epsilon_m, \epsilon_{-m}), \tag{6}$$

where $\phi_m(\epsilon_{-m})$ represents the best response (BR) function associated with BS m. Equation (7) describes the NEP, which is the solution to the competitive game among BSs.

$$\epsilon^*_m = \phi_m(\epsilon^*_{-m}) \quad \forall\, m \in M. \tag{7}$$

The stability and uniqueness of the NEP for the games have been calculated through successive iterations (negotiation) between the BSs and users via mean of simulation. It has been proved that symmetric wireless systems with proportional share resource allocation mechanism converge to the NEP reaching the nearest optimal performance [2]–[4], [6], [12].

V. Numerical Results

The requests of the files to be downloaded by the users arrive according to a Poisson process and the resources are allocated once per second based on the NEP. In this work we characterize the user's performance (QoS) by using the average user throughput and monetary expenditure per Megabyte. The BSs' performance is quantified by the average revenue per second. The pathloss has been modeled as expressed bellow:

$$L(d) = 35.3 + 38\log_{10}(d) \quad in\ units\ of\ dB, \tag{8}$$

where d denotes the distance between the BS and the mobile terminal. In our experiment we have neglected shadow fading and modeled interference as coming from constantly transmitting BSs. As in [2], we use a truncated version of the Shannon bound that has been adjusted to include efficiency losses, leading to the peak data-rate:

$$R_{i,j} = \min\left(W\log_2\left(1 + \frac{\Gamma_{i,j}}{2}\right), R_{max}\right), \tag{9}$$

where $W = 3.84$ MHz is the channel bandwidth, $\Gamma_{i,j}$ represents the signal to interference and noise ratio and R_{max} denotes the maximum bit-rate that can be achieve by the user.

A. Simulation Settings

Extensive simulations in MATLAB were carried out with a granularity of one second (auction cycle) for two wireless access providers. Table. I summarizes the simulation parameters that were used. These values have been taking from the prior analysis introduced in [2].

TABLE I
SIMULATION PARAMETERS VALUES

Parameters - with units in square brackets	Value
BS Transmit Power (P) [W]	20
Users distribution	Uniform
Cell Radius [meters]	440
Number of Competing BSs (M)	2
File size (q) [Megabyte]	1
Maximum bite-rate (R_{max}) [Mbit/s]	7

B. Simulation Results

Figure 3 shows the BR function for the non-cooperative game under different levels of competition where there, in average, 0.4 packets/BS/s enter the system. In this figure A represents the percentage of overlap of the two wireless access networks coverage.

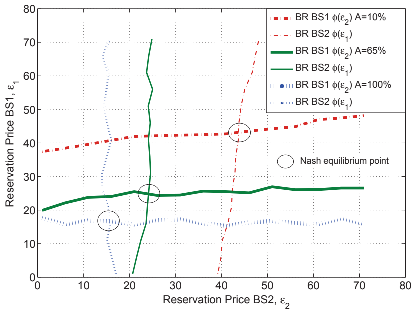

Fig. 3. Average revenue per BS as a function of the reservation price, ϵ.

Based on the results in Figure 3 we observe that there exist at least one NEP in the system.

1. User Performance The experienced users' QoS in terms of throughput and average price per transferred file as a function of the potentially offered load, D_0, is shown in Figure 4. These depend on the load demand density and are affected by the level of competition introduced with the coverage overlap between networks (representing different levels of competition).

It can be observed that for low load demand, the throughput experienced by users degrades considerably as the level of competition increases. This is due to the fact that the fraction of the resource that each user gets decreases as more users fall in the competition area (in the overlapping coverage).

When the load density increases (2.4 Megabits/second and higher, from λ=0.3 files/s) the throughput degradation is slightly smaller leading to less negative impact on the user's experienced QoS, compared to fully overlapping coverage.

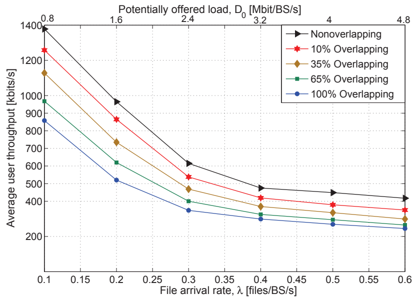

Fig. 4. Average throughput experienced by users for different levels of overlapping coverage as a function of the potentially offered load, D_0, (file arrival rate λ).

Figure 5 shows the average price per transferred Megabyte experienced by users. We observe that an architecture where BSs compete and share their resources implicitly, combined with autonomous trade-agents acting on behalf of the users, has the potential to reduce price. For networks with low demand density the average price per transferred Megabyte is affected (small increment) in a low scale.

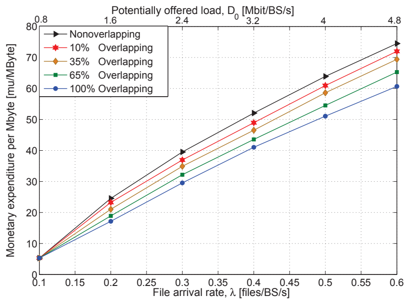

Fig. 5. Average price, p, per transferred Megabyte of data for different levels of overlapping coverage as a function of the potentially offered load, D_0, (file arrival rate λ).

As illustrated in Figure 5, the resulting user's monetary expenditure per Megabyte increases rapidly as a function of the potentially offered load, D_0, and on a slightly basis as the level of overlap (competition) is reduced.

2. Base Station's Revenue; The average revenue associated with the BS game for different levels of coverage overlap can be observed in Figure 6. As the overlapping area by the two wireless networks increases so does the level of competition and more users experience an *open access market*. The reservation price for the resource decreases as a consequence of the competition leading to lower BS's revenue.

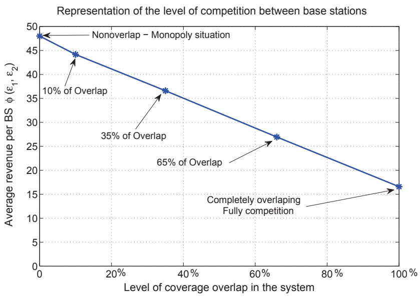

Fig. 6. Average base station's revenue per second and slot associated with the BS game as a function of the level of coverage overlap. On average 0.4 files/s arrive to each BS, each file is of size q = 8 Megabits.

Figures 4 and 5 show that the experienced user's QoS is affected for low demand density. However, we can notice that for load density higher than 3.2 Megabits/second (λ=0.4 files/s) the degradation is slightly smaller leading to less impact on the user's experienced QoS and providing a great gain (more than 50%) in the BS's revenue.

Generally, our results indicate that both users and access providers can benefit when a suitable overlap coverage by two networks is achieved. According to our results a proper percentage of overlap might be approximately 35% based on the interest or objective function of all the involved parties. We investigated the behavior of the system by considering only two wireless networks in order to get insight on to which extent competition can be beneficial for both providers and users.

VI. Conclusion

In this paper, we analyzed a competitive sharing scheme ("coopetition") where two access providers provide partially overlapping coverage in a competitive fashion as an option to maximize their revenue. We study how the balance between areas of exclusive coverage and overlap areas with provider competition affects the profitability of the access providers.

Access providers with symmetric wireless networks that overlap partially in coverage compete with each other by selecting a reservation price. It has been shown that, under our assumptions, the system converges to a unique Nash equilibrium point. Results indicate that the fraction of coverage overlap does play an important role for both the performance of the system and the profitability of the access providers.

We observe that as the level of overlap increases the revenue that each base station decreases significantly. In addition, the user's experienced throughput degrades considerably for low demand density meanwhile the cost per transferred Megabyte is affected in a low scale. Further, we conclude that a win-win situation for both users and access providers can be achieved with a suitable coverage overlap by two networks.

Acknowledgment

The authors would like to thank the Swedish International Development Agency (SIDA), and VINNOVA (MODyS project) for their partial support of this work. We would also like to acknowledge Professor Gerald Q. Maguire for his valuable comments, which have helped us to improve this paper. The contributions from initial discussions with Dr. Ki Won Sung, Saltanat Khamit and Dr. Johan Hultell are hereby acknowledged.

References

[1] J. Markemdahl, Östen Mäkitalo, J. Werding, and B. G. Mölleryd, "Business innovation strategies to reduce the revenue gap for wireless broadband services," *Communications and Strategies Journal*, vol. 1, no. 75, 2009. [Online]. Available: http://econpapers.repec.org/RePEc:idt:journl:cs7502

[2] M. Blomgren and J. Hultell, "Demand-responsive pricing in open wireless access markets," in *Proceedings of the IEEE Vehicular Technology Conference VTC-Spring*, 2007.

[3] R. T. Maheswaran and T. Baçar, "Nash equilibrium and decentralized negotiation in auctioning divisible resources," *Group Decision and Negotiation Journal*, vol. 12, no. 5, 2003.

[4] M. Blomgren and J. Hultell, "Decentralized market-based radio resource management in multi-network environments," in *Proceedings of the IEEE Vehicular Technology Conference VTC-Spring*, 2007.

[5] R. T. Maheswaran and T. Baçar, "Coalition formation in proportionally fair divisible auctions," 2003.

[6] D. Fudenberg and J. Tirole, *Game Theory*, 1991.

[7] R. T. Maheswaran and T. Baçar, "Decentralized network resource allocation as a repeated noncooperative market game," in *Proceedings of the* 40^{th} *IEEE Conference on Decision and Control*, vol. 5, 2001.

[8] D. Niyato and E. Hossain, "Radio resource management games in wireless networks: an approach to bandwidth allocation and admission control for polling service in ieee 802.16," *Wireless Communications, IEEE Journal*, vol. 14, no. 1, 2007.

[9] I. Stoica, H. Abdel-Wahab, K. Jeffay, S. Baruah, J. Gehrke, and C. Plaxton, "A proportional share resource allocation algorithm for real-time, time-shared systems," in *Proceedings of the* 17^{th} *IEEE Real-Time Systems Symposium*, 1996.

[10] I. S. Hussein, H. Abdel-wahab, and K. Jeffay, "On the duality between resource reservation and proportional share resource allocation," in *Proceedings of Multimedia Computing and Networking*, 1997.

[11] L. Abeni, G. Lipari, and G. Buttazzo, "Constant bandwidth vs. proportional share resource allocation," vol. 2, 1999.

[12] J. Hultell, "Access selection in multi-system architectures: cooperative and competitive contexts," *Licentiate Thesis in Telecommunications*, Kungliga Tekniska Högskolan KTH, Sweden 2007.

Paper III: Competitive Pricing with Heterogeneous Demand in Open Wireless Access Market

Pamela Gonzalez-Sanchez, Saltanat M. Khamit, Jens Zander
In proceedings of the 3^{rd} International IEEE Congress on Ultra Modern Telecommunications and Control Systems (ICUMT), Budapest, Hungary, October 2011.

Competitive Pricing with Demand Heterogeneity in Open Wireless Access Market

Pamela Gonzalez-Sanchez, Saltanat M. Khamit, Jens Zander
Royal Institute of Technology KTH, Radio Communication Systems, 164 40 Kista, Sweden
Emails: {dpgs, khamit, jenz}@kth.se

***Abstract*—In order to maximize the network profit competitive service providers shall utilize their resources efficiently and price their services taking into account the demand responsiveness in the market. Pricing strategies play an important role in the network performance since they explicitly influence the user demand. Demand uncertainty would cause providers to face lower profits. In this paper, we analyze the price-demand relationship and based on that, we study a competitive pricing game and address an open wireless access market (with different market shares) where service providers' objective is to maximize their profits. The resources are allocated among the users through a proportionally fair divisible auction mechanism. Simulation results show that a resource allocation model, which attracts users to actively participate in the auction, assures fair access while maintaining service providers' profit by adapting the pricing policy with a change in the user demand. Our analysis reveals that the service providers can establish a competitive price of the resources, while capturing a reasonable portion of market share. Under this setting, service providers could learn and predict which pricing policy is beneficial in a competitive environment.**

***Index Terms*—Wireless access markets; coverage overlap; competition; resource allocation; nonuniform distribution**

I. Introduction

Current developments in mobile phone industry are aiming to meet the user requirements and to facilitate opportunities for service providers to increase their profits. With the introduction of these new technologies (e.g., *smart phones*), which are capable of accessing different radio access technologies [1], [2], the booming of the wireless open market is more likely to happen.

High data rate services at a relatively low cost are guaranteed with a growing mobile broadband penetration, while uncertainty in service providers profit still remains (see illustration of this problem in Figure 1). Within wireless communication industry, profit maximization consists of complex and integrated processes. Apparently, the provided services should generate enough profit to exceed investment costs as a respond to a change in the user demand, however this is not the case. Nevertheless, profit maximization could be achieved when the service provider reaches a high resource utilization at a profitable price charged to the user.

In a real world, the usage of mobile data services varies, and the reasons why this happens depend on any country's economic development, urbanization rate, demographical and other aspects. It is quite obvious to conclude that all over the world a variety in mobile data services offered is mostly motivated by different user demands in different areas.

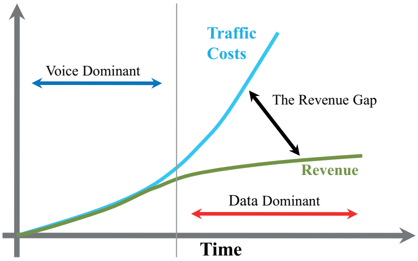

Fig. 1. The decoupling of the generated data traffic by wireless users and the revenue perceived by service providers is addressed, nowadays, as the problem of *the revenue gap*.

Aiming to get insight on the system performance in more realistic scenarios, in this paper, we model a nonuniform distribution of the users across the service area.

A. Related Work

The prominent changes in the wireless telecommunication market are presented in [3], where the authors gave an overview of evolution in an open wireless market. In our work, some implications can be found within a line of the "state of the art" of [3].

In [4], the authors developed a framework to study a demand-responsive pricing in context, where access points (APs) with fully overlapping coverage compete for users. Available spectrum are partitioned through a proportional fair divisible auction. Their results showed that in scenarios where access providers (APs) compete in an open access market the system performance is better, compared to a case where APs cooperate. In this paper, we follow their auction model and study a competitive pricing strategy with changes in user demand.

In our previous work [5], the focus was on how the service providers (SPs) should deploy their networks, striving a balance between areas of exclusive coverage, where each SP has a monopoly situation, and overlap areas with provider competition, aiming to achieve maximal profitability. The users were assumed to be uniformly distributed across the area of interest. How the level of competition (level of overlap between two networks) affects the system performance in terms of users QoS and SP revenue was analyzed.

A competitive spectrum allocation mechanism in wireless networks with heterogeneous coverage was addressed in [6]. The authors investigated whether or not it is profitable for a small SP to deploy its network and compete against another SP who provides a wide service area. Unlike their work, we are interested in an equal service coverage access setting amongst competing SPs assuming a nonuniform user distribution and a variation in market share, so that there is no market power for service providers.

B. Problem Definition

We, basically, study a scenario where a wireless access market is shared between two different SPs, which own their networks. N competing users who are nonuniformly distributed within the coverage area. The scenario of interest is shown in Figure 2. The networks are deployed with areas of exclusive coverage (monopoly situation) and partially overlapping area (competition for users). We are interested to answer the following research question:

- Which pricing strategy should the SPs implement in order to maximize their profits in a competitive environment with a heterogeneous demand and under different market shares?

In the following (Section II), a description of the network settings, the resource allocation mechanism and the utility function used to evaluate the user's and BSs' performance can be found. In Section III, we describe the wireless access market experienced by the users based on their location and the pricing strategy. The performance evaluation based on simulation analysis is addressed in Section IV. Concluding remarks are presented in Section V.

II. System Model

We analyze a scenario where two wireless networks are deployed in a densely populated area with nonuniformly distributed users. Considering that a uniform user distribution leads to lower multi-user interference and consequently higher system capacity (hence these models can lead to overestimation of system capacity), we have modeled the user population with a Gaussian distribution to approximate our model to real scenarios. The probability density function of the users' distribution a can be expressed as below:

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

where μ is the mean (location of the peak of the demand), σ^2 is the variance (the measure of the width of the distribution) for the user position l within the system area [0 - L] where $L = 3 * R$. Here R is the cell radius defined in Table I.

We assume an interference-free system and that the two networks, belonging to different SPs, overlap partially in coverage. We focus on communication in the downlink direction, e.g., from the base stations (BSs) to the mobiles.

A. Wireless Access Market - Model

The users experience two location-based wireless markets: *monopoly access market* and *open access market* as illustrated in Figure 2.

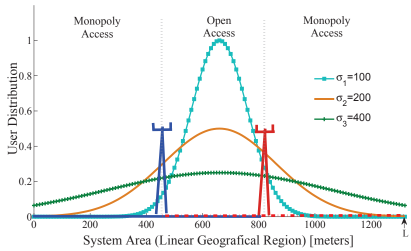

Fig. 2. Network deployment scenario - where σ represents different market shares between the two competing wireless access networks.

The monopoly market is observed while users are located in the non-overlapping areas, since there is only one BS providing access to its network. When the users are within the overlapping coverage by the two networks, they experience an open access market. A competitive game takes place among the BSs, who selfishly, try to maximize their own expected profit per second, as defined in Equation (7).

The users are able to pick the BS that offers the highest peak data-rate at the lowest price (highest *estimated utility*). Each BS broadcasts its reservation price among the users located within its coverage area. Note, that a price differentiation is used by the BSs, meaning that the users in the monopoly coverage area might experience higher costs in the absence of any competition. The algorithm for the competition between BSs and the user decision-making process used in our system model is represented in Figure 3.

As explained in [5], we model a file download in a TDMA system and apply a trade-agent based mechanism for the bidding process. The trade-agents, who are entities located in the BSs, act on behalf of the users and their objective is to maximize their users' utilities during the file transfer. User j competes against others for resources (transmission time), $x_{i,j}$, during each auction round i. In order to be able to download a file of size q, the trade-agent j should submit a positive bid to a SP.

Considering that profit-seeking service providers may chose only the better users (i.e., those users that generate the maximum profit) and denied the transactions from all the others,

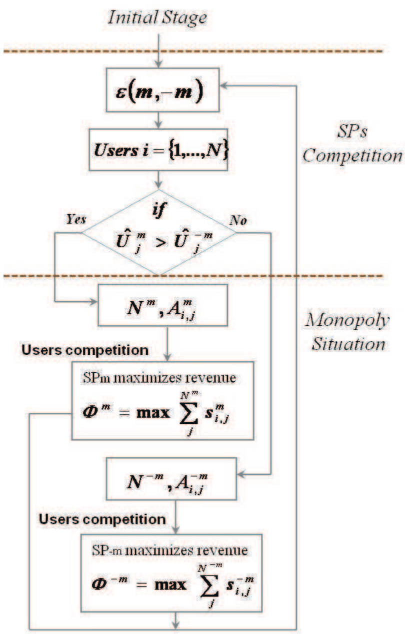

Fig. 3. SPs competition, demand split and users competition

a mechanism that allows the users to actively participate in the decision-making process is needed. From the user's point of view - in order to assure fairness among the users - we have used the proportionally fair auction mechanism for the recourse allocate process (this method is explained in detail in [5]) and based on their bids users will get a portion of transmission time defined by Equation (2) in the following:

$$x_{i,j}(s) \quad = \quad \frac{s_{i,j}}{s_{i,j} + \sum_{k \neq j} s_{i,k} + \epsilon} \in [0,1), \qquad (2)$$

where $\sum_{k \neq j} s_{i,k}$ represents the strategies (bids) of all the opponents' trade-agents k and ϵ is the reservation price or the price of the resource established by each SP, $\epsilon \in [\epsilon_{min}, \epsilon_{max})$. ϵ_{min} is a nonzero price floor below which the resource will not be sold. Note that this price floor is a representation of the fixed cost incurred by the SP, $\epsilon_{min} = Cost$. For this study we have assumed a fixed cost $\epsilon_{min} = 2$, which has been previously considered in [7].

Assuming that the peak data-rate of a single user j from a trade-agent j, remains unchanged during the entire file transfer and that this applies for all the users, i.e. $R_{i,j} = R_{z,j}$ for $\forall\ i, z$. The total demand associated with the other trade-agents, thus $\sum_{k \neq j} s_{i,k} = \sum_{k \neq j} s_{z,k}\ \forall\ i, z$. Note that z is the last round of the auction. Due to these assumptions, each trade-agent will place identical bids in all the auctions.

B. User Model

1) Utility Function: In this analysis, we assume that a user picks the BS that provides the highest *estimated utility* and it is given the choice to not enter the system if the price established by the BS is too high. The user maximization problem is introduced in Equation (3).

$$\begin{aligned} &maximize \quad \hat{U}_{i,j}^m(R_j^m, \epsilon_m) \\ &\forall j \in \{1, ..., N\}, m \in \{1, 2\}, \end{aligned} \qquad (3)$$

where $\hat{U}_{i,j}^m$ is the user's estimated utility which is used as the decision-taking parameter defined as bellow:

$$\hat{U}_{i,j}^m \quad = \quad \frac{R_{i,j}^m}{\epsilon_m}. \qquad (4)$$

Here $R_{i,j}^m$ is the peak data-rate that the user experiences based on its location and ϵ_m is the reservation price broadcasted by the BSs.

2) Acceptance Probability: Let us define x_1 as the coverage of BS_1 and x_2 as that of BS_2. Then, it is clear that user j located at $x_1 \cap x_2$, (see Figure 4) will therefore prefer, initially, BS_1 if and only if $\hat{U}_{i,j}^1 > \hat{U}_{i,j}^2$ during auction 1.

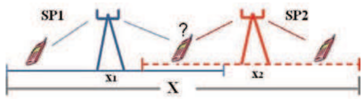

Fig. 4. Base stations location - linear geographical region

Once the user has decided which BS provides the best service, its satisfaction and so the wiliness to pay for the offered service can be measured with an acceptance probability defined as follows:

$$A_{i,j}^m \quad = \quad 1 - e^{-c(\hat{U}_{i,j}^m)^{\mu}(s_{i,j}^m)^{\zeta}}, \qquad (5)$$

where the c, μ and ζ are appropriate positive constants, 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 2). This acceptance probability model is a modified version of the one used in [6]–[8]. 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.

C. Base Stations BSs - 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 $a^m_{i,j} \in \{1,0\}$ such that $a^m_{i,j} = 1$ if user j chooses SP_m and $a^m_{i,j} = 0$ 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 6).

$$\sum_{m}^{2} a^m_{i,j} \leq 1 \qquad (6)$$

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:

$$maximize \sum_{j=1}^{N} \left(s^m_{i,j} . A^m_{i,j} \right). \qquad (7)$$

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

III. Performance Evaluation

The user acceptance probability, the monetary expenditure per transferred Megabyte, the average user throughput and the average BS profit, as a function of the resource price have been used to measure the system performance. We model the pathloss as expressed bellow:

$$L(d) \quad = \quad 35.3 + 38 \log_{10}(d) \quad in\ units\ of\ dB, \qquad (8)$$

where d denotes the distance between the BS and the mobile terminal. In our experiment we have neglected shadow fading and modeled interference as coming from constantly transmitting BSs. As in [4], we use a truncated version of the Shannon bound that has been adjusted to include efficiency losses, leading to the peak data-rate:

$$R_{i,j} \quad = \quad \min\left(W \log_2 \left(1 + \frac{\Gamma_{i,j}}{2} \right), R_{max} \right), \qquad (9)$$

where $W = 3.84$ MHz is the channel bandwidth, $\Gamma_{i,j}$ represents the signal to interference and noise ratio and R_{max} denotes the maximum bit-rate that can be achieve by the user.

A. Simulation Settings

Extensive simulations were carried out with a granularity of one second (auction cycle) for two wireless access providers. Table. I summarizes the simulation parameters that were used. These values have been taken as a reference from the prior analysis introduced in [4], [5]. We have generated the users locations (nonuniformly distributed across the area of interest) by using a Gaussian distribution.

TABLE I
Simulation Parameters Values

Parameters - with units in square brackets	Value
BS transmit power (P) [W]	20
Users distribution	Gaussian
Cell radius [meters]	440
Number of competing BSs (M)	2
File size (q) [Megabyte]	1
Maximum bite-rate (R_{max}) [Mbit/s]	7
Number of users (N)	50

B. Simulation Results

The system is analyzed under different levels of market share (inversely proportional to $\sigma = 100, 200, 400$).

1) Base Station's Profit: Figures 5 and 6 show the average profit per BS for $\sigma = 100$ and $\sigma = 400$. These results show that there is a max-min behavior on the generated profit. For certain price values, only one BS is able to maximize the utility of its network meanwhile the other BS gets the minimum possible. When both BSs applied the same price to the resource, an equilibrium point in profit is observed. When one decides to deviate from that point the opponent BS maximizes its profit and the one that deviates obtain the minimum possible value.

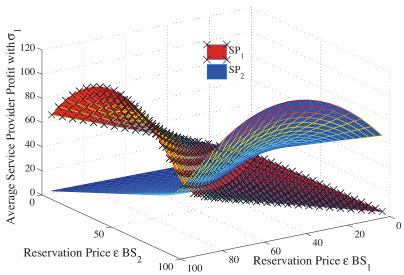

Fig. 5. Average profit per BS per second in the System based on a demand-responsive pricing mechanism with market share, $\sigma = 100$. A case under "highly competitive" regime.

Figure 7 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.

2) User Performance: Since the users are given the choice to not enter the system if the reservation price of the resource is too high, we show in Figure 8 how they respond to the price established by the BSs. We demonstrate that with a higher level of market share (small σ) the users accept the service with high probability when the reservation price is relatively low. For high price values the users become more sensitive

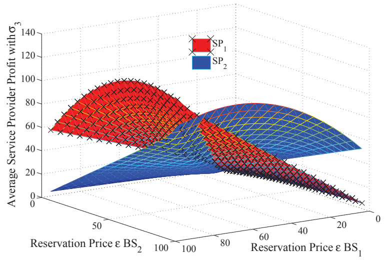

Fig. 6. Average profit per BS per second in the System based on a demand-responsive pricing mechanism with market share, $\sigma = 400$. A case under "less competitive" regime.

Figure 7 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.

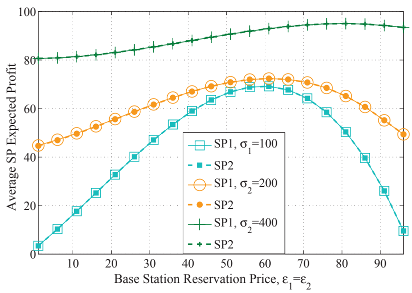

Fig. 7. Expected BS profit per second as a function of the reservation price when $\epsilon_1 = \epsilon_2$.

2) User Performance: Since the users are given the choice to not enter the system if the reservation price of the resource is too high, we show in Figure 8 how they respond to the price established by the BSs. We demonstrate that with a higher level of market share (small σ) the users accept the service with high probability when the reservation price is relatively low. For high price values the users become more sensitive and the probability of accepting the service drops drastically.

Figures 9 and 10 show the quality of service, QoS, experienced by users in terms of average throughput per second and monetary expenditure per transferred Megabyte.

We observed that for high level of market share, $\sigma = 100$, (e.g., when almost all the users fall in the competition area),

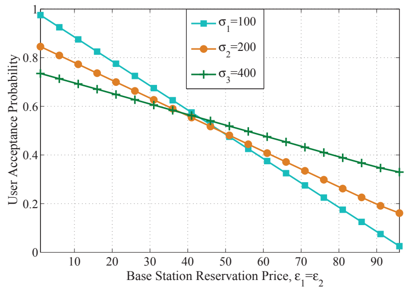

Fig. 8. The user responsiveness in the system, denoted by *Acceptance Probability* as a function of the reservation price during each auction cycle. We observe how the probability that the user accepts the service from a SP varies under different market shares, σ.

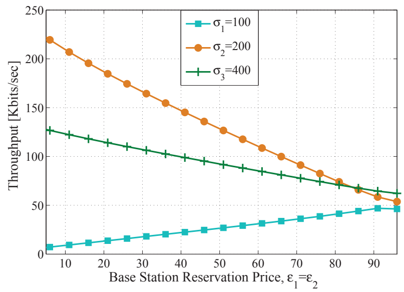

Fig. 9. *Average user Throughput* per second experienced by users in the system as a function of the game among BSs, the selection of reservation price for the resources.

the users get the lowest throughput (see Figure 9). This fact can be explained considering that when the broadcasted reservation price is low, all competing users want to transmit and submit a positive bid. Since fairness is guaranteed, all of them will get a small portion of transmission time. This is due to the knowledge that the time slot is divided among all competing users, the more users actively bid for the resource the shorter time and lower throughput they get.

Figure 10, on the other hand, illustrates as expected, that competition makes prices go down, but this does not, necessarily, mean that it is optimal for the user performance. The shorter transmission time a user gets the longer it takes to download a file. The waiting time accumulates and the user might withdraw its bid in a auction, this negative consequence is, however, out of the scope of this work.

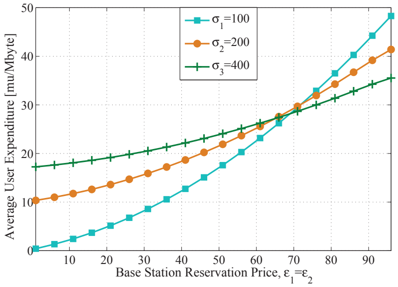

Fig. 10. *Average user monetary expenditure* per transferred MByte as a function of the game among BSs, the selection of reservation price for the resources.

IV. Conclusion and Future Work

In this work, we studied a demand-based profit maximization strategy where a competitive pricing game has been used. An open wireless access market (with different size of market share) has been addressed, where two given networks overlap in service areas. The service providers' objective is to maximize their profits, meanwhile the users, selfishly, maximize their own utilities (higher data-rate at lower cost). Attained simulation results show that the competing service providers tend to aggressively drop the service price to capture a larger number of users in the highly populated area, while user throughput dramatically fails with a growth in service transactions (congested system). Our analysis reveals that the SPs may retain the demand and hence increase their profits by establishing a reservation price close to a market-oriented one. We believe that the SPs could learn and further adapt which pricing settings are viable in order to be competitive and sustainable in an open wireless access market. Under our assumptions and based on these observations we conclude that the optimal size of market share could be gained based on the behavior of the user demand and be beneficial for both users and SPs.

Further extensions of this work would be to devise some pricing schemes, or to study how SPs price their services under a cooperative scenario. Additionally, pricing games evaluated in scenarios with an interference-limited system would be interesting and worth to investigate.

Acknowledgment

The authors would like to thank VINNOVA (MODyS project) and the Swedish International Development Agency (SIDA) for their partial support of this work.

References

[1] T. Janevski, "5G mobile phone concept," in *Proceedings of the* 6^{th} *IEEE Consumer Communications and Networking Conference, CCNC*, January 2009.

[2] A. Tudzarov and T. Janevski, "M-RATS: Mobile-based radio access technology selector for heterogeneous wireless environment," in *Proceedings of the* 18^{th} *Telecommunications forum, TELFOR*, Serbia, Belgrade, November 2010.

[3] F. Beltran, J. Gutierrez, and J. Melus, "Technology and market conditions toward a new competitive landscape in the wireless access market," *IEEE Communications Magazine*, vol. 48, no. 6, June 2010.

[4] M. Blomgren and J. Hultell, "Demand-responsive pricing in open wireless access markets," in *Proceedings of the IEEE Vehicular Technology Conference, VTC-Spring*, Dublin, Ireland, April 2007.

[5] P. Gonzalez-Sanchez and J. Zander, "Deployment strategies in competitive wireless access networks," in *Proceedings of The International Conference on Advances in Cognitive Radio COCORA*, Budapest, Hungary, April 2011, [Best Paper Award].

[6] S. M. Khamit and J. Zander, "Competitive spectrum allocation in heterogeneous coverage areas," in *Proceedings of the the European Wireless, EW*, Vienna, Austria, April 2011.

[7] O. Ileri, D. Samardzija, and N. Mandayam, "Demand responsive pricing and competitive spectrum allocation via a spectrum server," in *Proceedings of the IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Network, DySPAN*, Baltimore, MD, November 2005.

[8] O. Ileri, D. Samardzija, and N. B. Mandayam, "Dynamic spectrum access models: Toward an engineering perspective in the spectrum debate," *IEEE Communication Magazine*, 2007.

Paper IV: Competitive Access-point Deployment in Mobile Broadband Systems

Pamela Gonzalez-Sanchez, Jens Zander
In proceedings of the 10^{th} Scandinavian Workshop on Wireless Ad-hoc Networks (ADHOC'11), Stockholm, Sweden, May 2011.

Competitive Access-point Deployment in Mobile Broadband Systems

Pamela Gonzalez-Sanchez, Jens Zander
Royal Institute of Technology KTH, Radio Communication Systems, 164 40 Kista, Sweden
Emails: {dpgs, jenz}@kth.se

***Abstract*—The case of a competitive wireless access market operated by an Incumbent service provider (SP) and an entrant SP (which hereinafter interchangeably refers to a Newcomer SP) is analyzed in this paper. Clearly, when a Newcomer service provider gets into the wireless market this will have to compete against the market rules of the Incumbent SP and implement optimum schemes to break through the marketplace. Motivated by this, and due to a possible variety of scenarios and dimensions on this problem, in this paper we investigate access-point location as a competitive game amongst different SPs. We aim to study a simple competitive network deployment strategy that provides insight for real scenarios and thus contribute to improve future network deployment models for profit-seeking SPs. We assume that an Entrant SP is willing to deploy a wireless network (i.e., hot-spot) aiming to be competitive in a market that is monopolized by an existing network operator. An open wireless access market is observed when both networks overlap in coverage. Through simulation analysis we intend to understand the behavior of the system in terms of profit generated for the Entrant SP and establish whether or not it is suitable to deploy a network and if so, where it should be. On the other hand, it is also interesting to observe how this new competitive environment affects the profitability of the Incumbent SP and what is the impact of this new setting on the users satisfaction. Our results indicate that an Entrant's profitability depends on the Incumbent's strategies and location as well as on the behavior of the demand.**

***Index Terms*—APs location; competitive game; wireless access markets; Incumbent SP; Newcomer SP; nonuniform distribution**

I. Introduction

Based on the growing demand for wireless communication services, in the near future, it is likely that heterogeneous wireless access networks will coexist and provide different services either in a competitive or cooperative manner. Based on their technologies, these networks may differ in offered QoS, price and coverage area. These new features will allow the user to get connected to the best access network at any time [1]. On light of this, it is highly important to analyze what are the issues that a Newcomer operator (hereinafter operator refers to a service provider, SP) should focus on when getting into the wireless market. Research studies, [2]–[4], indicate that during the planning process of a network deployment there are, mainly, three important aspects to be considered:

- a reliable prediction of radio wave propagation,
- the behavior of the traffic demand, and
- a model for configuration and positioning of base station that ensures that most of the demand is captured while at the same time mitigates interference.

In this work, we investigate a deployment strategy based on competitive access-points (APs) location game with heterogeneous demand. By varying the behavior of the demand we model different market shares and study the performance of the system. We investigate coopetition schemes among SPs, where the SPs cooperate when deploying their networks (avoiding full overlap, i.e., aiming less competition for users) but at the same time competition for users in the overlapping areas is addressed. This motivated due to the difficulty of addressing cooperation as a business model among profit-seeking service providers. Based on this, network deployment strategies that consider these issues should be devised.

A. Previous Work

Most of the earlier contributions on *network deployment strategies* are concentrated on cooperative environments where multiple coverage in the same area (overlap) is avoided as possible. These studies have been developed considering that all the deployed base stations (BSs) belong, more likely, to the same SP [2] and offer, mainly, voice services. This current market structure in the mobile area is called (*monopoly*), a market with no competitors, where the incumbent SP has captured an important share of the market.

In [5] a game theoretic approach is used to analyze the problem of determining locations of base stations (belonging either to the same or to competing SPs), taking into account the impact of these decisions on the behavior of intelligent mobile terminals who can connect to the base station that offers the best utility. Assuming an uniform user distribution across the area of interest and through Stackelberg equilibrium in the combined BS location and mobile association problem the authors determined where to locate the BSs so as to maximize the their utilities (aggregate throughput of the mobile associated with it). Also in [6], the authors address the problem of optimum BSs placement taking into account the fairness criterion like global, proportional, harmonic and max-min fairness. Unlike the two previous works, we focus on the economic analysis (the impact on the SPs profitability) of competitive APs location game among different SPs considering a nonuniform user distribution in the area of interest.

In our previous work [7], we have investigated how the SPs should deploy their networks, striking a balance between areas of exclusive coverage, where each provider has a monopoly situation, and overlap areas with provider competition, to achieve maximal profitability. Users were assumed to be uniformly distributed across the service area. We analyzed how the level of competition (level of overlap between two networks) affects the system performance in terms of users QoS and SP revenue.

B. Problem Definition

Envisioning that users expectations will be realized through service offerings that not only include traditional voice services but also video-on-demand, TV service, Internet access, and others, multiple wireless access technologies will coexist and be integrated in a seamless manner in the future [8]. Clearly, Newcomer SPs entering the wireless market will have to compete against the market rules of the Incumbent wireless SPs, and should implement optimum schemes to break through the marketplace. Motivated by this, in this paper we investigate AP placement as a competitive game. We aim to study a simple network deployment strategy that provides insight for real scenarios and thus contribute to improve future network deployment models of profit-seeking service providers. More specifically, through simulation analysis we intend to investigate the following research statement:

- *Establishing, whether or not, it is suitable for the Newcomer SP to deploy a network in a duopoly market according to the location of an Incumbent SP, and if so, where it should be.*

Basically, we aim to understand the behavior of the system in terms of profit generated for the Newcomer SP. Furthermore, it is also interesting to observe how this new competitive environment affects the profitability of the Incumbent SP and what is the impact of this new setting in the users' satisfaction.

The rest of the paper is organized as follows. Section II addresses the system model, user objective and APs maximization problem. In Section III, the performance evaluation and simulation results are explained and Section IV contains concluding remarks.

II. System Model

We analyze a scenario where two wireless networks, like *"hotspots"*, are deployed in a densely populated area with N nonuniformly distributed competing users. We model the user population with a Gaussian distribution and its probability density can be expressed as below:

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

where μ is the mean (location of the peak of the demand), σ^2 is the variance (the measure of the width of the distribution) for the user position l within the system area [0 - L]. Here, L represents the maximum longitude of the area of interest in our analysis.

Since the the objective is to determine the profitability of the Newcomer SP and the optimal location of its AP, we model the system as a competitive game varying the Newcomer AP's position across the coverage area. An open wireless access market is addressed when the two networks overlap in coverage. We focus on communication in the downlink direction, i.e., from the APs to the mobiles. The APs and the mobile users are deployed within the area of interest. The basic scenario under consideration is illustrated in Figure 1.

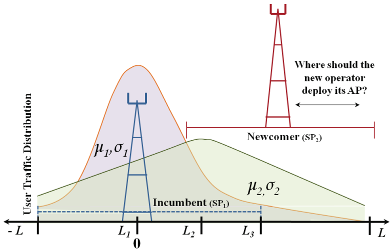

Fig. 1. Illustration of a problem that the Newcomer SP faces when getting into the wireless market.

A. Wireless Access Market - Model

The users experience two location-based wireless markets: *monopolistic access market* and *open access market* [7].

The monopoly market is observed while users are located in the nonoverlapping areas, since there is only one AP providing access to its network. When the users are within the overlapping coverage by the two networks, they experience an open access market. A competitive game takes place among the APs, who selfishly, try to maximize their own expected profit per second (this is defined later on this paper by Equation (7)).

The users are able to pick the AP that offers the highest peak data-rate at the lowest price (highest *estimated utility*). Each AP broadcasts its reservation price among the users located within its coverage area. Note that a price differentiation is used by the APs, meaning that the users in the monopoly coverage area might experience higher costs in the absence of any competition.

The two market shares, represented by (μ_1, σ_1) and (μ_2, σ_2) respectively, and assuming a fixed location for the Incumbent the main objective is to observe the Newcomer's profit in both cases when the Incumbent is properly located according to the demand and when it is not.

As explained in [7], we model a file download in a TDMA system and apply a trade-agent based mechanism for the bidding process. The trade-agents, who are entities located in the APs, act on behalf of the users and their objective is to maximize their users' utilities during the file transfer. User j competes against others for resources (transmission time), $x_{i,j}$, during each auction round i. In order to be able to download a file of size q, the trade-agent j should submit a positive bid to an AP.

Resources are allocated using a proportional fair auction mechanism (details on this method can be found in [7]) and based on their bids the users will get a portion of transmission time, which is defined by Equation (2) in the following:

$$x_{i,j}(s) \quad = \quad \frac{s_{i,j}}{s_{i,j} + \sum_{k \neq j} s_{i,k} + \epsilon} \in [0, 1), \qquad (2)$$

where $\sum_{k \neq j} s_{i,k}$ represents the strategies (bids) of all the opponents' trade-agents k and ϵ is the reservation price or the price of the resource established by each SP, $\epsilon \in [\epsilon_{min}, \epsilon_{max})$. ϵ_{min} is a nonzero price floor below which the resource will not be sold. Note that this price floor is a representation of the fixed cost incurred by the SP, $\epsilon_{min} = Cost$. For this study we have assumed a fixed cost $\epsilon_{min} = 2$, which has been previously considered in [9].

Assuming that the peak data-rate of a single user j from a trade-agent j, remains unchanged during the entire file transfer and that this applies for all the users, i.e. $R_{i,j}$=$R_{z,j}$ for $\forall\, i, z$. The total demand associated with the other trade-agents, thus $\sum_{k \neq j} s_{i,k}$=$\sum_{k \neq j} s_{z,k}$ $\forall\, i, z$. Note that z is the last round of the auction. Due to these assumptions, each trade-agent will place identical bids in all the auctions.

B. User Model

1) Utility Function: In this analysis, we assume that a user picks the AP that provides the highest *estimated utility* and it is given the choice to not enter the system if the price established by the AP is too high. The user maximization problem is introduced in Equation (3).

$$maximize \quad \hat{U}^m_{i,j}(R^m_j, \epsilon_m) \qquad (3)$$
$$\forall j \in \{1, ..., N\}, m \in \{1, 2\},$$

where $\hat{U}^m_{i,j}$ is the user's estimated utility which is used as the decision-taking parameter defined as bellow:

$$\hat{U}^m_{i,j} \quad = \quad \frac{R^m_{i,j}}{\epsilon_m}. \qquad (4)$$

Here $R^m_{i,j}$ is the peak data-rate that the user experiences based on its location and ϵ_m is the broadcasted price of the resource by AP m.

2) Acceptance Probability: Let us define l_1 as the coverage of AP_1 and l_2 as that of AP_2. Then, it is clear that user j located at $l_1 \cap l_2$, (see Figure 2) will therefore prefer, initially, AP_1 if and only if $\hat{U}^1_{i,j} > \hat{U}^2_{i,j}$ during auction 1.

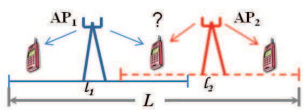

Fig. 2. Access-points location - Linear Geographical region

Once the user has decided which AP provides the best service, its satisfaction and so the wiliness to pay for the offered service can be measured with an acceptance probability defined as follows:

$$A^m_{i,j} \quad = \quad 1 - e^{-c(\hat{U}^m_{i,j})^{\mu}(s^m_{i,j})^{\zeta}}, \qquad (5)$$

where the c, μ and ζ are appropriate positive constants, and $s^m_{i,j}$ represents the price that the user pays during each auction cycle, and it is equivalent to the bid that this user submits to the AP, (see Equation 2). This acceptance probability model is a modified version of the one used in [9], [10]. After the first stage (auction 1), if the user starts transmitting, it should remain connected to this AP until the file transfer is completed.

C. Access-point Profit Maximization

The AP'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 $a^m_{i,j} \in \{1{,}0\}$ such that $a^m_{i,j} = 1$ if user j chooses AP m and $a^m_{i,j} = 0$ otherwise.

One constraint that should be considered is that for any user j a maximum of one AP should be assigned (as defined in Equation 6).

$$\sum_{m}^{2} a^m_{i,j} \leq 1 \qquad (6)$$

The demand-based profit maximization problem for the APs 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:

$$maximize \sum_{j=1}^{N} \left(s^m_{i,j} \cdot A^m_{i,j} \right). \qquad (7)$$

The summation of all the users that choose AP m formes the generated demand which accepts the service with a probability $A^m_{i,j}$.

III. Performance Evaluation

The average profit per AP per second and the user responsiveness through an acceptance probability, both as a function of the Entrant's location, have been used to measure the system performance.

The pathloss and the peak data-rate experienced by the users have been modeled as explained in [7], [11].

A. Simulation Settings

A simulation analysis (Matlab) was carried out with a granularity of one second (auction cycle) for two wireless network service providers. Table. I summarizes the simulation parameters used in our analysis. These values have been previously considered in the studies described in [7], [12].

B. Simulation Results

For the purpose of simulation analysis, we first define the suitable resource price for the Entrant SP based on the pricing that the Incumbent SP has established.

1. AP Profit Maximization

TABLE I
SIMULATION PARAMETERS VALUES

Parameters - with units in square brackets	Value
AP Transmit Power (P) [W]	20
Users distribution	Gaussian
(μ_1, σ_1)	$(L_1$, 100)
(μ_2, σ_2)	$(L_2$, 500)
Newcomer's Location 1, L_1 [meters]	0
Newcomer's Location 2, L_2 [meters]	220
Newcomer's Location 3, L_3 [meters]	660
Cell Radius [meters]	440
Number of Competing APs (M)	2
File size (q) [Megabyte]	1
Maximum bite-rate (R_{max}) [Mbit/s]	7

We consider two cases: when the Incumbent has monopolized the market establishing a high price for the resource. The Entrant (Newcomer) SP gets into the market with a lower price to attract the demand.

A fixed price is assumed for the Incumbent, varying the reservation price of the Newcomer in order to determine the exact value that maximizes its profit under our specific assumptions. We analyze the system's behavior for different market shares, which are depicted above in Figure 1. The optimal price for the Newcomer was calculated only for $\sigma_1 = 100$ which presents a highly competitive scenario (meanwhile, $\sigma_2 = 500$ corresponds to a less competitive environment).

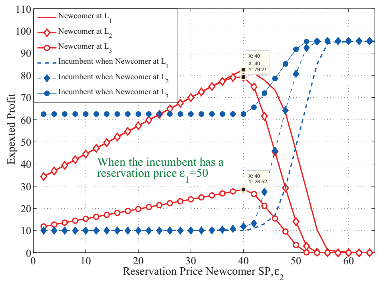

Fig. 3. Optimal price of the Newcomer SP given the resource price of Incumbent in the wireless access market; Incumbent price $\epsilon_1 = 50$, high price services.

Figure 3 shows that there is a price that maximizes the Newcomer's profit, independently of its location, for any given price established by the Incumbent. However, as already known, it is observed that the Incumbent is the one directing the course of the market, by establishing the price of the services and that the Newcomer should first study the strategies of its competitor. In this figure, L represents the different locations for the Newcomer under which the optimal price was calculated.

Once we have defined the optimal price of the Newcomer SP given the price of the Incumbent, we carry out the competitive AP location game to estimate the suitable positioning of the Newcomer's AP.

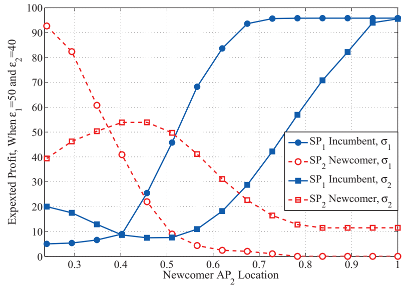

Fig. 4. Expected per AP per second as a function of the Newcomer's AP location. The Newcomer SP gets into the market with a lower price for the services.

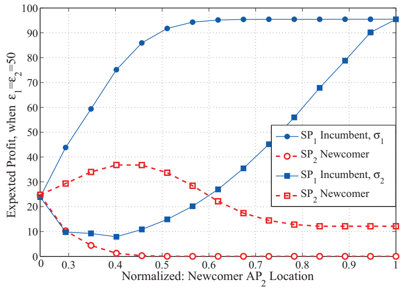

Fig. 5. Expected profit per AP per second as a function of the Newcomer's AP location. The Newcomer SP gets into the market pricing the services equally to the Incumbent.

Figure 4 illustrates that for a highly competitive environments, which is represented by $\sigma_1 = 100$ in our study, the Newcomer has a shorter suitable range to place its AP. As this moves away from the Incumbent's AP its profit decreases leading to the minimum possible value ($profit = 0$) under these conditions. This is an expected behavior considering that when the Newcomer deploys its AP co-located with the Incumbent, this is able to capture most of the demand with the strategy of offering cheaper services (in comparison to the Incumbent's price) leading to higher profits. For less competitive settings, $\sigma_2 = 500$, the suitable deployment range gets wider but a trade off in the expected profit is observed. This is due to the fact that the user acceptance probability drops in the absence of an open market (see Figure 6). We also clarify that when the Newcomer places its AP co-located to the Incumbent, and with settings μ_1 and σ_1, the whole demand is in coverage, whereas with settings of μ_2 and σ_2 a small portion of the users get in outage stage (out of coverage) .

In Figure 5 we observe the AP's expected profit when the Newcomer enters the wireless market with an equal pricing strategy (imposing the the same price as the Incumbent). We have assumed a high price for the service $\epsilon_1 = \epsilon_2 = 50$ considering that the users have been given the choice to not enter the game if the established prices are too high. With higher prices, they both obtain higher gains since the users are still willing to pay the price for good quality services (this can be observed bellow in Figure 6).

2. User Satisfaction

Figure 6 shows the average user acceptance probability (based on the experienced QoS) in the system as a function of the Newcomer's AP location in the wireless market. Due to the competition the users get better services at lower prices, hence their satisfaction grows. When the Newcomer moves its AP away from the Incumbent the users experience monopoly prices (e.g., the Incumbent price, which is represented by a higher price) and their reaction is to withdraw the system (we observe how the probability of accepted services decreases).

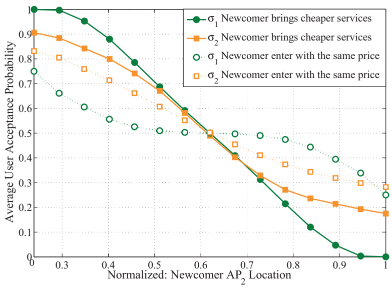

Fig. 6. Average user acceptance probability, "*user preference*", in the system as a function of the newcomer AP location.

IV. Conclusion

In this paper we investigated a location game among competing access-points aiming to get insight from an economic perspective on network deployment strategy for real scenarios. Specifically, we have analyzed whether or not it is suitable for a Newcomer to deploy a network considering the location of the Incumbent and if so, where it should be. Based on our simulation results we may conclude that a prior analysis based on the strategies implied by the Incumbent SP should be implemented by the Newcomer, before entering the market. We observe that there exist a price equilibrium that maximizes the Newcomer's profit independently of its location. When the Incumbent is properly located according to the demand and both SPs have the same service price, then there exist less possibilities for an Entrant to be self-sustained in the wireless market. However, decreasing the service price seems to be a good strategy to attract the demand, but considering real scenarios, an Incumbent will also decrease its price and this may end up in a *price war* leading to a negative impact in their profitability. On the other hand, when the Incumbent is not properly located, the case of (μ_2, σ_2), the Entrant is more like to succeed.

Acknowledgment

The authors would like to thank VINNOVA (MODyS project) and the Swedish International Development Agency (SIDA) for their partial support of this work.

References

[1] W. Zhang, "Bearer service allocation and pricing in heterogeneous wireless networks," in *Proceedings of the IEEE International Conference on Communications, ICC 2005*, 2005.

[2] R. Mathar and T. Niessen, "Optimum positioning of base station for cellular radio networks," *Journal on Wireless Networks*, vol. 6, no. 6, 2000.

[3] K. Johansson, *Cost Effective Deployment Strategies for Heterogeneous Wireless Networks*. KTH Information and Communication Technology, Ph.D. dissertation, Sweden, 2007.

[4] J. Markemdahl, Östen Mäkitalo, J. Werding, and B. G. Mölleryd, "Business innovation strategies to reduce the revenue gap for wireless broadband services," *Communications and Strategies Journal*, vol. 1, no. 75, 2009. [Online]. Available: http://econpapers.repec.org/RePEc:idt:journl:cs7502

[5] S. Ramanath, E. Altman, V. Kumar, V. Kavitha, and L. Thomas, ""fair assignment of base stations in cellular networks"," in 22^{nd} *World Wireless Research Forum (WWRF) Conference, Paris, France*, May 2009.

[6] E. Altman, A. Kumar, C. Singh, and R. Sundaresan, "Spatial sinr games combining base station placement and mobile association," in *INFOCOM 2009, IEEE*, 2009.

[7] P. Gonzalez-Sanchez and J. Zander, "Deployment strategies in competitive wireless access networks," in *Proceedings of The International Conference on Advances in Cognitive Radio, COCORA 2011*, Budapest, Hungary, April 2011.

[8] F. Beltran, J. Gutierrez, and J. Melus, "Technology and market conditions toward a new competitive landscape in the wireless access market," *IEEE Communications Magazine*, vol. 48, no. 6, June 2010.

[9] O. Ileri, D. Samardzija, and N. Mandayam, "Demand responsive pricing and competitive spectrum allocation via a spectrum server," in *Proceedings of the* 17^{th} *IEEE Real-Time Systems Symposium*, 2005.

[10] O. Ileri, D. Samardzija, and N. B. Mandayam, "Dynamic spectrum access models: Toward an engineering perspective in the spectrum debate," *IEEE Communication Magazine*, 2007.

[11] P. Gonzalez-Sanchez, S. Khamit, and J. Zander, "Competitive pricing with heterogeneous demand in open wireless access market," in *Submission to the* 3^{rd} *International Congress on Ultra Modern Telecommunication and Control Systems, ICUMT 2011*, Budapest, Hungary, October 2011.

[12] M. Blomgren and J. Hultell, "Demand-responsive pricing in open wireless access markets," in *Proceedings of the IEEE Vehicular Technology Conference VTC-Spring*, April 2007.