SHORT-TERM SPECTRUM SHARING WITH ECONOMIC AWARENESS IN 5G NETWORKS

by
Huiyang Wang

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Prof. Eryk Dutkiewicz

School of Electrical and Data Engineering
University of Technology Sydney
Sydney, Australia

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ABSTRACT

The next Generation Mobile Networks 5G is expected to start rolling out by 2020, targeting at significantly faster mobile data speeds and increasingly massive machine communications. As we are entering into a whole new wireless time, where the blend of spectrum policy and technology becomes more important, the networking practices are tightly coupled with economic considerations. Therefore, a novel economic-driven spectrum policy should be designed to support all spectrum access methods with flexibility to take advantage of potentially new spectrum sharing paradigms.

In this thesis, we present the feasibility of putting economic models in the existing dynamic spectrum sharing architectures, from three aspects: spectrum sublicensing at a small scale, spectrum auction design, and licensed and unlicensed band selection. We point out the challenges under each scenario and propose solutions to address these problems.

First, for the spectrum sublicensing, we introduce the concept of the protection zone to enable multiple operators to spatially share the spectrum and ensure exclusive usage without any interference. Furthermore, the trade-off between the precision of boundary estimation and the cost of sensing networks is analysed. Second, for the spectrum auction, we study how an interference graph influences performance of the auction algorithm and guarantees fairness and truthfulness. Additionally, we further propose a negotiable auction for a more efficient spectrum allocation based on a mixed graph which offers a base station a second chance if the original request is rejected. Unlike the existing work, our proposed solution with a

faster grouping scheme performs better in a dense situation, hence it accommodates more base stations. Third, for the licensed and unlicensed band selection from the perspective of operators, we build a finite game and present performance comparisons of different strategies. Moreover, the analysis of the Nash equilibrium is provided and so are the suggestions on how to achieve high benefits for different scales of operators.

We apply our design and findings to the potential spectrum sharing architectures, i.e., Licensed Shared Access and Spectrum Sharing System. We strengthen the coupling of the sublicensing scheme with the spectrum sharing platforms by enabling each base station as an individual bidder and let them bid for a contour based sublicense, ensuring the exclusive right and interference protection. Additionally, we also analyse the unlicensed and licensed band selection from the perspective of operators and prove the equilibrium existence in the spectrum market. In conclusion, the short-term sublicensing in the secondary market has not been fully studied and put into practice yet. The thesis has given rise to an integration of spectrum technology and policy. It is believed that, in the future, the economic-aware spectrum policy design could be incorporated into communication technology to realize an innovative, efficient and flexible sharing model.

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This research is supported by an Australian Government Research Training Program Scholarship.

Name of Student: Huiyang Wang

Signature of Student:

Date:

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Dedicated to My Beloved Parents

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List of Symbols

Symbol	Description
M	number of spectrum blocks or sellers
P_t^m	allowed maximum transmit powers on spectrum block m
f	frequency
p_i^j	buyer i's transmit power on the spectrum block j
P_r	the signal strength at the edge of a cell
d_0	assumed to be 1-10 m indoors and 10-100 m outdoors
N	number of base stations or buyers
p_i	buyer i's payment
D_i	shape of the contour of buyer i
$v_i(x, y)$	buyer i's valuation density in the space domain
a_i	allocation result $\in \{0, 1\}$
$\mathbb{R}$	revenue of the auction
$\rho(x, y)$	density of sensors in a region
c	the cost of the sensing or sublicense of the buyer
τ	the cost of one sensor
λ	the average distance between sensors
$\lvert\mathbf{B}\rvert$	the area of a bounded region $\mathbf{B}$
d_{ij}	the distance between buyer i and buyer j
P_h	the high received power by the sensor
P_l	the low received power by the sensor

Symbol	Description
P_b	the contour boundary power
P_s	the power of the base station
d_h	the distance from the base station to the high sensor
d_l	the distance from the base station to the low sensor
d_b	the distance from the base station to the contour boundary
w	number of the whole tiles
h	number of the half tiles
μ	boundary sensitivity
$\mathbf{V}$	a set of vertices in the Euclidean space
$\mathbf{E}$	a set of edges in the Euclidean space
v	a vertex
e	an edge
$\mathcal{T}$	function of a Delaunay triangulation for set $\mathbf{V}$
b_i	buyer i's bid for a spectrum block
l_i	buyer i's location
G	the adjacency matrix of the interference graph
p_i	buyer i's payment
$\|\beta\|$	the number of channels
ω	the weight of a buyer
Ω	a group of nodes
seq	sorted vertices
$\mathbf{b}$	the bid set of a group
$\mathbf{r}$	set of requested coverage ranges
θ_i	buyer i's ratio of these ranges
γ_i	buyer i's determined range
η_i	buyer i's satisfaction

Symbol	**Description**
B	total bid of a buyer
U	buyer's utility
A_i	effective coverage
$\mathcal{M}$	allocation mechanism
$\mathbb{S}$	spatial efficiency
$\mathbb{B}$	buyer satisfaction
Ω^B	group bid
B_α	benchmark of group
s	the player's strategy
$\mathcal{K}$	the player set
u	player's utility or payoff
C^P	average spectrum resource of the buyers under PAL
C^G	average spectrum resource of the buyers under GAA
α	the spectrum of PAL
δ	the spectrum of GAA
r	profit rate
$\mathcal{B}$	total spectrum resource for PAL and GAA use
m	subscriber mass
$\hat{M}$	total subscriber mass
x	the probability of play some strategy

List of Publications

Journal publication

- **Huiyang Wang**, Diep Nguyen, Eryk Dutkiewicz, Gengfa Fang, Markus Dominik Mueck, "Negotiable Auction based on Mixed Graph: A Novel Spectrum Sharing Framework", in IEEE Transaction on Cognitive Communications and Networking, 2017. (Corresponding to Chapter 5)

Conference publications

- **Huiyang Wang**, Eryk Dutkiewicz, Diep Nguyen, Markus Dominik Mueck, "Game Theoretic Analysis of Sublicensing for PAL and GAA Bands in Spectrum Access System," in 28th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2017. (Corresponding to Chapter 6)
- **Huiyang Wang**, Eryk Dutkiewicz, Beeshanga Abewardana Jayawickrama, Markus Dominik Mueck, "Dection of Contour Boundary for Sublicensing in Spectrum Access Systems," in 17th International Symposium on Communications and Information Technologies, ISCIT 2017. (Corresponding to Chapter 3)

- **Huiyang Wang**, Eryk Dutkiewicz, Beeshanga Abewardana Jayawickrama, Markus Dominik Mueck, "Design of Contour based Protection Zones for Sub-licensing in Spectrum Access Systems," in IEEE 82nd Vehicular Technology Conference, VTC Spring, 2017. (Corresponding to Chapter 3)
- **Huiyang Wang**, Eryk Dutkiewicz, Gengfa Fang, Markus Dominik Mueck, "A fair spectrum sharing framework based on topological sort and max weight for femtocells," in Australian Communications Theory Workshop (AusCTW), 2016. (Corresponding to Chapter 4)
- **Huiyang Wang**, Eryk Dutkiewicz, Gengfa Fang, Markus Dominik Mueck, "Framework of Joint Auction and Mixed Graph for Licensed Shared Access Systems" in 2015 IEEE International Symposium on Dynamic Spectrum Access Networks, DySPAN 2015. (Corresponding to Chapter 5)
- **Huiyang Wang**, Eryk Dutkiewicz, Gengfa Fang, Markus Dominik Mueck, "Spectrum Sharing Based on Truthful Auction in Licensed Shared Access Systems," in IEEE 82nd Vehicular Technology Conference, VTC Fall, 2015. (Corresponding to Chapter 4)
- **Huiyang Wang**, Eryk Dutkiewicz, Gengfa Fang, Markus Dominik Mueck, "An Auction Framework Based on Flexible Transmit Powers in the Licensed Shared Access Systems," in 15th International Symposium on Communications and Information Technologies, ISCIT 2015. (Corresponding to Chapter 3 and 4)

Other

- Pierce Rixon, Gengfa Fang, Ying He, **Huiyang Wang**, Markus Mueck, Eryk Dutkiewicz, Michael Heimlich, Beeshanga Abewardana Jayawicjrama, Panagiotis Demestichas, Andreas Georgakopoulos, "Licensed Shared Access," IEEE

SIG White Paper on Novel Spectrum Usage Paradigms for 5G, Chapter 6, 2014 (Corresponding to Chapter 2)

- **Huiyang Wang**, DiepNguyen, Eryk Dutkiewicz, Markus Dominik Mueck. submitted as a patent disclosure: "5G: 3.5 GHz Spectrum Sharing A Short Term Online Agreement on Spectrum Sharing for the Priority Access Licensed Systems" (Corresponding to Chapter 6)

- Gengfa Fang, Markus Dominik Mueck, Eryk Dutkiewicz, **Huiyang Wang**, submitted as a patent disclosure: "Sharing Agreement based Spectrum Sharing for Priority Access Users in 3-tier SAS." (Corresponding to Chapter 2)

Chapter 1

Introduction

This chapter provides an overview of this thesis. Section 1.1 states the background of the thesis, including the diverse traffic requirements of the future networks, spectrum sharing solutions, the potential of the economic-aware shared accesses and the main challenges we aim to tackle. Section 1.2 presents the motivation behind the thesis work. Section 1.3 describes the key contributions of the thesis. Section 1.4 introduces the organization of the thesis.

1.1 Background

1.1.1 5G Overview

The 5th generation mobile networks (5G) aims at zero-distance connectivity between anybody and anything at anytime and anywhere. This could be built as a 'hyper connected' society by more intelligently and comprehensively, integrating Long Term Evolution (LTE), WiFi and Internet of Things (IoT) technologies [2] [3], together with more flexible and scalable management [4] [5], as shown in Fig. 1.1. It requires great efforts to achieve the goal imposed by the anticipated much faster speeds, lowered latency, and larger diversity of applications [6] [7] [8]. To support the exponential growth in mobile data traffic, three key directions are being explored: base station densification [9] [10], additional spectrum resource [11], more efficient spectrum allocation [12] [13]. Additionaly, two basic concerns in 5G should

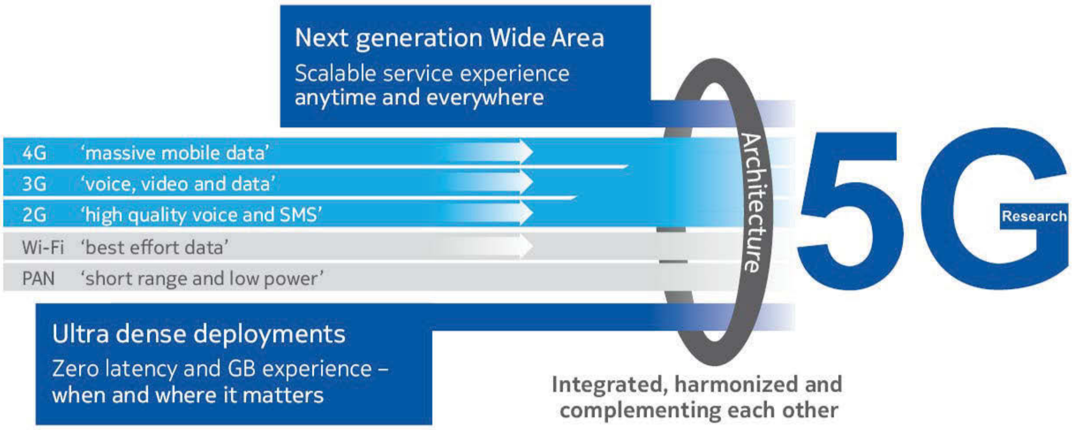


Figure 1.1: Symbiotic integration of existing and new technologies [5].

be addressed first of all: diversity and harmonization.

Diversity

With the development acceleration of the mobile devices and applications, 5G will enable mobile networks to dynamically allocate spectrum to satisfy the varying needs of a hugely diverse set of connections, ranging from smart household appliances at home, automated vehicles on the roads, to the industrial machinery in the factories as well as the wearable devices with people [14] [15].

For mobile operators, 5G spectrum sharing will enable operators to opportunistically aggregate more underutilized spectrum for dynamic sharing. Additionally, so far, the main industry focus has been on licensed/unlicensed spectrum sharing. However, it is important to note that access to the licensed/unlicensed spectrum can extend 5G in multiple dimensions, including enhanced end-user data rates with open access to more spectrum, more efficient local and private network operation, and new deployment use scenarios for industrial applications. The recently proposed spectrum sharing platforms, such as Spectrum Access System (SAS) [16] [17] and Licensed Shared Access (LSA) [18] [19] have witnessed that the interest in 5G shared spectrum is growing.

Harmonization

A widely harmonized architecture for wireless spectrum sharing is needed to ensure 5G services meet future expectation and deliver on the full range of potential capabilities. 5G radio accesses will be built upon both new spectrum allocation policy and the evolution of the currently existing wireless technologies. Considering the replacement of the legacy systems, governments should aim to identify sufficient and flexible 5G spectrum for future requirements so they have the flexibility to easily make it available for 5G services when required [5].

For instance, the regulator in the United States, the Federal Communications Commission (FCC), has recently agreed to make 5G be designed to natively support all spectrum types with the flexibility to take advantage of potentially new spectrum sharing paradigms, thanks to the design of frame structure SAS with forward compatibility [16] [17]. A local centralized component in the evolution of all mobile technology generations has been the use of wide frequency bands to support higher speeds and larger amounts of traffic.

1.1.2 Dynamic Spectrum Sharing

The explosion of different types of wireless communications is leading to an impending spectrum famine. Wireless spectrum is a scare resource and very valuable, so it is likely to become congested to accommodate diverse types of networks, users, applications and interfaces in the 5G era [20]. As a result, dynamic spectrum sharing has gained increasing interest from governments, industry and regulators, such as FCC in the United States and European Conference of Postal and Telecommunications Administrations (CEPT). Gradually breaking the traditional long-term spectrum management policy, the dynamic spectrum sharing in short-term fashion has broad connotations that encompass various solutions to the evolution of spectrum allocation [21].

Dynamic Spectrum Sharing (DSS) is increasingly being seen as a core in 5G networks by leading regulators to develop short-term licensing solutions. Therefore, we need to investigate different concerns of spectrum regulation which reflects this dynamic reality.

- Both the licensed and unlicensed spectrum should be jointly considered and shared. Licensed spectrum should remain the core in the 5G spectrum management model, while unlicensed bands can play a complementary role.
- Technology neutral spectrum sublicenses are essential. They allow bands which are used for existing mobile technologies to be easily refarmed for 5G thus ensuring spectrum is used most efficiently.
- Governments and regulators need to adopt national policy measures to encourage long-term heavy investments for short-term sublicensing in 5G networks.

This concept of "dynamic sharing" could be achieved in a manner of short-term sublicenses and local centralization.

Short Term

The continuing rise in the social media and applications as an important part of how we interact with people and business via the wireless network is opening up new kinds of spectrum consumption roads. The regulatory, technological and economic changes are being driven by the way people use the wireless services and will spawn new business models and technical solutions in wireless service provision and spectrum management practices. More importantly, many of them will rely on short-term spectrum usage by the Dynamic Spectrum Access (DSA) methods that could enable efficient use of spectrum resources in both time and space domain. Flexible working practices facilitated by mobile access networks and devices are already essential and common, and are allowing enterprises to conduct operations across boundaries that previously inhibited their growth.

Three separate long-term spectrum models, i.e., traditional licensed model, traditional unlicensed model and traditional government model (shown in Fig. 1.2) could be performed by the short-term assignment functions under LSA and SAS. The conversion of a long-term spectrum license into a short-term spectrum sublicense involves (i) the event where the license holders and the sublicensees reach an

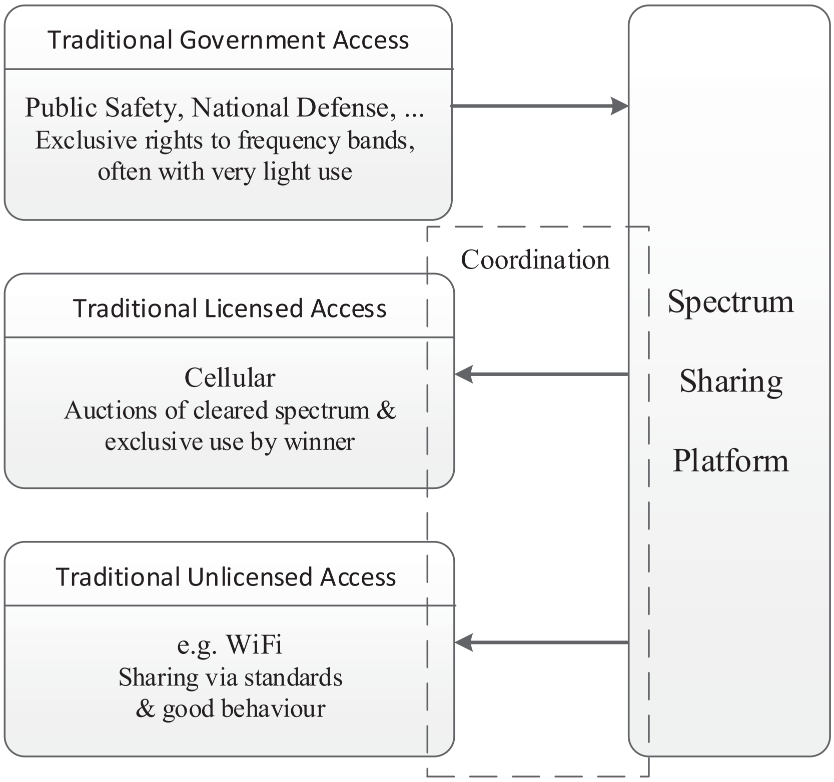


Figure 1.2: Spectrum sharing platform.

agreement on spectrum sharing with the interference consideration. (ii) a spectrum sharing platform that provides them with different tiered accesses and interference monitoring. If structurally additional resources are required, the short-term assignment can be realized and can be obtained supplementary resource from the long-term assignment function via the spectrum sharing platform. This is because the spectrum sharing platform can satisfy more services by resource partitioning and constraint processing based on the small scale of sublicense.

Centralized Coordinator

The hybrid of distributed and centralized technologies is 5G's cornerstone for realizing breakthroughs in the transformation of Information and Communications Technology (ICT) network infrastructure. A local centralized coordinator plays a significant role in managing diverse accesses of mobile distributed devices while limiting the interference constraints among them. The largest telecommunications standard bodies like the US's FCC and the European Telecommunications Standardization Institute (ETSI, through the Radio Spectrum Policy Group (RSPG)) have been developing their future spectrum management architectures that consider spectrum sharing as a core feature. These architectures are referred to as SAS by FCC and LSA by RSPG and CEPT [17] [19].

Both SAS and LSA, the potential spectrum regulatory frameworks in 5G, support the opening of licensed but underutilized spectrum bands of primary/Incumbent users for commercial use. A spectrum geolocation database acts as a local centralized database in the dynamic spectrum shared systems [22], providing information of the available spectrum to secondary networks or sublicensees. Incumbents will be guaranteed protection from harmful interference from the secondary licensees, while the secondary licensees will be required to vacate the spectrum band when an Incumbent registers a conflicting requirement in the database. As centralized spectrum sharing platforms, SAS and LSA can provide unique regulation, diverse services and meet the coexistence requirements by aggregating licensed and unlicensed spectrum.

1.1.3 Economic-aware Sharing

Markets move faster than spectrum regulation, coupled with an ever growing demand for spectrum. In particular, trading temporarily idle spectrum (at various timescales) is considered as a promising solution to improve the spectrum utilization. To break the long-term spectrum allocation, spectrum sharing with economic awareness is a novel enabler for short-term spectrum reform. Breakthroughs in wireless network innovation will drive economic and societal growth in entirely new ways.

The auction mechanism is an effective solution to expedite the reform of spectrum allocation in 5G networks. With the reference of the spectrum geolocation database, it can provide secondary networks with idle and non-continuous spectrum blocks without interference. Because of privacy issues, cellular operators have no idea of the others' deployments. So the inter-cell interference should be well coordinated with economic-ware competition in the centralized sharing scenario.

1.1.4 Challenges

The short-term sublicensing solutions should support very diverse services and be compatible with different accesses. Moreover, in the spectrum market, incumbents are sellers while base stations are buyers. When spectrum trading occurs, there are some issues that should be considered when designing economic mechanisms.

Gradual Evolution

Spectrum refarming is most effective when spectrum licenses are technology neutral without additional expense. This drives competition by encouraging operators to upgrade their networks and will allow 5G services to be rolled out much faster. However, before the refarming is completed, how to arrange the spectrum frequency for various uses and how to impose interference constraints are complex regulatory issues.

Fortunately, SAS and LSA can provide a friendly blend of coexistence of licensed and unlicensed spectrum. Specifically, for example, LSA, proposed to allow the management of large blocks of spectrum that cannot be cleared, but are frequently unused, can provide 100 MHz of bandwidth to alleviate the rapidly growing demand. However, these newly proposed architectures have not been fully studied yet.

Economic Robustness

Individual rationality and *truthfulness* are two major concerns for economic models.

Everyone is rational and hopes to gain profit as much as possible. In the competitive activity, the strategy set is important for the LSA Controller to make an all-satisfactory decision. Everyone in the system will get non-negative utilization. In an auction, sellers are free to express the reserve price for the spectrum which they own and decline the requirements if the licensee's bid is lower than the reserve price. Licensees will never pay more than their bids.

In a marketing process, because rational cheating or lying happen often, some solutions should be proposed to guarantee a truthful trade environment. A well designed payment rule can avoid market manipulation, hence breaks monopoly and protect small firms.

1.2 Motivation

Motivated by the recently proposed spectrum sharing architectures LSA and SAS, we would like to enable short-term spectrum sharing with economic awareness to provide an insight into the spatial efficient and flexible design of sublicensing.

The specific major goals in this thesis are as follows.

- The future 5G networks are required to accommodate heterogeneous base stations. Our goal is to propose formal, yet intuitive formulations, establish the complexity of the problem, and to develop practical algorithms for short term sublicensing.
- There is recognition across the globe that communications networks support not only rapid growth in efficiency and productivity, but also play an increasingly key role in driving innovation and commercial benefit.
- LSA and SAS are two architectures for the efficient and flexible use of current spectrum resources, with the purpose of keeping pace with increasing mobile data usage demands. However, they are still in the initial stage and not fully studied yet.
- In addition to the view of the system, how the users behave and perform also matter. Game theoretical analysis should be provided to examine users' equilibrium and network overall performance.

1.3 Contributions

To extract a feasible and flexible framework for dynamic spectrum sharing among different operators, we propose an online short-term license mechanism with economic awareness. In order to address the above challenging and significant problems of the framework, this thesis makes four major contributions. We take LSA and SAS as case studies to investigate how the short-term sublicensing with economic awareness could be achieved in this two spectrum sharing platforms.

- We propose a dynamic and flexible spectrum sharing solution based on small scale of spectrum license. By enabling each base station as an individual bidder, we let the base stations bid for a temporary sublicense based on the self-reported contour. First, the base stations need to register in a spectrum sharing platform and bid for an available spectrum chunk if their primary networks are congested. Then the spectrum sharing platform collects the bidding information from all the base stations and further calculate an interference-free allocation. (Chapter 3.)

- We put effort into designing an online spectrum auction mechanism as a business-involved tool to improve the spectrum efficiency. Interference graph is a significant component for the allocation scheme. Different graph processing schemes (topologies sort, degree sort, random order and bid sort) and allocation methods (equal allocation, sum weight proportional allocation, and maximum weight proportional allocation) are compared and analysed for fairness and truthfulness. (Chapter 4)

- A negotiation auction is proposed to offer the sublicensee a second chance to win if the original request is rejected. Instead of the binary undirected interference graph, we construct a mixed graph to better quantify the interference between secondary spectrum licensees. In a competitive situation, where a large number of base stations are located in a certain region, this improves spatial efficiency and accommodates more base stations, particularly in a dense area. (Chapter 5)

- Licensed and unlicensed band selection from a common spectrum pool is studied from the perspective of operators who own various base stations. Equilibrium of the operators is demonstrated in the non-cooperative way. We also enable the local centralized coordinator to form pair coalitions for the operators to further reduce the utility loss that causes by the operators' difference (Chapter 6).

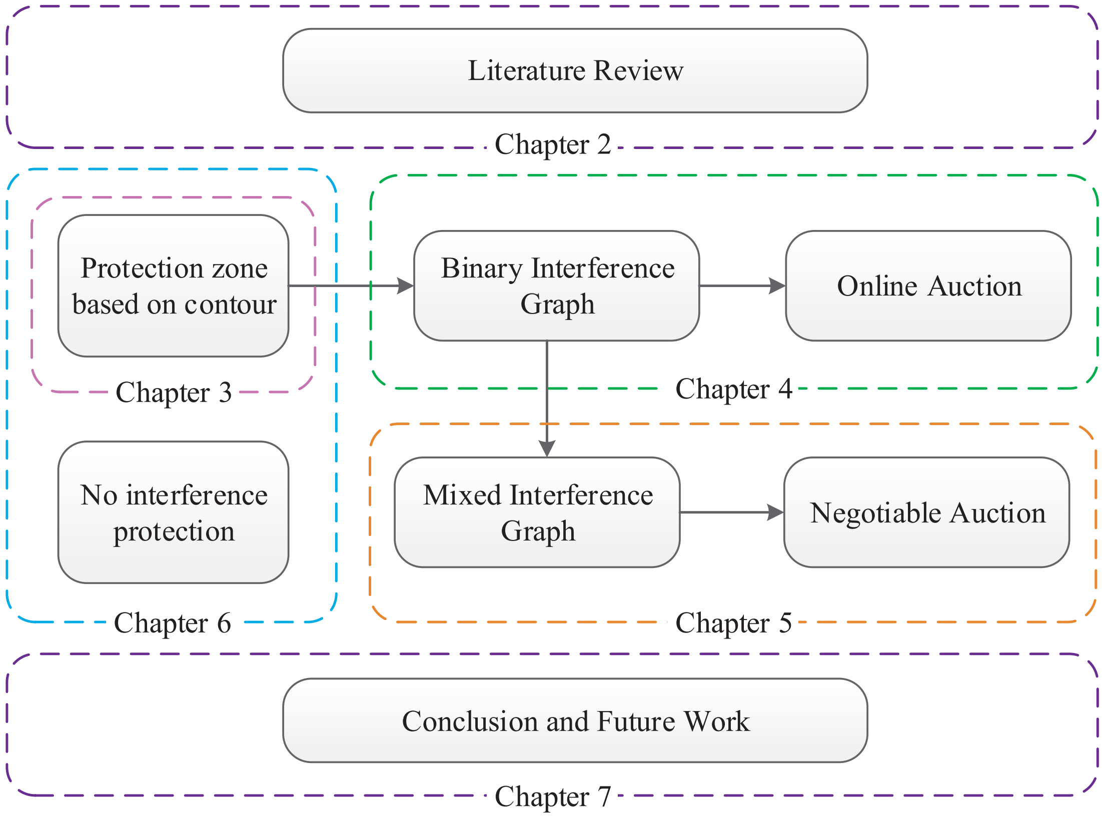


Figure 1.3: Thesis organization.

1.4 Thesis Organization

The remainder of the thesis is structured as follows, as shown in Fig. 1.3.

In Chapter 2, we summarize a comprehensive literature review of ongoing standardization activities and economic-aware spectrum sharing solutions in recent years. We first present the current state of the art of spectrum sharing architectures, i.e., Licensed Access Shared (LSA) and Spectrum Access System (SAS) in Section 2.1. Then, in Section 2.2, we discuss the sublicensing scheme for the secondary spectrum market, particularly for the boundary area. Section 2.3 describes the flexibility of online spectrum auction in various-demand networks. Section 2.4 introduces game theory for spectrum sharing among different operators.

In Chapter 3, we propose a new spectrum allocation policy in the secondary spectrum market about sublicensing and interference identification, particularly in the boundary area. Under the new spectrum policy, base stations are enabled to ask for an interference-free sublicense on contour basis in the spatial domain. The advantage of sublicensing for the secondary markets is stated in Section 3.1. The concept of contour-based protection zone is introduced and explained in Section 3.2. In Section 3.3, sensor networks are introduced to monitor and measure the contour regions. In Section 3.4, an interference-free allocation approach is demonstrated for the contour-based sublicensing to power up future commercial potential under the developing spectrum sharing platforms. Section 3.5 provides the simulation results for the sublicensing scheme in the secondary spectrum market.

In Chapter 4, we describe an online auction for short-term spectrum license from the perspective of the system. The challenges of spectrum auction are first pointed out in Section 4.1. We point out the challenges in Section 4.2 and formulate this problem in Section 4.3. The details of the bidding process is presented in Section 4.4. In Section 4.5, truthfulness is proved. In Section 4.6, numeral simulations are run and compared with existing works. We summarize this chapter in Section 4.7.

In Chapter 5, we focus on addressing the spatial efficiency of spectrum allocation among different operators. Considering the interference protection in the spatial domain, we further offer the base station a second chance as negotiation for spectrum sharing. We first introduce it in Section 5.1. In Section 5.2, the formulation of this problem is presented. Then in Section 5.3, the details of the Size-Negotiable Auction Mechanism (SNAM) are described and the properties of the SNAM are given. A toy example is given for better understanding of the mechanism in Section 5.4. The properties of negotiable auction is discussed in Section 5.5. Simulation results are analysed in Section 5.6 and this chapter is summarized in Section 5.7.

In Chapter 6, we provide a game theoretical analysis of unlicensed and licensed band selection for operators with various numbers of base stations. The game mode is first formulated in Section 6.2. Then Nash equilibrium is analysed in Section 6.3. In particular, a two-player game is presented and a pair coalition scheme is proposed to reduce utility loss in Section 6.4 and simulation results given in Section 6.5. We summarize this chapter in Section 6.6.

Finally, Chapter 7 concludes the work in this thesis and gives the outlook for future work.

Chapter 2

Literature Review

We investigate a larger number of previous literatures and ongoing activities to map out the structure of 5G and have a vision of the three following key pillars that will make the future network a reality.

1. More spectrum should be used to serve various applications. The amount of available spectrum needs to be expanded in two ways: adopting new frequency bands, like the 30 GHz band, and using spectrum more efficiently in a dynamic fashion, with regard to how and when it is employed.

2. Wireless networks will become much denser with many more heterogeneous cells. To support varying spectrum demand, more base stations or access points will be deployed in the heterogeneous 5G networks, ranging from macro cells to femto cells.

3. Another goal is to get the best possible network performance by carrying forward a gradual and profitable evolution, evolving existing radio access technologies and building new 5G wireless access technologies. Additionally, the evolution should be developed at an affordable cost to enable operators to maintain and improve their profitability.

2.1 Spectrum Sharing Architectures

The purpose of this section is to help illuminate the current discussion with regard to new proposed architectures for managing shared access radio frequency spectrum around the world, with a special focus on the U.S. and Europe.

2.1.1 Spectrum Management

The existing mobile bands alone would not be able to support extensive levels of data traffic growth, nor could they provide the improved quality of experience that 5G will offer consumers. To provide different access methods, the short-term based spectrum management mechanism would play a useful complementary role to new 5G spectrum thus providing heterogeneous cells with a reasonable mixture of coverage and capacity.

The frequency bands, also known as spectrum are a highly regulated resource whose management in most countries is usually deferred to a government agency [17] [23] [24]. In fact, a large portion of the spectrum is lightly used and has low average occupancy values. The primary reason for this is that traditional spectrum allocation mechanisms mainly focus on avoiding interference between wireless users and on the type of use given to spectrum rather than on the efficient use of spectrum and the maximization of socio-economic benefits. Thus, rigid spectrum management policies are in part to blame for creating an artificial spectrum scarcity and new allocation solutions to improve spectrum use efficiency need to be established [25].

Spectrum management by regulating agencies and bodies refers to the selection of a regime governing:

- the allocation of spectrum frequency bands to specific uses, such as commercial, scientific, military, emergency services;
- the assignment of usage rights to different spectrum users, such as broadcasters, communication operators, public agencies;
- clearance of bands for new applications and users migration;
- policy responses to technological and commercial developments [26] [27].

In recent years, debates on the best ways to manage the spectrum have traditionally tended to be from the first two aspects (in terms of allocating which applications and which users should have access to which static bands) to all of the four aspects (in terms of allocations according to varying demands) [12] [21] [28]. This is due to the dramatic growth in services and users requiring spectrum resource and the need from the government for increasing openness and fairness in making decisions.

The pressing need to make available additional spectrum resource to meet the requirements of rapid growth in wireless applications of all kinds lends urgency to these debates. Therefore, the growth of commercial mobile broadband services and the ecosystem of smart devices provide key drivers to develop an increasingly capable and harmonized spectrum managing platform. A spectrum sharing framework should be established under the responsibility of the administration, comprising the identification of the primary users, secondary licensees, the spectrum to be made available under thus a spectrum framework, and the corresponding conditions for access to the spectrum by both incumbent and licensees [29].

Nevertheless, another key challenge is how to ensure protection for the license holder and secondary licensees. For instance, LSA was firstly proposed in 2011 while SAS started in 2012. In Europe, the interference protection of Incumbents is considered to be essential to encourage them to open up their underutilized spectrum and reach agreements with the secondary licensees [30]. In the U.S., the novel protection mechanisms are even more critical; proposed protection and exclusive zones affect up to 60% of the US population in the 3.5 GHz band [17]. More details of LSA and SAS are presented as follows.

2.1.2 Licensed Shared Access

For the Political issue, ETSI is developing corresponding LSA Standards in response to the mandate, with the purpose of providing harmonised technical and regulatory conditions for mobile/fixed communications networks (MFCN) [19]. For the Regulators, the CEPT Working Group (WG), Frequency Management (FM) Project Team (PT) 52 and Project Team 53 are working on a report about "common technical sharing solutions for the shared use of 2300-2400 MHz band for wireless broadband (WBB) and incumbent services/applications". Finalized deliverables include

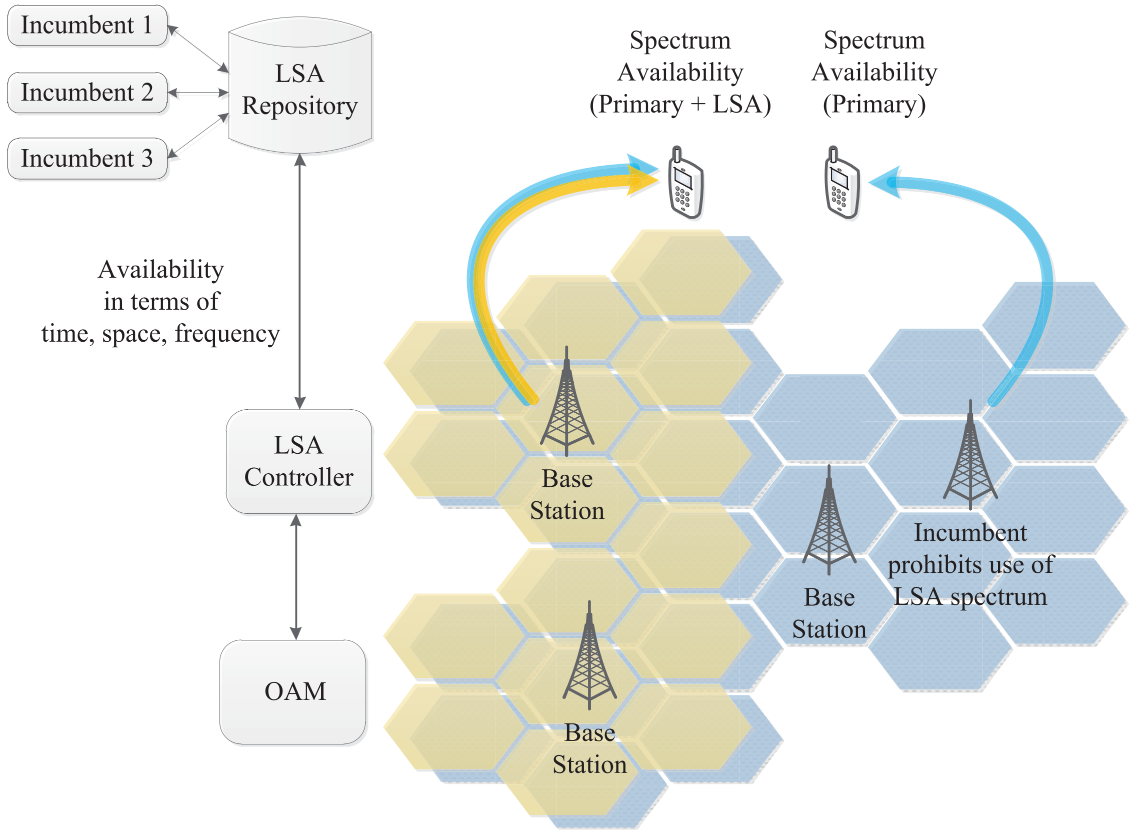


Figure 2.1: LSA achitecture: Incumbent users, secondary base stations, LSA Repository, LSA Controller and OAM [19] [31].

- "Harmonised technical and regulatory conditions for the use of the band 2300-2400 MHz for MFCN"
- "Cross-border coordination for MFCN and between MFCN and other systems in the frequency band 2300-2400 MHz"
- "ECC Report 205: Licensed Shared Access (LSA)".

A general system overview is illustrated in Fig. 2.1. The architecture is defined in ETSI Technical Specification (TS) 103 235 [1] [31] [32]. In this document, spectrum management mainly depends on a centralized database LSA Repository. Incumbents are required to provide a priori usage information to the LSA Repository on the availability of spectrum over the time and space domain. Relying on this information, the secondary licensees are either granted access or requested to vacate the sharing bands through the control mechanism known as LSA Controller. The LSA Repository is considered to be located outside of a specific Mobile Network Operator (MNO) network and typically provides information on a multitude of such networks. The LSA Controller, on the other hand, is part of a MNO network. Both entities interact through an interface which is currently defined in ETSI. The LSA system will address the needs of following stakeholders:

- Incumbent user(s), i.e., Incumbent users who may sub-license spectrum to LSA secondary licensees under certain conditions and agreements.
- LSA sublicensee(s), operating a wireless system under a sharing agreement, typically a MNO providing WiFi or LTE services;
- National Regulation Administrations (NRAs), which will monitor spectrum sharing activities and measure the interference.

LSA Repository is required to update and deliver information about the Incumbents' available spectrum to the LSA Controller, such as which spectrum bands are available in a certain region at a certain time, and which bands must be protected from being accessed.

LSA Controller manages and makes decisions about the spectrum access, depending on both the data in the LSA Repository and the requirements of the Licensees.

OAM, (Operation, Administration and Maintenance) is the interface entity between the Licensees and the LSA Controller.

A trial of LSA has been presented in [33], which demonstrates the concept is technically achievable. In addition, the business model over LSA is comprehensively analysed in [34].

2.1.3 Spectrum Access System

Similar to LSA, SAS is a dynamic sharing solution and adopted by the FCC, which manages accesses to spectrum across three tiers of users: incumbents (Incumbent Access), operators (Priority Access, PA) and mobile users (General Authorized Access, GAA), as illustrated in Fig. 2.2. 150 MHz spectrum of 3.5 GHz band is a tempting target in this system. A Priority Access License (PAL) is defined as a non-renewable authorization to use a 10MHz channel in a single census tract for three years. The PAL holder could be any kind of stakeholder, including who even does not have infrastructures and who can lease the spectrum to a Secondary PAL

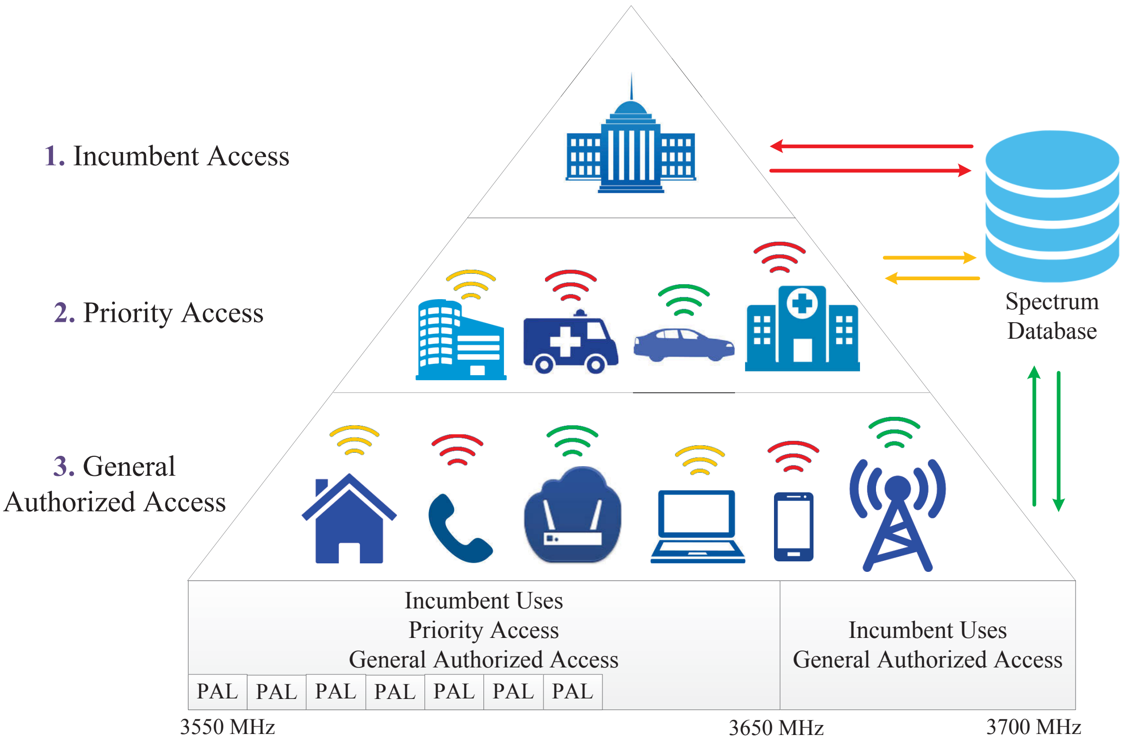


Figure 2.2: SAS architecture.

owners. The protection zones can be defined in a dedicated grid map [17] [23].

The comparison of LSA and SAS is shown in Table 2.1. One important difference from LSA lies in the fact that SAS is designed to ensure coexistence with incumbent users who are not able to provide any prior information to a centralized database. In [17], the incumbents are military services using networks operated mainly close to U.S. coastal areas. For this reason, the FCC proposes a step-by-step approach. First of all, SAS can be operated throughout the US territory except within Exclusive/Protection Zones close to coastal areas. In a second step, an Environmental Sensing Capability (ESC) component will be added which performs spectrum sensing tasks. The spectrum access decisions for PA users and GAA users are ultimately based on those sensing results. In the latter case, the operation of the system is possible even within the Protection Zones. It is obvious that the ESC component needs to comply with strict rules and undergo corresponding certification in order to ensure confidentiality of sensitive information related to military incumbents.

Both Europe and U.S. have already proposed their spectrum sharing architec-

Table 2.1: Comparison of LSA and SAS [1].

LSA	1. Incumbent user: be provided an incentive to accept the necessary changes in its right. 2. Licensee users: avoid harmful interference to the incumbent; provide regulatory certainty.
SAS	1. Incumbent Access: at the top of the hierarchy, incumbent federal and commercial radar and satellite will receive protection from all Citizens Broadband Service users. 2. Priority Access: license is assigned through auction on a census tract basis for three years; a maximum of 70MHz. 3. General Authorized Access: some degree of opportunistic access to unused Priority Access channels; a minimum of 80MHz.

tures. Additionally, Australian Communications and Media Authority (ACMA) also agrees that the spectrum sharing and /or licensing approaches should be further investigated in 5G [35]. The ACMA consistently advocates the sharing of spectrum in an effort to maximise the overall public benefit derived from use of the spectrum. As with all forms of resource sharing, spectrum sharing requires some degree of compromise between multiple spectrum uses or users.

2.2 Spectrum Market

Spectrum resources for mobile networks are vital to meet the rapidly increasing capacity and coverage demand, plus the encouragement of economic novelty, so it can be traded as a common product. Spectrum market, motivated by the design of more efficient and flexible spectrum management, regarding the spectrum owner as a seller, and the sublicensee as a buyer, constructs the strategical mechanism to improve the monetary revenue and system performance of seller and buyer respectively.

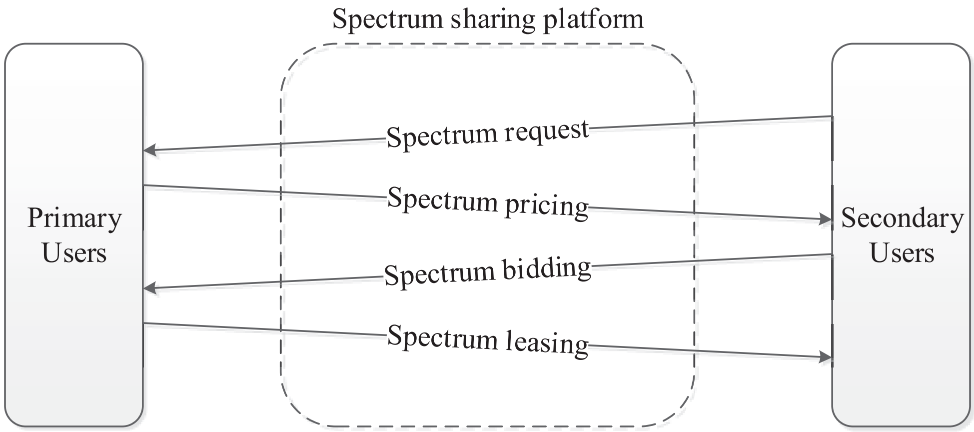


Figure 2.3: A typical spectrum market platform with primary users and secondary users as seller and buyer respectively.

2.2.1 Spectrum Market Framework

Markets have been proposed as an effective way to allocate resources, and definitely work for the wireless resource. Such spectrum market platforms could be operated by a primary spectrum owner to lease spectrum for secondary use/sublicensing, or by a neutral third party that pools and leases spectrum from multiple operators or government agencies. Fig. 2.3 demonstrates a typical spectrum market that is formulated with primary user and secondary user as seller and buyer [36].

The main workflow has been highlighted in the spectrum markets. Additional detailed technical issues and features are not discussed include networking functions, such as handoff of information interaction, spectrum pricing, and spectrum policing to enforce property rights. Perhaps more difficult to resolve are policy issues associated with the transition away from current allocations. It remains to be seen whether the potential benefits of spectrum markets can overcome the obstacles to the necessary spectrum policy reforms [37] [38] [39].

2.2.2 Flexible Spectrum Sharing

Flexibility means integration of licensed and unlicensed, long-term and short-term spectrum sharing. A flexible solution should provide the spectrum customers on-demand responses [40].

Both licensed sharing and unlicensed sharing should be jointly considered to support the diverse needs. Licensed spectrum is essential to guarantee the vital long-term heavy network investment needed for 5G, and high quality of service. The risks surrounding network investment are significantly increased without the assurances of long-term and reliable spectrum access. Licensed spectrum, which enables wider coverage areas and better quality of service guarantee, has be central to the growth of widespread, affordable mobile broadband services - rather than just best effort data services in small urban hotspots. Unlicensed spectrum will also play a complementary role especially by allowing operators to guarantee a certain level of quality of service. Hence, using licensed spectrum and then augmenting the user experience by simultaneously employing unlicensed bands is not only flexible but also maximizes the benefits of unlicensed spectrum while eliminating the disadvantages, such as a poor user experience if the bands are congested.

Short-term sublicensing is a basic enabler to realize the flexible spectrum sharing [41]. Allowing multiple short-term spectrum blocks to be traded or rented across a local region monthly, weekly, daily even hourly would provide incentives for more efficient spectrum use, and encourage alternative models for dynamically sharing spectrum resources. A key consequence is that spectrum ownership could be separated from the provision of wireless services. This would lower entry barriers, and thereby facilitate the introduction of more diverse sets of services.

Basic Principle

The literature [42] presents an overview of different spectrum regulator directions and forums, in addition to their activities related to the development of spectrum sharing models. Special emphasis is put on the European and US regulatory recently proposed solutions for dynamic spectrum sharing. Factors for developing a successful sharing architecture are also discussed. Furthermore, for a dynamic spectrum sharing architecture to be employed, it must protect the rights of entrant users without impact on the legacy systems, also known as harmonization. It must also create a reasonably straightforward opportunity for an entity that wishes to access a shared spectrum to do so in a manner that is neither overly complex nor costly to implement.

Market design mechanisms for network resources allocation have existed for a wide variety of scenarios and have been fairly well explored [43] [44] [45]. In particular, designing suitable dynamic online auctions for short-term spectrum leasing has proved to be rather challenging. A number of such issues for spectrum markets must operate in the presence of interference externalities. Here, interference externalities depict the phenomena of property of wireless spectrum with respect to spectral spatial reusability. That is two or more users utilizing the same frequency band at nearby locations mutually interfere with each other. Hence, a buyer's value for a given "spectrum asset" may depend in part on the allocation of other assets to other buyers. Such effects are known in economics as externalities. Then a non-cooperative game model could be built upon this situation. Always, the utility functions characterizing the preference of sellers and buyers are used to describe the externalities [46]. Moreover, market design becomes more complicated for double-sided exchanges in which there are both multiple buyers and sellers. Such a setting could also arise in spectrum markets, for example, when multiple license holders seek to lease their spectrum to multiple secondary service providers.

Ongoing Activities

Many spectrum management agencies have investigated the use of economic tools to overcome these challenges above, including an analysis of the truthful economic value of the spectrum, pricing the spectrum, allowing spectrum trading, and assigning limit spectrum to multiple users adopting auction. In fact, spectrum sharing has been gaining commercial interest in both US and Europe. In US, as mentioned in [16], spectrum sharing in SAS can and should be used to enhance efficiency among all users and expedite commercial access to extra spectrum bands where technically and economically feasible. On the other hand, in Europe, the concept of LSA has been defined by CEPT [19] and ETSI [18] [31] [32] and tested on live field trial [33].

Dynamic Spectrum Sharing (DSS) based on the promising cognitive radio technology is a powerful approach for overcoming the emerging problem of spectrum shortage, and it has gradually become one of the most important ways to improve spectrum efficiency and to further enhance Quality of Service (QoS) or ensure QoS requirements of the secondary users [47]. Dynamic spectrum sharing presents technical challenges across the entire networking protocol stack. The challenges and recent developments in dynamic spectrum sharing access models can be found in [21].

2.3 Short-term Sublicensing

Determining an efficient and optimal spectrum allocation is complicated by radio propagation characteristics, which can vary substantially across frequency, locations and variations in application requirements. From the beginning of commercial radio to the present day economic factors, a historical review of the evolution of spectrum licensing on spectrum access concludes with the prediction of the emergence of user-free spectrum access systems. In the coming spectrum access systems, a user can access the spectrum any time and anywhere by ordering a temporary license regardless of who they are. Therefore, a short-term sublicensing can provide flexibility and overcome the shortage of static long-term licensing [25] [48].

2.3.1 Boundary Identification

To ensure interference-free operation between different sublicensees, boundary identification/detection is essential to limit the transmission power and is also necessary for the license holder to calculate the license area to charge the sublicensees.

It is clear that due to random effects of shadowing and path loss, some locations are below a particular desired received signal threshold and thus leading to a arbitrary coverage shape, which is difficult to measure. Sensor networks are widely used for the boundary detection [49] [50]. However, the coverage estimation in theory may differ a lot from that in practice. For a circular coverage area having radius R from a base station, let there be some desired received signal threshold γ. In theory, given a known likelihood of coverage at the cell boundary, the percentage $U(\gamma)$ of useful service area is defined as [51]

$$U(\gamma) = \frac{1}{\pi R^2} \int P_r[P_r(r) > \gamma] dA = \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^R P_r[P_r(r) > \gamma] dr d\theta \qquad (2.1)$$

where r represents the radial distance from the transmitter and $Pr[P_r(r) > \gamma]$ is the probability that the random received signal at distance r exceeds the threshold γ within an incremental area dA, and it is defined as

$$\begin{aligned} P_r[P_r(r) > \gamma] &= Q\left(\frac{\gamma - \overline{P_r(r)}}{\sigma}\right) \\ &= \frac{1}{2} - \frac{1}{2}erf\left(\frac{\gamma - \overline{P_r(r)}}{\sigma\sqrt{2}}\right) \\ &= \frac{1}{2} - \frac{1}{2}erf\left(\frac{\gamma - [P_r - (\overline{PL}(d_0) + 10n\log(r/d_0))]}{\sigma\sqrt{2}}\right) \end{aligned} \tag{2.2}$$

where the shadowing effect is modeled as lognormal shadowing with σ, n is the path loss exponent, d_0 is assumed to be 1-10 m indoors and 10-100 m outdoors, $Pr(.)$ is the probability function and $erf(.)$ is the error function, σ the standard deviation of , n is the path-loss exponent, and d_0. Here, in order to determine the average path loss $\overline{PL}(r)$ referenced to the cell boundary $r = R$, it is clear that

$$\overline{PL}(r) = 10n\log(\frac{R}{d_0}) + 10n\log rR + \overline{PL}(d_0). \tag{2.3}$$

From the above discussion, it is complicated to theoretically calculate the precise boundary. Actually, the boundary calculation is useful for an operation to well deploy its base stations, but not suitable for a multi-operator scenario. However, in practice, a protection zone could be pre-announced and a sensor network can be adopted to measure and monitor the boundary.

ETSI Reconfigurable Radio Systems (RRS) introduces 3 Zone types

- **Exclusive Zone** - geographical area within which LSA Licensees are not allowed to have active radio transmitters.
- **Restriction Zone** - geographical area within which LSA Licensees are allowed to operate radio transmitters, under certain restrictive conditions (e.g., maximum Effective Isotropic Radiated Power (EIRP) limits and/or constraints on antenna parameters).
- **Protection Zone** - geographical area within which Incumbent receivers will not be subject to harmful interference caused by LSA Licensees' transmissions. Neighbouring LSA systems must ensure that (aggregate) interference levels are below a (given / pre-defined) threshold, typically no LSA band usage is possible within a protection zone.

2.3.2 Online Auction

Spectrum auctions have been used by governments to assign and price spectrum for about 20 years [52]. Spectrum auctions to date have been long-term auctions in which the winner is granted a license for 10-25 years. However, the long-term auction can not properly reflect "dynamic sharing". Unlike traditional spectrum sales that often involve long contracts (e.g. multi-year) and large coverage areas (e.g., country, cities), spectrum sharing in future networks will likely involve much shorter contracts over much smaller coverage areas. A new online short-term auction should be dedicatedly designed to realize the DSA. A well designed auction mechanism should consider both buyer satisfaction (how much a buyer could be satisfied) and revenue (total profit from the buyers).

The traditional manual auction for spectrum allocation is no longer suitable and efficient for dynamic spectrum access systems, such as LSA and SAS. Spectrum sharing between different MNOs should not only consider the interference between them but also their selfish behaviours when sharing. Authors in [53] investigated the performance loss due to selfish behaviour under a self-enforcing protocol. [54] [55] proposed contract-based approaches to solve the conflicting of sharing. To accommodate the above heterogeneity, on-line auctions based on short intervals in the time domain and small areas in the space domain [56] have recently been proposed. Zou *et al.* [57] considers an auction-based power-allocation scheme to solve power competition of multiple secondary users but cannot guarantee truthful behaviours. Sodagari *et al.* [58] presents a truthful spectrum auction mechanism but does not consider spatial re-usability of the spectrum. In [59] [60] the proposed double auction mechanisms achieve not only spatial re-usability in geolocation by grouping bidders but also has an anti-cheating property through a proper choice of winner determination and payment rule. However, the coverage of the base stations is not taken into account. Researchers in [61] [62] [63] proposed mechanisms of truthful double auction for heterogeneous spectrum which considers heterogeneity factors in frequency but not in ranges/coverages. Yang and Lin *et al.* [64] [65] very recently proposed a group buying-based spectrum auction to provide small firms with more opportunities in case they cannot afford an entire spectrum chunk in a large region. Another significant issue is the privacy; for example, Li *et al.* in [66] presented PPER to protect users' bid privacy but the bidders are terminal user pairs rather than base stations. The mechanism in [67] achieves approximate truthfulness, privacy preservation. However, the bidders are assumed to be distributed in homogeneous conventional hexagons, while in a future spectrum market, base stations from different operators are heterogeneous and arbitrarily distributed.

2.3.3 Spatial Efficiency

From an economic perspective a common objective of any resource allocation is to maximize efficiency, meaning the total utility (summed over all agents requesting the resource) derived from the allocation. Furthermore, spectrum allocation is more complicated because of its spatial reusability and properties of unlicensed and licensed. Numerous auction-based spectrum sharing models have been proposed recently. However, compared with negotiation, auction stifles communications between the bidders and the sellers [68]. Moreover, along with the spatial reuse, we observe that the ability to adjust the coverage of a spectrum bidder is also a unique feature of the radio spectrum, compared with general merchandise items in conventional auctions. This distinguishing character lends bidders room for further negotiation while auctioning. This work explores a hybrid approach between auction and negotiation for spectrum sharing.

To accommodate the above heterogeneity, particularly for spatial efficiency, spectrum bidders need to simultaneously negotiate/auction on various features and attributes. Note that existing auction-based spectrum sharing schemes (e.g., [66] [59] [61] [63] [67] [58]) often only considered payment. In such cases, *single-attribute auctions* were often recruited and proved to be an efficient tool (with regards to both economic- and operation- robustness). To account for coverage negotiation (in addition to payment), in this work, we design a *multi-attribute auction* mechanism [69] so that both payments and coverage ranges for auction winners can be determined.

2.4 Game Theoretical Analysis of Spectrum Allocation

At present, markets for network resources have become significantly promising, where spectrum resource is concentrated with extensively attentions of both licensed and unlicensed spectrum. Dynamic management, also referred to as dynamic spectrum access, is a set of techniques based on theoretical concepts in network information theory and game theory that is being researched and developed to improve the performance of a communication network as a whole [26] [27]. A game is a description of strategic interaction that includes the constraints on the actions that players can take and the interests. The three basic components of a game are the set of *players*, set of *strategies* available for each player and set of *payoff* for each player.

2.4.1 Games for Existing Resource Allocations

Game theory has been extensively applied in microeconomics, and lately has received attention as a useful tool to design and analyse resource allocation algorithms.

Resource sharing is at the heart of economics, which provides the network theorists the ideas from mathematical economics and optimization to achieve optimization in large scale networks. For instance, we know that network utility maximization (NUM) has its roots in ideas from economics, and has been successfully employed in Transmission Control Protocol (TCP) design in wired congestion control and power control for wireless networks. As shown in [70] NUM guides engineering design as opposed to truly incorporating economic incentives. It is not robust to manipulation by increasingly sophisticated users, who act strategically and often have economic interests at stake. In fact, it was shown in [71] that the Kelly mechanism can have arbitrary bad efficiency when users behave selfishly and strategically. Thus, there is a need to go beyond the current distributed optimization-based NUM framework to a game-theoretic and market economics-based network market design.

In related areas of wireless communications, game theoretic approaches have been used with considerable success. For example, efficient decentralized power control algorithms have been devised using non-cooperative game theory [72]. There also have been many new DSS schemes proposed in recent works in both the licensed and unlicensed spectrum band; for instance, the proposal of a more advanced hierarchically sharing scheme between exclusive spectrum and unlicensed spectrum, termed on dynamic spectrum leasing in [73]. Researchers in [74] propose a game theoretic framework to analyse the selfish behaviour of cognitive radios. This work represents a first step in understanding the spectrum sharing problem for cognitive radio networks. However, this work is based on homogeneous models and could be extended to address more practical scenarios, such as the case of users with unequal powers, power controlled networks, as well as the case of heterogeneous users, characterized by different utility functions.

WiFi networks are playing an increasingly important role in offloading the primary cellular networks, and the spectrum allocation on WiFi Access Points (APs) in the unlicensed band is another typical of a non-cooperative game. [75] proposes a crowdsourced wireless community network by encouraging individuals to share their available APs. This can fully utilize the capacity of millions of WiFi APs already installed, without requiring new installation by any single operator. Meanwhile, by joining such a community network, a user can use not only his own AP but also other users' APs. Clearly, the success of such a crowdsourced network largely depends on the active participations and contributions of many WiFi owners, and hence requires the careful design of a proper economic incentive mechanism. The large-scale deployment of WiFi networks is often restricted by the limited coverage of each single WiFi AP, which is much smaller than the coverage of a cellular tower. However, this work is mainly focused on the unlicensed band.

Recently more efforts have been applied in extending LTE to the unlicensed spectrum and coexistence with WiFi. However, the one key technical challenge for LTE running in the unlicensed band is that it can heavily degrade the WiFi network performance. To address this issue, industries have proposed two major solutions for LTE and WiFi coexistence: Listen before Talk [76] [77] and Carrier-Sensing Adaptive Transmission (CSAT) [78] [79].

Femtocells are a solution that helps to reduce the capital and operational expenditure of a mobile network while enhancing system coverage and capacity. However, the avoidance of interference is still an issue that needs to be addressed to successfully deploy a femtocell tier over an existing macrocell network [80]. To remain competitive in the wireless communication market, vendors and operators need to make the reduction of both network cost and complexity a priority in future deployments of cellular systems. Both cross-tier interference and co-tier interference could be analysed by the tool of game theory.

2.4.2 Game Theoretical Analysis in Sublicensing

There are several reasons for using a game theoretic approach. First, since game theory explicitly recognizes the interdependence across radios, it can be used as a synthesis tool to provide decentralized algorithms for adaptive resource allocation. Second, the game theoretic concept of equilibrium provides a useful analysis tool; if we specify a simple algorithm that converges to equilibrium, then we can characterize the long-run behaviour of the system, which may be measured against a global, system-wide objective.

Since optimal resource allocation for different operators in a competitive environment is not straightforward, we propose spectrum allocations according to a game theoretic algorithm. Another challenging problem in spectrum sharing is to optimize a general utility function with only partial knowledge of the network and users. In such cases, game theory can provide a mathematical model that describes the interaction between various players which tries to maximize their payoffs.

We adopt a centralized system to form a cooperative game, which focuses on predicting where pair coalitions will form and resulting collective payoffs. Therefore, thanks to the SAS and LSA, the cooperative game becomes possible and avoids utility loss because of selfish behaviours. LSA and SAS can provide players with a high-level approach of coalitions.

2.5 Summary

A general overview of the research works has been provided in this chapter. Recent developments in radio access technologies are radically changing the management of the spectrum, progressing from exclusive licensing with static conditions towards more flexible sublicensing schemes which allow dynamic spectrum assignment.

First, we have provided a detailed overview of spectrum sharing architectures LSA and SAS, which are under development and typically will be the enablers to improve the spectrum efficiency. Based on these architectures, the possibilities and advantages of economic-aware spectrum sharing are then described. Second we have presented the solutions of sublicensing by enabling the base stations as bidders and spatially dividing their protection zones. Third, we have reviewed the existing approaches that are able to extract a truthful value from the whole online auction, which is used to improve the efficiency and effectiveness of the forthcoming platform. Last but not least, we have analysed the advantages and disadvantages of the existing studies of access methods, and provided game theoretical studies for band selection that can be leveraged for heterogeneous base stations.

The issues we address in this thesis exist at the intersection of technology, economics and policy. Since this developing and rapid growing spectrum sharing platform will typically provide a new way for spectrum sharing, we have worked to achieve its acceleration, and present the potential for business decision makers, researchers, analysts in the wireless supply chain and policy makers.

Chapter 3

Design of Contour based Protection Zones for Sublicensing

The traditional long-term spectrum allocation approaches are deficient in 5G networks. In this chapter, we aim to define the sublicenses based on a small scale in the space domain for heterogeneous base stations from different operators. Rather than being coordinated by an operator, each base station is enabled to directly communicate with the spectrum sharing platform as a single sublicensee to request a contour based protection zone. To monitor and measure the contour area, two kinds of sensor networks are proposed and analyzed in this chapter.

3.1 Introduction

With the rapid development of mobile networks, a nationwide spectrum license authorized for a long term is no longer efficient. In the coming 5G era, a short-term license affords more flexibility and efficiency for both wireless users and providers. As a novel economic resource, spectrum should be dynamically managed in the future networks both in theory [21] and in practice [33]. How to design the policy of short-term license becomes a critical problem. Exclusive spectrum access and unlicensed access are two basic methods. Exclusive spectrum access will certainly be needed in 5G mobile systems to guarantee quality of service (QoS) while unlicensed access, on the other hand, offers unpredictable QoS but it is for free. However, other regulatory options may be needed in addition to coordinate the interference between them. Standard bodies are developing sharing policies; for example, in 2011 the Radio Spectrum Policy Group (RSPG) in Europe proposed Licensed Shared Access (LSA) for spectrum sharing [30] [81], and in 2012 USA's Federal Communications Commission (FCC) started to develop Spectrum Access System (SAS) [17] [82]. Considering the interference issue, the cell planning is a crucial part of base station deployment within one single operator's communication network. Although inter-operators' sharing can improve the spectrum efficiency and many algorithms are proposed for this purpose, the problem has remained challenging in multiple operators because of private issues and mutual interference [83] [84]. Fortunately, SAS can provide a flexible platform for multi-operators' spectrum sharing. It is a three-tiered framework, including (i) Incumbent Access (highest privilege), (ii) Priority Access and (iii) General Authorized Access (GAA) (lowest privilege).

In this chapter, we focus on the spectrum spatial efficiency of PAL in SAS. The latest FCC report [17] proposed to allocate the PAL by auction for a three-year term on census tract basis. The Priority Access Licensees could be anyone, even those who have no infrastructure. The PAL owner can use the spectrum with protection from the GAA users' interference. In some cases, the PAL owner can lease a sublicense to a Secondary PAL (SPAL) user for the purpose of monetary gain. As a charged user, the SPAL user also needs protection from harmful interference from other SPAL and GAA users. One of the challenging problems is how to define the protection zone for each owner and SPAL user. Although the protection zone is discussed as -96dBm contour in [17], the coordination between different stakeholders is not given. To ensure exclusive sublicenses we introduce a spatial interference-free radio map to formalize and minimize the interference, as shown in Fig. 3.1. Note that the spatial interference-free radio map could help monitor spectrum usage in a region and provide the sublicensees with reference to the channel quality.

The spectrum allocation between multiple operators is investigated in [40] and spectrum sharing in a heterogeneous network is analysed in [76] [85]. To solve the competition, an economic tool is also widely used to solve the conflicting problem in a dense region [86] [87]. In a business driven model, SPAL users pay PAL owner for

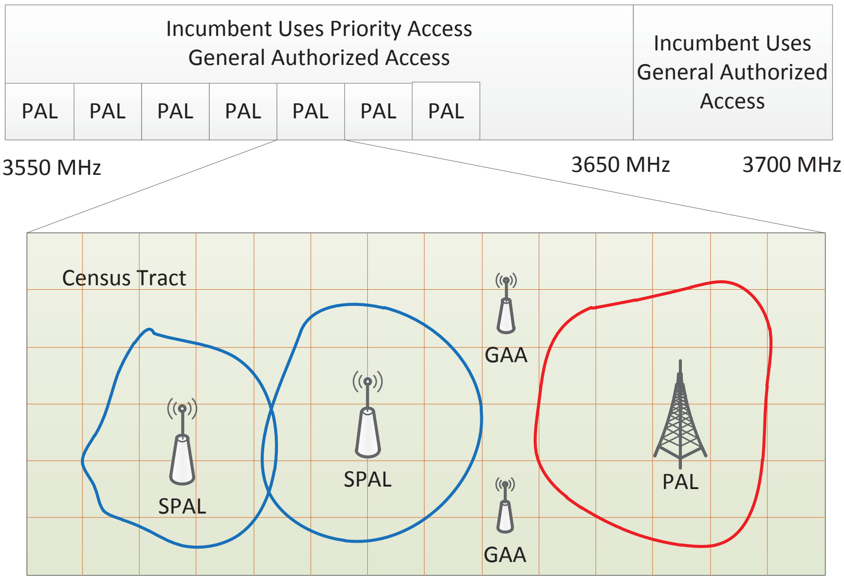


Figure 3.1: Protection zones can be defined in a dedicated grid map.

the sublicenses; in return, PAL owner needs to provide them with a QoS guarantee. However, none of the existing works mention how to construct the interference restraints based on the protection zone. We propose to further divide the protection zone into coverage based pieces and enable the base stations from different operators as bidders to decide when and how much to bid to access the spectrum. To our best knowledge, this is the first investigation to present a detailed solution of protection zones.

The novelty of this chapter is adopting sensor networks to solve complex interference contours among multiple operators. By taking advantage of the fact that the power falls off with distance of signal propagation, we can reuse the same frequency at spatially separated locations. For a given region, it can be easily divided into cells by one operator, so long as the interference between co-channels stations is kept below acceptable levels. When it comes to sharing of multiple operators, the easy way to coordinate interference is pre-defining protection zones, which involves a few steps of computation. In our method, each active -96dBm contour represents a base station's coverage area. The radio map criteria includes the proper resolution and maximizing of the profit of spectrum trading. Simulation results show how finely to grid a region and achieve a higher profit.

The rest of the chapter is organized as follows. In Section 3.2, the preliminaries and problem formulation are provided. In Section 3.3, we present the details of our proposed solution. Section 3.4 describes the construction of the interference graph. We provide simulation results and discussion in Section 3.5, and finally summarize this chapter in Section 3.6.

3.2 Sublicenses

3.2.1 Preliminaries

Inter-operator shared access is a complementary new alternative for spectrum sharing, where multiple operators jointly use a part of licensed spectrum. Although it can improve the spectrum efficiency, the exclusive use and interference protection from each other turn out to be new challenges. SAS can enable the short-term licenses but still needs to call for a more flexible regulatory regime where, for example, different operators may use exclusive bands with different authorization modes, such as PAL and GAA. PAL is a license lasting for three years in a census tract [17] with interference protection, while GAA is based on opportunistic access and is without any QoS guarantee. When the GAA band is congested, more operators will seek good QoS from PAL band. In this case, PAL owner can earn money by leasing a sublicense.

The SAS will incorporate information from a sensing network, which will be used to detect available spectrum and monitor the behavior of SPAL users, e.g. SPAL users' actual contours. Moreover, given the critical importance of the interference-free operations in the band, we must ensure that SPAL users' base stations report their prices and contours as their protection zones. Then SPAL users can be protected in the same privilege as the PAL users.

Both PAL and SPAL users should report their protection contours on the basis of the network deployment, as long as they are within the boundaries established by the objective default protection contour. They should work with SAS Administrators and tailor their self-reported PAL protection zone to their contours. The approach will provide flexibility to a PAL user while it will also bring up an objective problem of determining a maximum protection contour and minimizing the risk that PAL user might claim protections beyond the extent of their actual network deployment. Under a system relying on pure self-reporting, we are concerned that PAL users would be effectively encouraged to deploy their networks efficiently and seek protection for extremely low signal levels or in areas without facilities that are in actual use.

3.2.2 Network Models

In the sublicensing model, all the base stations act as buyers to pay for sublicenses in the spectrum sharing platform. We assume that a network consists of M available scattered spectrum blocks and N base stations from different operators in a given area. The spectrum sharing platform first collects all the requests and then makes an allocation decision to maximize the revenue and ensure it is subject to no interference.

Sublicensee

The traditional network expansion technologies will no longer be able to handle the rapid growth of user population and satisfy their wireless volume demands [88]. In the future the heterogeneity of networks will become more prominent, in terms of cell size and access methods. Moreover, the shape and size of potential SPAL users heavily differ from each other. One of the feasible ways is to define a protection zone for the sublicensees. Spatial division is more flexible and involves low computation.

In the beginning, the spectrum sharing platform will release the available information to all the base stations, including the maximum permitted transmit power, frequency and the bandwidth of each spectrum block, as shown in Fig. 3.2. Let $\{P_t^1, P_t^2, ..., P_t^M\}$ denote the maximum powers on M spectrum blocks and $\{f_1, f_2, ..., f_M\}$ denote the frequencies. The base stations then submit their preferences of transmit powers and the corresponding bids. Assume that in a spectrum market where demand is greater than supply, the buyers want to win as many spectrum blocks as possible. We offer every base station a flexible transmit power. Thus they can not only reduce their prices but also lower the risk of overlapping the neighbouring cells if transmitting at the permitted maximum power. For buyer i,

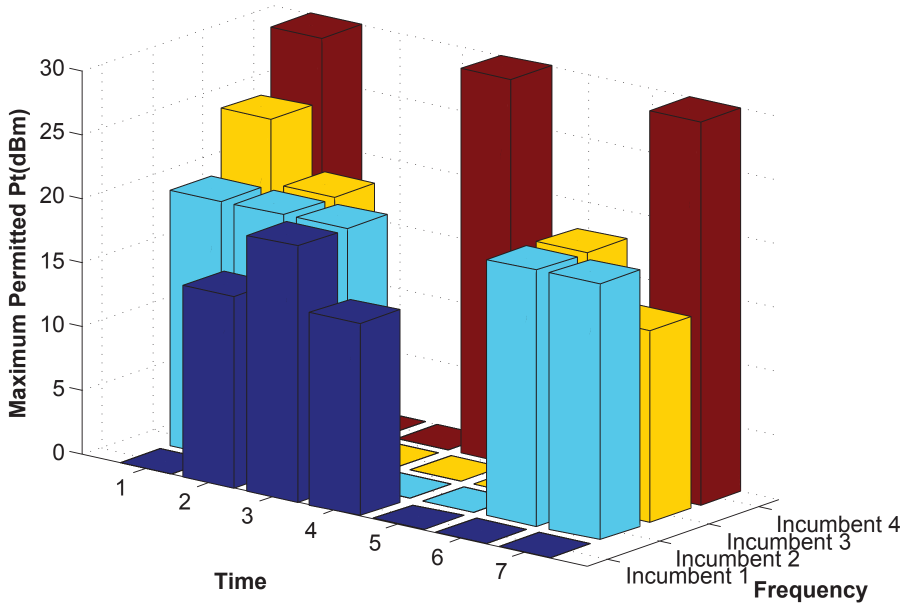


Figure 3.2: Scattered spectrum blocks.

it can submit a power profile $\boldsymbol{p}_i = (p_i^1, p_i^2, ...p_i^j..., p_i^M)^{\mathrm{T}}$ for all the spectrum blocks, where p_i^j denotes buyer i's transmit power on the spectrum block j, but it cannot be greater than the permitted maximum power, namely $p_i^j \leq P_t^j$.

Assume all the buyers will bid rationally. The bid should depend on the transmit power. We use the Simplified Path Loss Model [51] to model the signal propagation and calculate the estimated coverage radius of the cell by the following formula:

$$P_r(\mathrm{dBm}) = P_t(\mathrm{dBm}) + K(\mathrm{dB}) - 10\gamma \log_{10}\left[\frac{d}{d_0}\right] \tag{3.1}$$

where K is a unitless constant as

$$K(\mathrm{dB}) = -20\log_{10}(4\pi d_0 f/c) \tag{3.2}$$

which depends on the antenna characteristics and the average channel attenuation. P_r is the signal strength at the edge of a cell. d_0 is a reference distance for the antenna far-field, and γ is the path loss exponent. Moreover, d_0 is typically assumed to be 1-10m indoors and 10-100m outdoors. γ is suggested as 2.7-3.5 in small cells [51]. Then it is easy to get the cell radius by

$$d_i^j = d_0 10^{\frac{p_i^j - P_r + K}{10\gamma}} \tag{3.3}$$

Interference-free Allocation

The spectrum sharing framework can be illustrated with a set of N base stations competing for a limited number of sublicenses at a certain frequency band. Every potential base station needs to submit its -96 dBm contour, then the spectrum sharing platform will compute the interference-free protection zone sets and then allocate sublicenses to them. The shape of the contour actually could be arbitrary and it is difficult to tell the interference condition between them in a distributed regime. Therefore the centralized SAS is more suitable for the sublicensing allocation. Let the shape of contour i be $D_i : F(x, y) = 0$, and its payment is

$$p_i = \iint_{D_i} v_i(x, y) d\sigma \tag{3.4}$$

where $v_i(x, y)$ is the valuation density in the space domain. The spectrum allocation should ensure that contours are spatially independent, namely the protection zone could not overlap with anyone else. The allocation result is denoted by $a_i \in \{0, 1\}$. If SPAL user i is assigned a sublicense $a_i = 1$, otherwise $a_i = 0$ and accordingly it pays nothing, $p_i = 0$. PAL user's revenue $\mathbb{R}$ of the sublicensing comes from all the SPAL users, which is defined as

$$\mathbb{R} = \sum_{i=1}^{N} a_i \iint_{D_i} v_i(x, y) d\sigma \tag{3.5}$$

The cost of the PAL user is the number of sensors it uses to monitor the interference in the census tract. Assume that the density of sensors over the census tract is $\rho(x, y)$, which is the number of sensors over unit space. Let τ denote the cost of one sensor in term of monetary \$. Therefore, the cost of the sensing network over the area D_i is

$$c_i = \tau \iint_{D_i} \rho(x, y) d\sigma \tag{3.6}$$

The objective is to maximize the profit of sublicense trading, defined as

$$\begin{aligned} \mathcal{P}(\mathbf{D}, \mathbf{v}, \rho(x, y)) &= \arg\max_{a_i} \mathbb{R} - \textstyle\sum_{i=1}^{N} a_i c_i \\ &= \arg\max_{a_i} \textstyle\sum_{i=1}^{N} a_i \iint_{D_i} v_i(x, y) - \tau\rho(x, y) d\sigma \end{aligned} \tag{3.7}$$

$$s.t. D_i \cap D_j = \varnothing, \forall i, j \tag{3.8}$$

where $\mathbf{D}$ is the set of submitted contour areas $\mathbf{D} = \{D_1, D_2, \ldots, D_N\}$ and $\mathbf{v} = \{v_1, v_2, ..., v_N\}$. The constraint (3.8) aims to guarantee there is no overlapping between any two SPAL users' contours.

3.3 Contour in Sensor Networks

A design of sublicenses over regular grid and Poisson point field are demonstrated in this section, as shown in Fig. 3.3 and Fig. 3.4. The sensor network is placed not only to monitor the interference but also to measure the area of protection zone for the further pricing of sublicense.

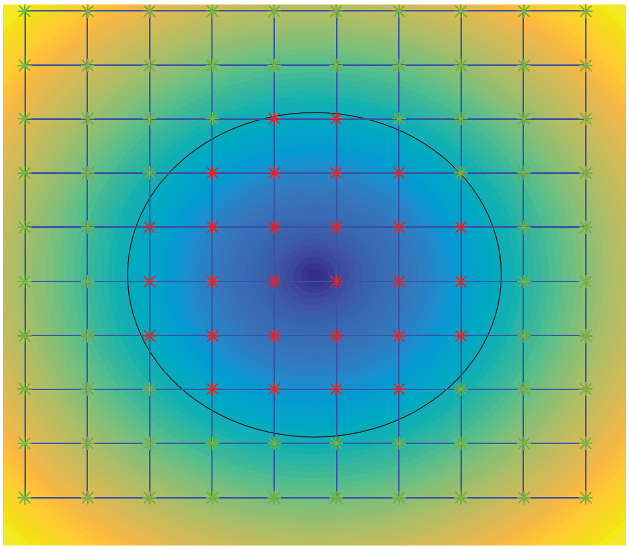


Figure 3.3: Contour based protection zone in a regular grid sensor network.

3.3.1 Resolution

As one of the significant aspects of precisely monitoring the contour, the number of sensors in a unit area is defined as the resolution of a sensor network. We consider the sensor networks in two independent cases: regular grid and Poisson point field.

Regular Grid

A regular grid sensor network is an easy model to deploy and compute. In this case (Fig. 3.3), N fixed sensors are placed at a regular grid to monitor the radio

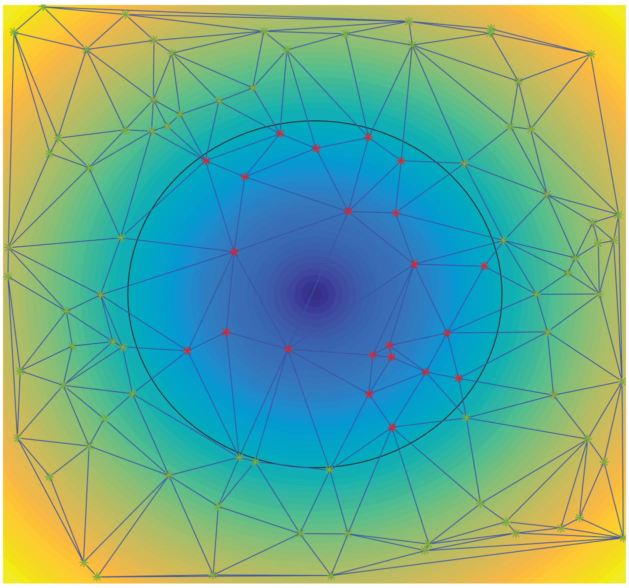


Figure 3.4: Contour based protection zone in a sensor network of Poisson Point Field.

environment in a certain region. We consider a bounded region $\mathbf{B}$, and let λ denote the average distance between sensors, and ρ be the sensor resolution/density of the region, which is equal to the number of the sensors in a unit area. So it is easy to compute the resolution of this regular grid network is

$$\rho = \frac{|\mathbf{B}|}{\lambda^2} \tag{3.9}$$

where $|\mathbf{B}|$ is the area of the region, and then the number of sensors N in a region $\mathbf{B}$ is set as $\rho|\mathbf{B}|$,

Poisson Point Field

On the other hand, the positions of sensors could also be irregular or mobile, hence the Poisson point field is employed, as shown in Fig. 3.4. Considering that the spatial Poisson point process features prominently in the spatial statistics, we assume the spatial sensors are Poisson points. This point process is applied in various sciences. It has been frequently used to model seemingly disordered spatial configurations of certain wireless communication networks. For example, models for cellular or mobile phone networks have been developed where it is assumed the phone transmitters, known as base stations, are positioned according to a homogeneous Poisson point process.

We also consider a bounded region $\mathbf{B}$. The number of points of a point process N existing in this region $\mathbf{B}$ is a random variable, denoted by $N(\mathbf{B})$. If the points belong to a homogeneous Poisson process with parameter $\rho > 0$, then the probability of n points existing in $\mathbf{B}$ is given by

$$P\{N(\mathbf{B}) = n\} = \frac{(\rho|\mathbf{B}|)^n}{n!} e^{-\rho|\mathbf{B}|} \tag{3.10}$$

Similar to (3.9), we also introduce λ as the average distance between two sensors.

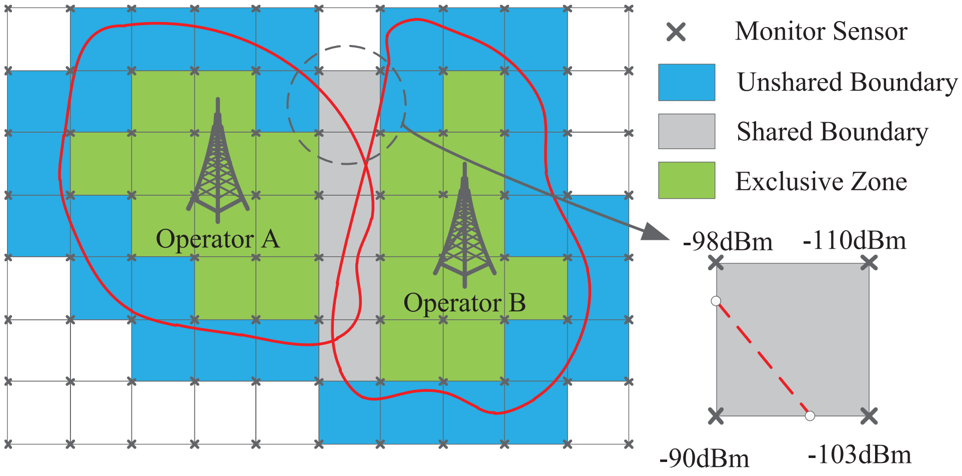
3.3.2 Boundary Detection

Previous researchers in sensor networking have largely studied the placement of sensor nodes. Generally speaking, the sensors' locations can be classified into two categories: regularly placed (in the manner of a grid) and randomly placed (in spatial Poisson distribution). The regular grid coverage strategies in distributed sensor networks is given in [89]. They present an integer linear programming solution to minimizing the cost of the sensor nodes for complete coverage of the field. Due to strict interference protection, the boundary identification is important to monitor SPAL or secondary base stations [49] [50]. It can not only protect the primary user but also ensure good QoS among different base stations.

However, unlike the existing distributed sensor network, SAS and LSA are actually locally centralized systems. The precise contour boundary of the base station could be estimated by collecting and calculating the sensing signal from all the local sensor nodes, as shown in Fig. 3.5.

In fact, the sensing signals from any three sensors can determine the location of a base station, as long as these three sensors can form a triangle, as illustrated in Fig. 3.6. Any triangular cluster of three sensor nodes can detect the base station's location; in turn, the boundary contour could be estimated in the triangle area. We assume that the base station is the centre of a circle, from the sensors' received signals we can determine the distances between sensors and the base station. Then we can plot a circle which has a sensor at the centre and the radius is the distance to the base station. The intersection of three circles is the location of the base station.

Mathematically, let (x_A, y_A), (x_B, y_B) and (x_C, y_C) denote the sensors' locations



(a) Contour Map (b) Estimated boundary

Figure 3.5: Sensor grid census tract: (a) sensor network is used to monitor the contours of secondary base stations; (b) Four sensors can estimate the boundary in one small area.

and (x_O, y_O) denote the base station's location. The distances d_{OA}, d_{OB} and d_{OC} can be determined by (3.3). The equations are as follows.

$$\begin{cases} (x_A - x_O)^2 + (y_A - y_O)^2 = d_{OA}^2 \\ (x_B - x_O)^2 + (y_B - y_O)^2 = d_{OB}^2 \\ (x_C - x_O)^2 + (y_C - y_O)^2 = d_{OC}^2 \end{cases} \tag{3.11}$$

A cluster of three sensor nodes can identify a centre (x_O, y_O), which is the base station's location.

However, in practice, because the contour is not a circle, this method does not work well. Instead of finding the location of the base station, we introduce an easier linear method. Note that we further assume a mirror base station is infinitely far away from the boundary and then we consider it is in the extension of the two sensors' line, as shown in Fig. 3.7.

For every two adjacent sensors whose distance between each other is λ, if one sensor's received signal is greater than the boundary power P_b = -96dBm, it is in the contour, otherwise it is outside of the contour. Let P_h denote the power higher than -96dBm, and P_l is lower than -96dBm. In addition, let P_s denote the power of the base station. The distance from the mirror base station to the sensor with high

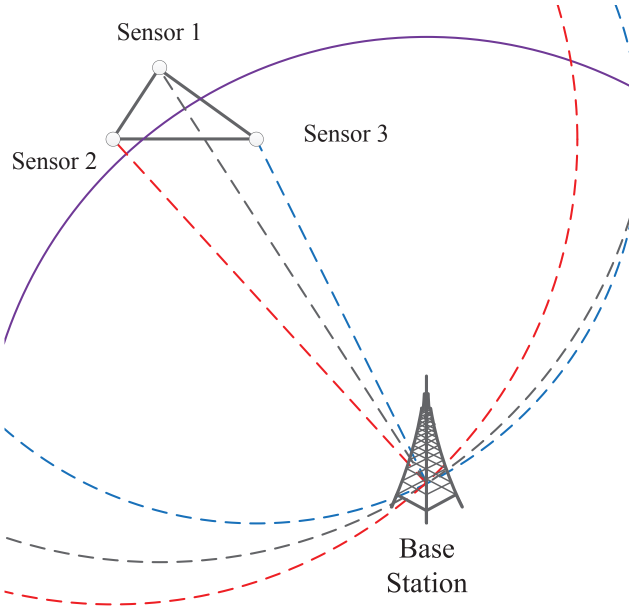


Figure 3.6: Three sensors can determine the location of a base station.

received power P_h is d_h, the distance to the sensor with low received power sensor is d_l, and the distance to the contour boundary is d_b. If two adjacent sensors both detect high/lower power there is no boundary point between them. Otherwise we need to find an estimated point. Therefore we have the path loss functions as

$$\begin{cases} P_s - P_h = 20\log(d_h) + 20\log(f) + C \\ P_s - P_l = 20\log(d_l) + 20\log(f) + C \\ P_s - P_b = 20\log(d_b) + 20\log(f) + C \\ \lambda = d_l - d_h \end{cases} \quad (3.12)$$

where C is a constant and f is the frequency that the base stations work on. From (3.12), we can easily find the estimated -96dBm boundary point E in Fig. 3.7.

3.3.3 Contour in Regular Grid

The shape of the contour is arbitrary because of the geographical environment, which makes the protection zone difficult to measure in practice. The cost of the sublicense is based on the area of the contour, so then the immediate question is how to estimate it.

The common method to estimate the area of an arbitrary shape is breaking it down into smaller unit tiles, which will help approach to a fine approximation. The

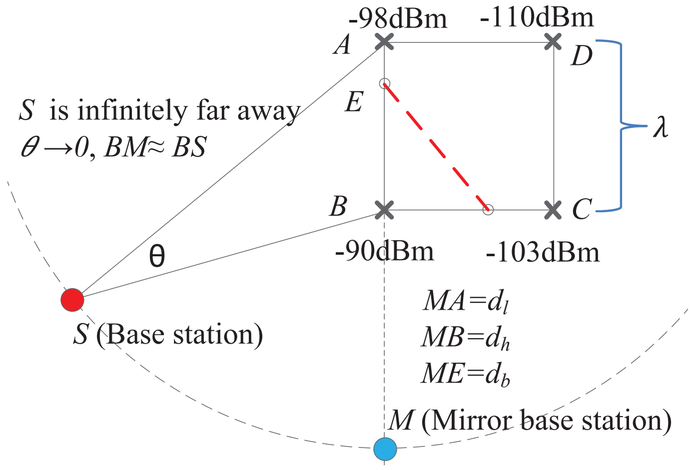


Figure 3.7: Mirror base station.

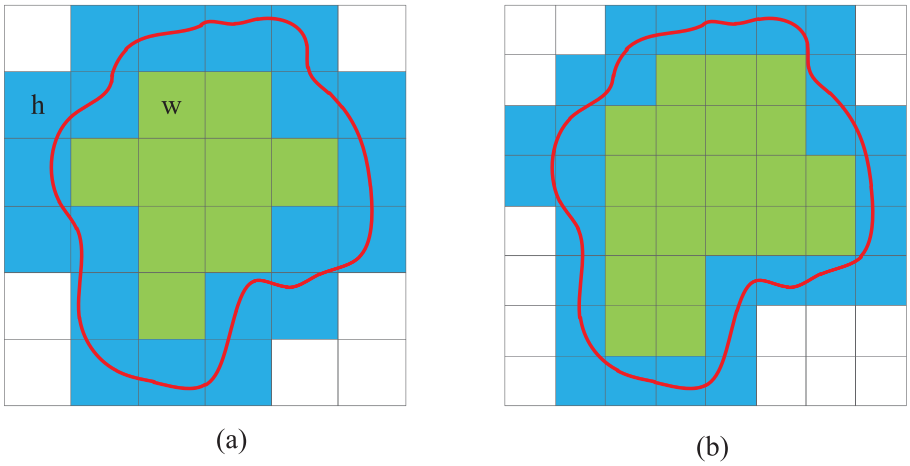


Figure 3.8: The grid is used to measure and monitor the protection zone. In this example, to not lose generality the area is normalized as $1km \times 1km$.The resolution in (a) is lower than that in (b), i.e., $\lambda_a = 1/6$ km, $\lambda_b = 1/8$ km.

smaller the tiles are, the better the approximation will be. One easy way is putting the arbitrary shape into a grid and count the number of tiles it covers. We assume that the sensors are uniformly deployed in a region, and at the nodes in a grid, as shown in Fig. 3.8. The resolution of a grid is

$$\rho = (\frac{1}{\lambda} + 1)^2 \approx \frac{1}{\lambda^2}, \lambda \ll 1 \qquad (3.13)$$

where λ is the size of the tile or the distance between two sensors in the same row/column, e.g. $\lambda_a = 1/6$ km in Fig. 3.8 (a) and $\lambda_b = 1/8$ km in Fig. 3.8 (b).

Then we use two types of tiles to estimate the area of the contour: boundary/half tile and interior/whole tile. Partial covering of a tile is usually counted as a half tile.

The boundary is covered by half tiles and the interior is covered by whole tiles. In fact, the boundary area, which is covered by partial tiles could also be another base station's boundary, so another parameter μ is defined as the *boundary sensitivity* and it is used to adjust the boundary importance. The price of the contour i is estimated as the unit tile valuation multiplied by the contour area

$$p_i \approx v_i(w_i + 0.5\mu h_i)\lambda^2 \tag{3.14}$$

where w_i is the number of whole tiles in a contour i, and h_i is the number of half tiles in a contour, and v_i is the average valuation per unit tile for the sublicense. The coefficient 0.5 is used to estimate the area of the half tile as 0.5, i.e., one half of the whole tile.

For example, in the grid of Fig. 3.8(a) the number of whole tiles is $w_a = 9$, while the number of half tiles is $h_a = 20$. In Fig. 3.8(b), the number of whole tiles is $w_b = 21$ while the number of half tiles $w_b = 26$. Therefore the prices under two different resolutions are

$$p_a = v(w_a + 0.5\mu h_a)\lambda_a^2 = v(9 + 20 * 0.5\mu)/6^2 \tag{3.15}$$

and

$$p_b = v(w_b + 0.5\mu h_i)\lambda_b^2 = v(21 + 26 * 0.5\mu)/8^2 \tag{3.16}$$

respectively.

Note that though a higher resolution contributes to a good precision, it needs a larger number of sensors and also results in higher cost. To guarantee interference protection between SPAL users, sublicenses should be assigned to non-overlapping contours, the allocation determination should optimize the profit. Success of the competing for protection depends on their pricing and overall determination in a conflicting situation. The sublicense rights are granted by the overall judgement.

The contour boundary is suggested as P_b= -96dBm in [17]. In practice, it is impossible or quite difficult to find the contour boundary by installing fixed grid sensor networks. In this chapter, we also introduce Poisson sensor networks to detect the boundary.

3.3.4 Contour in Poisson Point Field

Distributed sensor networks are essential for effective surveillance in outdoor field and for wireless environmental monitoring. A significant issue in the design of these networks is the deployment or placement of sensor nodes in the surveillance area. In a typical scenario, several different sensors are arbitrarily placed in a field rather than in a regular grid.

In the above subsection 3.3.3, the sensor network is assumed in a regular grid. However, it may cost a lot to deploy such a sensor network. Considering that mobile devices are capable of sensing, we propose to enable a centralized controller to collect the sensing information from the local mobile devices, then estimate the contour of a base station, as shown in Fig. 3.9.

Delaunay triangulation

Actually, the sensor nodes are not deployed in regular grid in the real world. We further put the identification nodes in a Poisson point field. Based on the idea of finding the boundary points between two sensor nodes, we first need to determine the uncrossing edges connecting all the sensor nodes in the region. Tessellations of space for a given set of points into non-overlapping cells play an important role in the fields of science on form and stochastic geometry [90].

The sensor nodes could be seen as a set of spatial Poisson distributions [91]. For

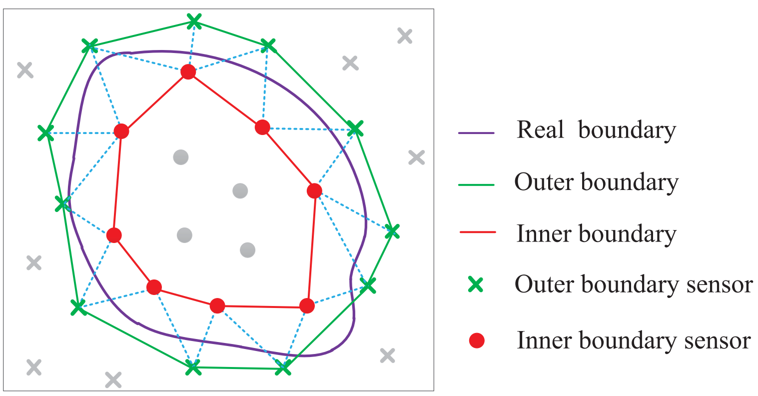


Figure 3.9: Boundary estimation in Poisson point field.

a set $\mathbf{V}$ of points (or vertices) in the Euclidean space, a Delaunay triangulation is a triangulation $\mathcal{T}(\mathbf{V})$ such that no point in $\mathbf{V}$ is inside the circum-hypersphere of any simplex in $\mathcal{T}(\mathbf{V})$ [92] [93]. It is widely used in wireless sensor networks [94]. Then this region is divided into non-overlapping triangles by set of $\mathbf{V}$ and $\mathbf{E}$, denoting the edge set.

Next, we detect every edge in the sensor networks. Let $e_{ij} \in \mathbf{E}$ denote the edge between vertex $v_i (\in \mathbf{V})$ and vertex $v_j (\in \mathbf{V})$, and w_i, w_j denote their received sensing signal. It is straightforward to tell the edge e_{ij} crosses the boundary if $w_i >$ -96 dBm while $w_j <$ -96 dBm. Then the boundary point at the edge could be calculated by (3.12). Furthermore, all the vertices at crossing edges less than -96 dBm form a set as an outer boundary $\mathbf{V}_o$ while the vertices more than -96 dBm form an inner boundary $\mathbf{V}_i$, as shown in Fig. 3.9. The gap between inner boundary and outer boundary will be treated as the shared boundary for further discussion in Section 3.4.

3.4 Construction of Interference Graph

3.4.1 Allocation

An interference graph G could be constructed upon the interference conditions determined as above in Fig. 3.10. Let vertices denote the base stations and edges denote the interference condition between them. If the base station i's contour (interior tile) overlaps base station j's contour, we say there is interference between them (we do not count the overlapping boundary tiles as interfering tiles). Then the next step is to find the independent vertices from the graph, which is modelled as graph colouring problem and proved to be NP-hard, which means that the problem is non-deterministic polynomial acceptable. Greedy algorithms are used for winner determination and the detailed further work can refer to [63] [86]. The allocation a_i is determined in this step to ensure a non-overlapping allocation as shown in Fig. 3.11.

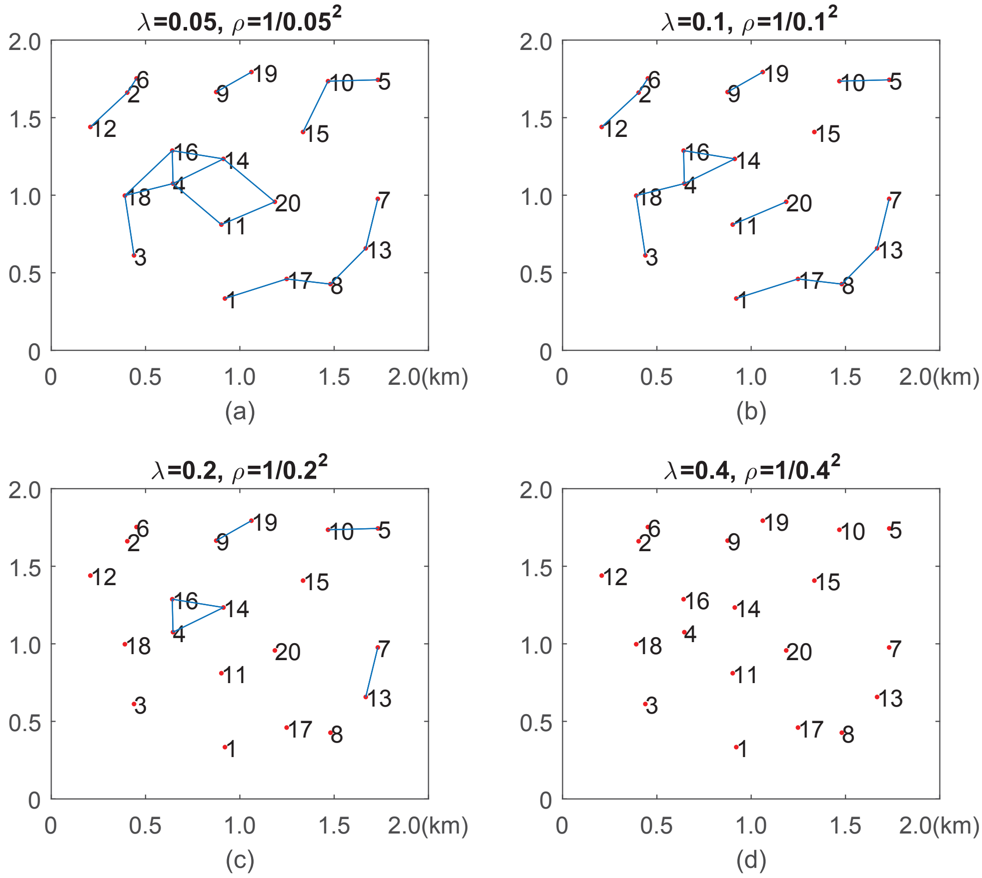


Figure 3.10: Area $2km \times 2km$: when the grid resolution varies from high to low, the interference graph becomes less complex.

3.4.2 Boundary Sensitivity

Typically, sensors or mobile devices are used to serve as measurement points for interference levels close to the Protection Zone borders. In a dense area, where a large number of SPAL users compete for the sublicenses, the interference on the boundary area is difficult to tell from each other. Because in some cases, the boundary tile is usually shared by more than one SPAL user. This is the reason we introduce *boundary sensitivity* μ, which is defined as the tolerance of the neighbours. It is used to judge the maximum number of shared users in a boundary tile. For example, if the boundary tiles are not allowed to share with anyone else, the *boundary sensitivity* μ is set as zero. For instance, in a sparse situation, the boundary area is still interference-free, and *boundary sensitivity* μ should be set as zero, which means that the sublicensee does not want to share the boundary tiles with anyone else.

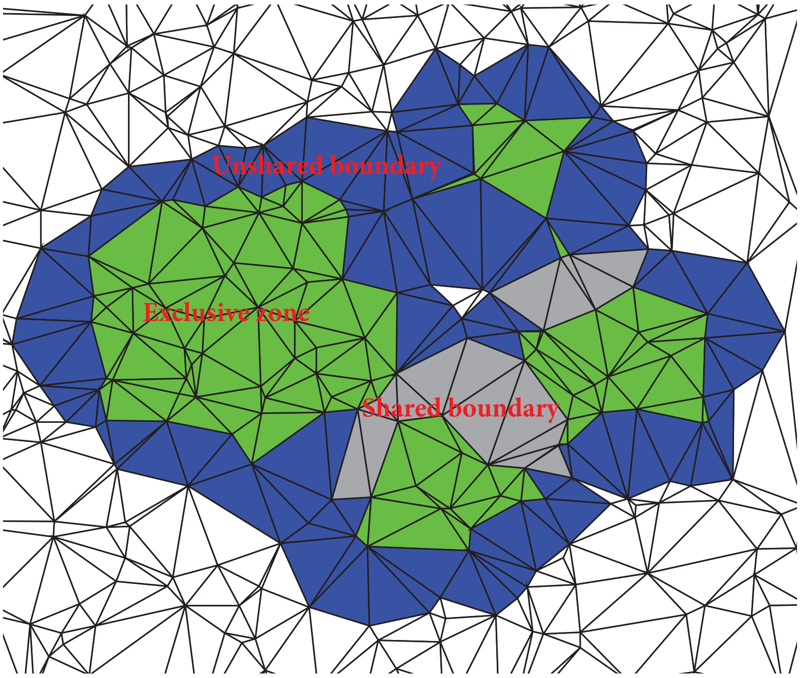


Figure 3.11: An interference-free allocation.

On the contrary, in a competitive situation, the boundary tile is probably shared by multiple base stations. Since the QoS is no longer as good as that in a sparse situation, the boundary is less valuable. In this case, the boundary sensitivity is set as the tolerance in terms of the limited number of SPAL users over the boundary area. If the number of shared users in a boundary tile is greater than the *boundary sensitivity*, the tiles will not be charged and no QoS guaranteed.

For example, in Fig. 3.15(b), ten sublicenses are allocated. Since they are close to each other, we cannot really tell the exclusive boundary of every allocated sublicenses and cannot guarantee QoS at the boundary. For instance, on the right side, the top two contours share one boundary tile. More simulation results will be presented in Section 3.5.

3.5 Simulation Results

In this section, we evaluate the performance of the proposed scheme, such as how the sensor network resolution and boundary sensitivity affect the allocation result and profit.

3.5.1 Methodology

We assume that $N = 20$ base stations are uniformly distributed in a $2km \times 2km$ census tract. To make this model more practical we further let the -96dBm contour of base station's radius be 200 meters. We run the simulation for 1000 times to mitigate the impact of randomness. In the simulation, the profits under different resolutions are compared and analysed.

Note that we assume that the winners have their business strategies to obtain the values of the allocated area and the profit, like provide advanced wireless services for the users in this region. Moreover, if any parameter changes, the optimal sensor distance could change accordingly, as equation (3.7). In addition, the existing works focus on spectrum sharing in the time domain or the frequency domain and we propose a sublicensing scheme in the space domain.

3.5.2 Boundary Estimation

We first demonstrate the simulation results of boundary estimations in two kinds of sensor networks. Note that the contour measurement is only a part of the proposed scheme, and the sensor networking in Poisson distribution and regular grid are compared. Fig. 3.12 demonstrates the boundary estimation in Poisson point field. Using a linear estimation between outer boundary and inner boundary, the contour boundary could be identified as the pink polygon. Fig. 3.13 compares the estimation accuracy of regular grid and Poisson point field. In this simulation, we generate an arbitrary contour and find that Poisson distribution is better than regular rigid, particularly when fewer sensors are used.

3.5.3 Resolution and Interference Graph

We then demonstrate how the resolution affects the Interference Graph, as shown in Fig. 3.10. An interference graph is widely used to assign spectrum to mutually interfering users. The nodes in the interference graph denote the users while the edges denote the interference between them. In Fig. 3.10, the graph is differently formed as the resolution ρ varies from $1/0.05^2$ to $1/0.4^2$. The interference graph

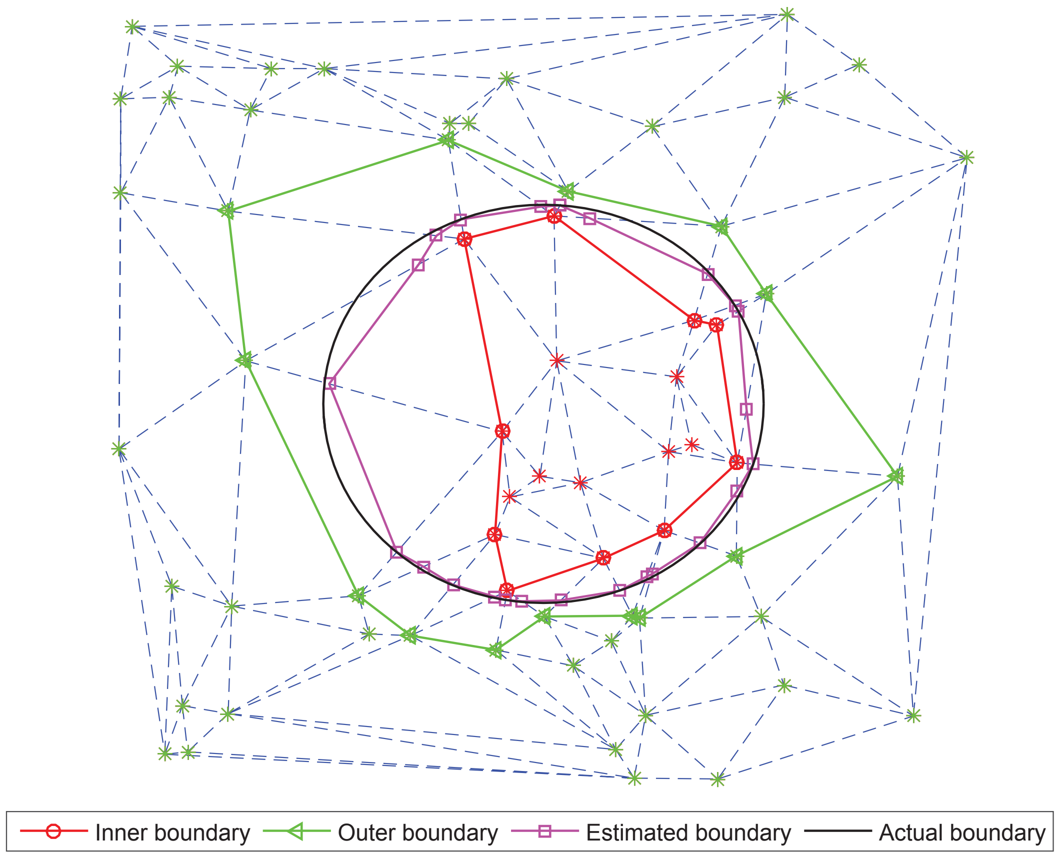


Figure 3.12: Boundary identification in Poisson sensor network.

is used for winner determination, so it directly results in a different allocation, as shown in Fig. 3.15. The colour scale indicates the number of shared SPAL users. Particularly, when the tile's colour value is -1, it is a whole tile and not shared.

When the resolution is high, the region is fine gridded and the interference graph is more complex than that under a low resolution. Since the range of the base station is 0.2 km, the minimum interference-free distance between two base stations is 0.4 km. When the distance of the two neighboring sensors is larger than 0.4 km, the sensing network cannot measure the area well.

3.5.4 Boundary Sensitivity

The boundary sensitivity will be used to judge the tolerance of the shared users, particularly in a competitive situation. As illustrated in Fig. 3.14, if μ is set as

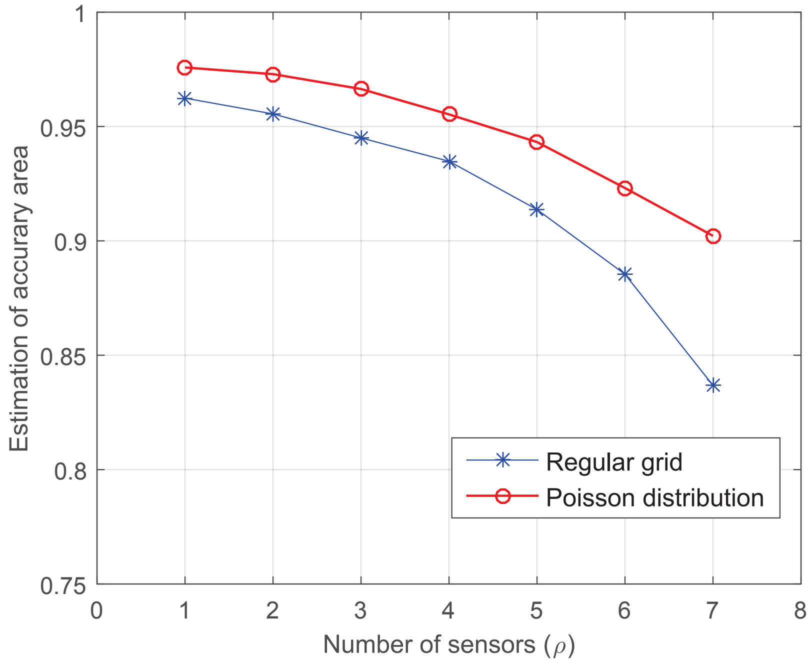


Figure 3.13: Comparison of estimation accuracy in different sensor deployments.

zero, the contour boundary tiles cannot be shared by anyone else; accordingly the boundary tiles will be ignored then profitable area is less. However, when μ is greater than zero, the total allocated area will increase then drop. Because the boundary area is usually partially covered by the half tiles, if the boundary area is shared by a limited number of users (the shared users only pay less), the total allocated area will increase with a little lower QoS. However, when the sensors are deployed more than every 0.125 km, the grid is too coarse to distinguish the protection zones, then the profitable allocated area falls down. Because the severely interfering boundary tiles are ignored, the estimation of protection zones is no longer precise.

3.5.5 Resolution and Profit

As illustrated in Fig. 3.16, the grid length λ varies from 0.01 km to 0.4 km, and $\mu = 2$. The valuation per unit space is normalized as $v_i(x, y) = 1$, while the cost τ of the each sensor is set as $\{10, 100, 500, 1000\}$, compared to v_i. The profit first increases from extremely low to the peak at $\lambda = 0.125$ km, then drops. This is because, when the resolution is high (λ is small), even though the contours can be

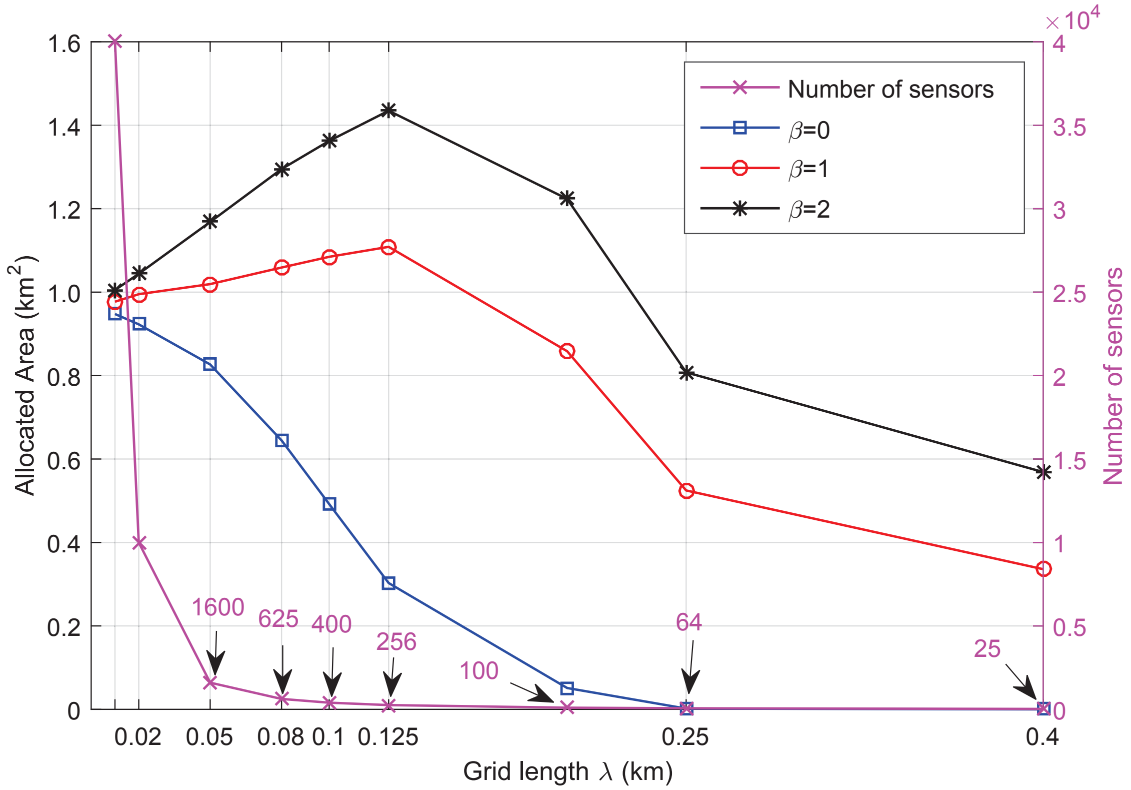


Figure 3.14: The number of the sensors will exponentially decrease along with the grid length. When the boundary sensitivity is set greater than zero, the total allocated area is optimized at $\lambda = 0.125$.

precisely measured, the cost of all the sensors is very expensive. When the resolution is low, the size of tile is large, then the estimation of contour area will be less precise. Accordingly, the cost is lower and the profit falls down. When the sensor is deployed every 0.125 km, we can achieve the highest profit.

3.6 Summary

Spectrum sublicensing for temporary use is a flexible and feasible solution for spectrum sharing between multiple operators, particularly on the platforms of SAS and LSA. In this chapter, we propose a sublicensing scheme to enable the spectrum trading in a secondary market, hence the spectrum efficiency can be improved as driven by business. Operation of small cell networks only based on dedicated sublicenses may not be feasible as more spectrum is needed; therefore, the flexible spectrum use and short-term spectrum access is a way forward for profitable sharing in the

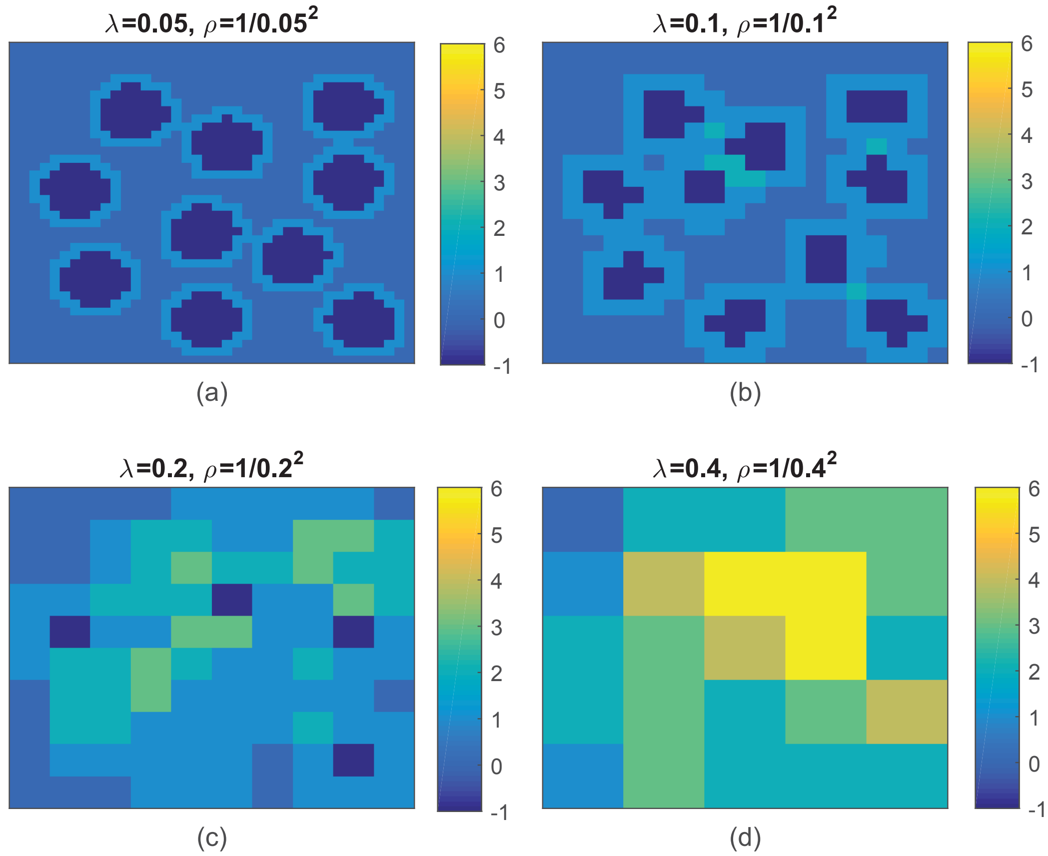


Figure 3.15: Sublicenses allocation. When the grid resolution varies from high to low, the protection zones cannot be measured precisely. The tile's colour scale indicates the number of shared SPAL users in that tile.

coming decades. The principle of allocation spectrum to individual base station based on a dedicated and exclusive sublicense will persist, as a method to ensure contour coverage and QoS. The proposed scheme can provide subsequent auction or other economic models with a reasonable interference graph. Since spectrum sharing in SAS has not yet been fully studied, this chapter demonstrates how to open a secondary spectrum market and assign available sublicenses to SPAL users. Based on the analysis of the simulation results, the importance of the boundary sensitivity should be adjusted by the density of interested SPAL users and the resolution also be optimized to maximize the profit.

In the next chapter, assuming that the contour based protection zones are submitted to the spectrum sharing platform, we will focus on the online auction design, which adopts the interference graph formation method and guarantees a fair and truthful spectrum allocation.

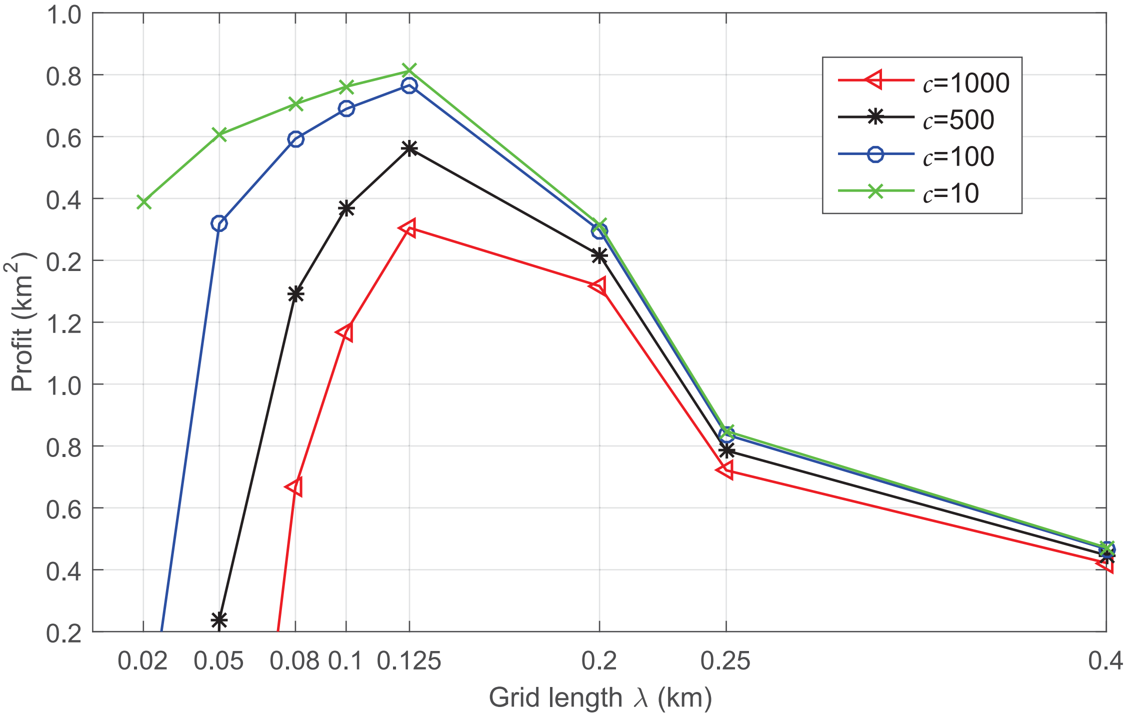


Figure 3.16: With the decrement of the grid resolution, no matter how the cost of sensor changes, the profit reaches the peak at $\lambda = 0.125$.

Chapter 4

Spectrum Sharing Based on Truthful Auction and Fair Allocation

In this chapter, we present a truthful and fair auction mechanism for spectrum sharing based on the LSA architecture. This proposal aims to allocate incumbents' available spectrum to base stations from different operators for the purpose of commerce.

4.1 Introduction

Wireless spectrum is very valuable and it is likely to become congested to accommodate diverse types of networks, users, applications and interfaces in the 5G era [20]. Therefore, to achieve the goal that future 5G systems will require a 1000-fold capacity growth compared to today's cellular systems, solutions from three key directions need to be explored [95], namely: base station densification, access to additional spectrum resources, and increase in spectral efficiency. As one of the three solutions, the spectrum sharing platform offers both Incumbents and licensees shared access to improve the spectrum efficiency. On the one hand, in fact, many licensed frequency bands held chiefly by governmental agencies are underutilised either over time or in space, yet complete redeployment of these systems and reallocation of the spectrum for commercial use will be unlikely. Incumbents are more likely to temporarily share the spectrum with the secondary licensees if they are rewarded in monetary terms [45] and also retain the ownership. On the other hand, considering that there is a significant spectrum crunch particularly faced by commercial Mobile Network Operators (MNOs) who have growing needs to find potential solutions to spectrum scarcity, MNOs may be prepared to temporarily pay for the extra spectrum band to offload their impending huge traffic.

Among network economic models, auction-based spectrum trading has been widely used with a long lasting history. Market manipulation could be quite detrimental to the fairness and efficiency of auctions. Truthfulness is quite helpful to prevent market manipulation. Authors in [96] studied the truthful auctions where secondary licensees had demands for fixed location (cells), and Vickrey-Clarke-Groves (VCG) [97] mechanism is used to maximise expected revenue while enforcing truthfulness. We agree with the basic idea in [98], which proposes a spectrum auction to support an eBay-like dynamic spectrum market, but the infrastructure is not discussed. [99] focuses on truthful online auction where buyer's requests have different arrival time and departure time, but with high complexity. A framework named TRUST is proposed in [59] for truthful spectrum auctions in double-sided markets, where there are both multiple buyers and multiple sellers. TRUST mainly focuses on how to keep the double spectrum auction truthful. Because spectrum can be spatially reused, a grouping buying apporach is used for interference-free alloction. However, none of the researchers discussed the scheme of group formation.

With a novel virtual group bidding mechanism, our proposal can efficiently exploit the spatial reusablity of spectrum to increase the spectrum utilization in auction-based dynamic spectrum access. We prove that the proposal can achieve economic properties including individual rationality and truthfulness to make it an economic-robust auction. Simulation results show the proposal has higher efficiency on spectrum utilization as well with other metrics. It is generally more efficient compared with any former design, especially when buyer's bids are variable.

Based on the above incentives from both Incumbent and licensees, we propose an online auction, and the auction based on LSA is shown as Fig. 4.1. To the best of our

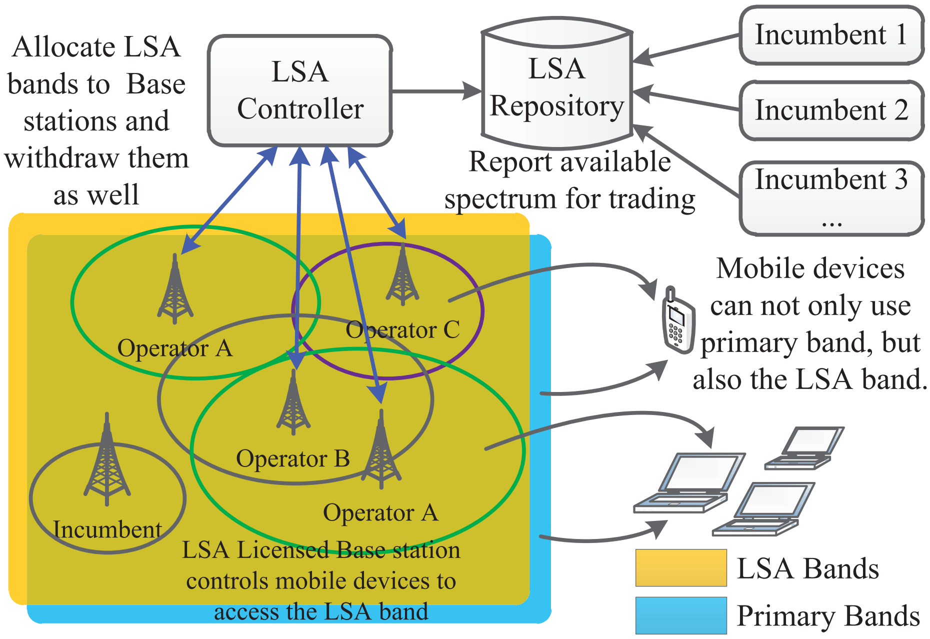


Figure 4.1: LSA auction architecture.

knowledge, this is the first proposal about auction design based on the LSA system. The auction mechanism can help solve the conflict problem, guarantee interference-free operations among MNOs and manage the spectrum allocation effectively. The main contributions of this chapter are as follows.

- We propose an online auction for the LSA architecture. The auction is applied to a new use scenario of inter-MNOs' sharing, where multiple base stations from various MNOs compete for spectrum chunks from a certain Incumbent at a certain time.

- The proposed LSA Auction (LSAA) mechanism combines an independent set selection by licensee bids and a rank-bid winner determination, topological sort allocation. We give the Incumbents the flexibility to express their reserve prices for spectrum leasing. In this way, incumbents can guarantee their minimum profits. Using a Rank-bid to calculate group bid also assists in auction truthfulness.

The rest of the chapter is organized as follows. Section 4.2 presents the challenges in a spectrum auction mechanism. In Section 4.3, the system model and assumptions are given and the detailed LSAA mechanism is explained in Section

4.4. The important property of truthfulness is proved in Section 4.5. Numerical simulation results are presented in Section 4.6, followed by the summary in Section 4.7.

4.2 Challenges

A well-designed spectrum auction mechanism should not only consider the truthfulness but also the spacial reusability of spectrum. Although previous models [59] [62] [61] are widely discussed, they can not be directly applied to our scenario. The challenges of incomplete information, economic robustness, NP hardness and fair allocation are coupled all together in the new auction mechanism.

4.2.1 Incomplete Information

Due to the security of private considerations, complete information in the spectrum market is not possible. So it is important for both incumbents and secondary licensees to acquire as much information as possible to make rational decisions. This incomplete information contains two meanings.

First, incomplete information exists between Incumbents and licensees. Incumbents have no knowledge about the deployment of secondary networks, and in turn, licensees may not have the full knowledge of the incumbents. Since an auction mechanism can help both incumbents to extract the valuation from the secondary licensees and make them bid truthfully, it is suitable to be used in an incomplete information spectrum market [45].

Second, incomplete information exists between licensees. We consider multiple base stations in different networks in a given geolocation area. Assume that these base stations (BSs) compete against each other for a spectrum band in this region, as shown in Fig. 4.2. In Fig. 4.2(a), it shows an example of a competition among multiple BSs from different MNOs in an incomplete information use scenario, where the BSs from the same MNO do not interfere to each other, but interfere if they are from different MNOs. The physical interference graph is constructed as shown in Fig. 4.2(b), where the edge between vertices means interference between two BSs.

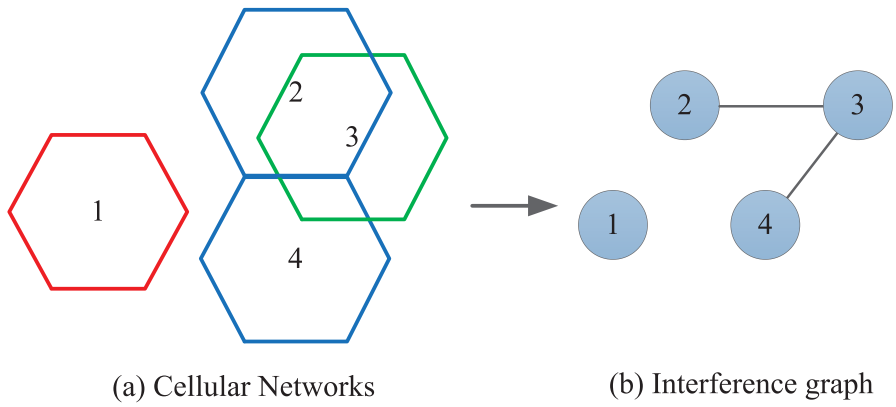


Figure 4.2: Interference between base stations: operators have different deployments of BSs, and their BSs could be interfered with the others if run at the same sharing band.

All the individual information will be reported to a centralized controller, i.e., the LSA Controller. Note that, instead of signal's physical interference, we adopt the the interference in term of protection zone as discussed in Chapter 3.

4.2.2 Economic Robustness

In the spectrum market, Incumbents are sellers while BSs are buyers. When spectrum trading occurs, there are some issues that should be considered when designing economic mechanisms.

Individual Rationality

Everyone is rational and hopes to gain profit as much as possible. In the competitive activity, the strategy set is important for the LSA Controller to make an all-satisfactory decision. Everyone in the system will get non-negative utilization. In our proposed LSAA, Incumbents are free to express the reserve price for the spectrum which they own and decline the requirements if the licensee's bid is lower than the reserve price. Licensees will never pay more than their bids.

Truthfulness

An auction is defined as truthful when no one bidder can gain more profit by bidding at a cheating valuation. In a marketing process, because rational cheating or lying happen often, some solutions should be proposed to guarantee a truthful trade environment. In the auction theory, a truthful bid can be made if the bidder's payment is not related to his own bid but depends on others [96] [99].

4.2.3 NP Hardness

To guarantee an interference-free allocation, the interference between base stations is modeled as a graph, and then the next step is to select the unconnected vertex sets. Graph colouring algorithm is often used to achieve interference-free allocation for base stations in such a situation, which is proved as NP hard [100] [101].

Basically, as mentioned in [61] [102], the way to find out an independent vertex set may affect the reusability of spectrum. In this chapter, we compare various methods of graph colouring and observe how they effect the final performance.

4.2.4 Fair Allocation

In many resource allocation problems, one seeks to allocate a limited sets of resources to a set of individuals with different attributes [103]. To allocate the limited spectrum resource to diverse interfering base stations, fairness is a significant concern. Fairness exists in two levels. First, how to allocate the resource between different groups. Second, for the winning groups, how to allocate the resource within one group and make sure every one is maximally satisfied. Since the bidders are heterogeneous, we compare three allocation schemes; as equal allocation, sum weight proportional allocation and maximum weight proportional allocation.

4.3 System Model

In this chapter, we consider multiple base stations in a given geolocation area. Assume that these base stations are homogeneous in terms of interference-free range but from different operators, and they compete against each other for a spectrum band in this region, as shown in Fig. 4.2.

Incumbents can post their available spectrum information in the Repository, e.g., reserve price μ, the spectrum band that contains M available channels, and scheduling (which is not considered in this chapter). If one base station wants to participate in the online auction, it needs to submit its sealed bid b_i per channel (should be equal to its truthful valuation $v_i = b_i$, and this will be explained later in Section 4.5) plus its location l_i to OAM and the LSA Controller. The bid is used for winner determination and channel allocation and the location is used for calculation of interference graph.

Assume that there are N base stations in the auction, the bid vector is denoted as $\{b_1, b_2, ..., b_N\}$ and the location vector is denoted as $\{l_1, l_2, ..., l_N\}$. When the LSA Controller receives all the requirements from the base stations, it can generate an interference graph $G \in \{0, 1\}$. $G_{ij} = 1$ denotes that base station j causes interference to base station i, while $G_{ij} = 0$ denotes no interference. The LSA Controller has to make a decision to allocate a spectrum band to the winners in an auction. If two base stations have an interference conflict, they should not be assigned at the same time. Basically this judgement can be described as:

$$\left.\begin{array}{lll} arg & \max \mathbb{R} = \sum_{i=1}^{N} a_i p_i |\beta_i| & (4.1.1) \\ s.t. & b_i \geq p_i & (4.1.2) \\ & \beta_i \neq \beta_j, \text{ if } G_{ij} = 1 & (4.1.3) \\ & \beta_i \leq M & (4.1.4) \end{array}\right\} \quad (4.1)$$

where $\mathbb{R}$ denotes the revenue of the auction, which is the summation of all base stations' payment. In the objective equation (4.1.1), $a_i \in \{0, 1\}$ denotes whether base station i wins: a_i is 1 if base station i wins; otherwise it loses, and $|\beta_i|$ denotes the number of channels and $\beta \leq M$. p_i in (4.1.2) denotes its payment. Note that in constraint (4.1.2), because of the economic property of individual rationality, the base station is not willing to pay more than it has bid, and hence for any base station i $b_i \geq p_i$. In addition, in constraint (4.1.3), if two base stations interfere, they cannot be allocated the same channel.

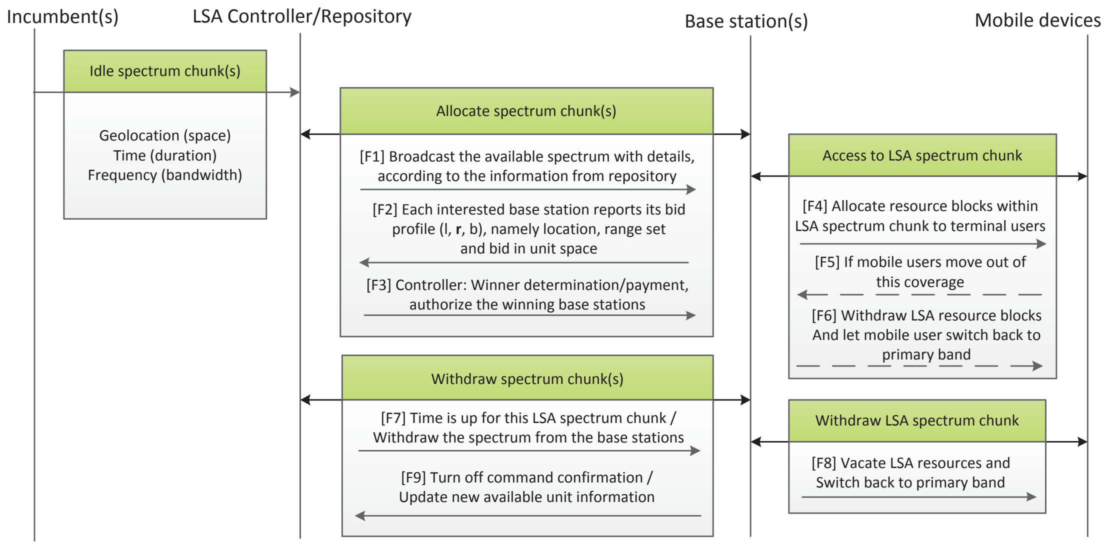


Figure 4.3: Bid Processing. Incumbents will update their available spectrum information to the repository and then the interested base stations will bid for the spectrum with the bid profile. If a base station wins it can provide its subscribers with good services.

4.3.1 Bid Processing

The bid processing involves information exchanging and decision making between the LSA Repository and the LSA Controller and submitted sealed bids from different base stations, as shown in Fig. 4.3. As a direct access point, a base station plays an important role in managing mobile devices and allocating resource blocks to them. Therefore, we suggest that the available spectrum chunk is first allocated to a base station. Then the base station further serves its subscribers. SNAM targets fine timescale auctioning. A base station has first hand information of its traffic load pattern. Specifically, the subscriber flow during a period of time in a weekend or weekday is relatively predictable. If a base station wins the spectrum, then these venues can provide good services. We suggest that SNAM runs hourly (but can be at a finer level as well).

Information Broadcast

In the LSA framework we assume that Incumbents will update the information about their available spectrum chunks in the LSA Repository. This can be broadcasted by the LSA Controller to all the base stations in that region.

Bid Submission

After receiving the available information each base station will then decide the bid profile, including the range set and bid based on its terrestrial property, business plan and other technical aspects.

Winner Determination and Result Announcement

The auctioneer make the allocation decision aiming to a fair and interference-free allocation and at the same time guarantee that the auction is economic-robust. After the auction, winners and their granted coverages are announced.

Note that LSAA can be fitted directly on the existing LTE systems, where the bidding information between a base station and auctioneer controller could be transmitted via the interface X1 through the Evolved Packet Core (EPC) and IP Multimedia Subsystem (IMS) [104]. The communication overheads could be put in a message packet that contains one bid profile from each bidder and one determination result from an auctioneer controller.

In fact, LSAA can provide small and large firms equal opportunity to access the spectrum by considering their coverage request. This gives small bidder/firms who request small coverage areas a fair ground to compete with large ones.

The entire workflow is shown as Fig. 4.4. After the LSA Controller collects all the bidding information from all the base stations, it can first calculate the interference graph. Because of interference among base stations and spectrum spacial reusability, grouping the independent vertices is a necessary part in the auction design. In addition, as long as any two base stations are grouped together they can share the same channel. However, before this grouping process, we introduce another step – Sorting. The structure of an interference graph has a direct influence on the grouping result and the vertex traversal is importantly involved within. When all the groups are formed, the group bid can be immediately calculated, which is used for the next step, Determination. Then, a payment rule is defined for each winner to pay for the spectrum and at the same time, they will be allocated the spectrum. Note that unlike the traditional auction, winners do not pay as much as they bid, but pay the damage they cause to the losers [105].

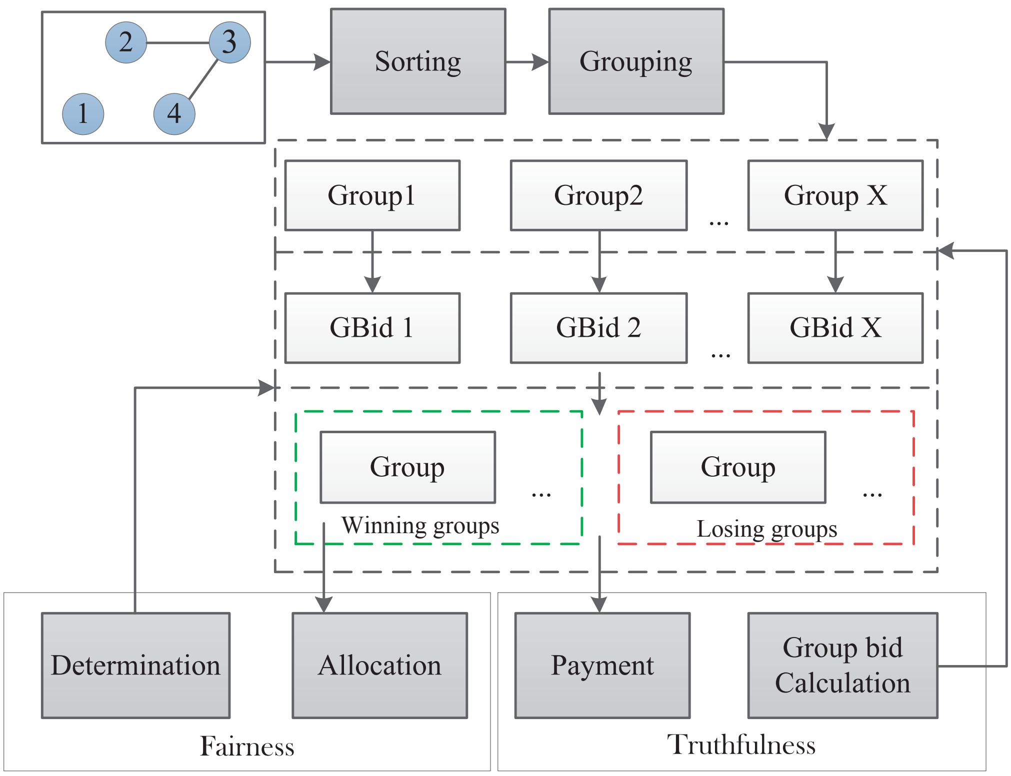


Figure 4.4: The workflow of LSAA.

4.4 Detailed LSAA

4.4.1 Sorting

An interference graph is used to guarantee interference-free operation by finding independent vertices from it. Let $G = (\mathbf{V}, \mathbf{E})$ be an interference graph where $\mathbf{V}$ is a set of vertices and $\mathbf{E}$ is a set of edges. Vertices denote the base stations, while edges denote the existence of interference between them. Unfortunately finding the maximum independent vertices set is an NP-hard problem [59]. Before grouping the interference-free vertices, we note that the search order has a great influence on the grouping result [59]. The existing works in this are based on two selection policies: assignment by the degree of nodes [63] (the degree of a node is the number of edges incident to the node) and by random assignment [59]. In this chapter, we introduce another two sorting schemes, topological sort and bid-rank sort. For all the sorting schemes, they can be categorized in two types: bid-independence and bid-dependence. We analyse these four sorting schemes as follows.

- **Random Sort**

  Random Sort is the easiest and straightforward sort scheme out of those four schemes. In the random sort scheme, the vertices are sorted randomly regardless of any properties of the vertices, such as bid and degree. All the vertices are seen equally and they are grouped together randomly.

  However, base stations are different in terms of bid that reflects the urgency for extra spectrum resource. In the random sort scheme, this concern is ignored.

- **Degree Sort**

  A vertex's degree is defined as the number of edges that are connected to it. Hence, the property of one vertex's degree can reflect the relationship between itself and all the neighbouring vertices. A high degree indicates a severe interference, while a low degree indicates a light interference. If a degree descending/ascending sorted sequence is put into the grouping process, the vertices with heavy/light interference will be grouped firstly.

  Compared with the random sort scheme, the degree sort scheme is more advanced, because it takes the neighbouring environment into consideration.

- **Bid Sort**

  The above random sort scheme and degree sort schemes are both bid-independent sort schemes, and they are investigated in [59] [63] [106]. However, the bid sort is apparently a bid-dependent sort. In practice, the traffic load of each base station varies from each other, which further leads to different bids. Unlike the existing works [59] [63] [106], to emphasize the importance of revenue, we adopt the selection policy based on bids, which means that the nodes should be sorted first by bids instead of degree or randomness. Although it is proved that the auction involving a bid-independent selection of independent vertices set is truthful, we also prove that the auction with a bid sorting pre-processing is also truthful in Section 4.5.

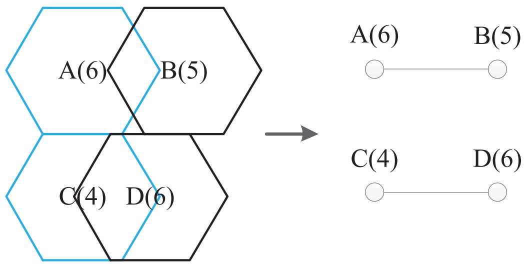


Figure 4.5: Different bids of four base stations.

Assume the function $rank(*)$ is used to sort the base station by the key as bid. For example, as shown in Fig. 4.5, since all the degrees of vertices are 1, the selection policy based on degree does not work. Under the random selection, there are two possible grouping results: $\{AD\}\{BC\}$ and $\{AC\}\{BD\}$. In order to obtain a higher revenue, we suggest the sorting of all the bids in a descending order: A, D, B, C, accordingly, we have $rank(A) = 1$, $rank(D) = 2$, $rank(B) = 3$, and $rank(C) = 4$. We first put node A into a group and delete its conflicting node B, then pick up the highest bid D from the rest of the nodes. Then node D's connecting node C has to be deleted. As a result, node A and node D are grouped together. This grouping process can repeat to deal with the rest of nodes C and D until no nodes are left. Finally we get the grouping result $\{AD\}\{BC\}$. It is obvious that the grouping result with $\{AD\}$ is better than the other one and it is exactly the result under our selection policy based on bid sorting.

- **Topological Sort**

  Topological sort is often used on applications of planning and scheduling because of the mutual constraints between different events [107]. In fact, the topological sort is a combination of degree sort and bid sort. In our proposed topological sort, the vertices are differentiated by the base station's bid, denoted as the weight of a vertex $\omega[n_i] = b_i$, and one single vertex's weight and its neighbours' weights are jointly considered as well. Then a directed

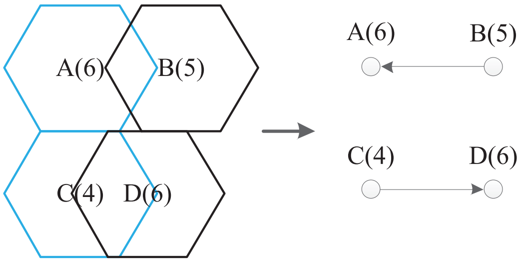


Figure 4.6: Directed interference graph.

interference graph $\hat{G} = (\mathbf{V}, \mathbf{E}, \omega[\mathbf{V}])$ can be constructed as below.

$$\hat{G}_{ij} = \begin{cases} 1, & \text{if } (i,j) \in \mathbf{E} \text{ and } \omega[n_i] < \omega[n_j] \\ 0, & \text{otherwise} \end{cases} \tag{4.2}$$

The direction of the edge depends on the weights comparison of the two vertices. For example, in Fig. 4.6 there are four base stations and the numbers in brackets () are their bids. The heavier weighted vertex is always pointed by the lower weighted vertex. Compared to the binary interference model in previous works [59] [61] [63], the key improvements of the directed graph is that the directed graph considers two extra factors: the vertex's weight and the relationship between vertices.

In addition, we use $rank[n_i]$ to denote the rank of vertex n_i after bid sort and adopt the convention that a higher rank corresponds to a higher priority. We further assume in the ordered sequence $\langle rank(n_1), rank(n_2), ..., rank(n_N)\rangle$, $rank(n_1) > rank(n_2) > ... > rank(n_n)$ stands. So the topological sort scheme can return an ranked vertex sequence where any two vertices n_i and n_j meet

$$\begin{cases} (i,j) \in \mathbf{E} \\ \omega[n_i] > \omega[n_j] \end{cases} \implies rank(n_i) > rank(n_j) \tag{4.3}$$

However, note that a topological ordering is possible if and only if the graph has no directed cycle, that is, if it is a directed acyclic graph (DAG) [107]. The constructed directed graph under the rule in equation (4.2) is proved to be a DAG as below.

We prove the following *Lemma 4.1* is true by contradiction.

***Lemma 4.1*:** The directed graph constructed under the rule under Topological Sort in Section 4.4.1 is a DAG.

Suppose not. [There ∃ a cycle ($v_1 \to v_2 \to ... \to v_n \to v_1$) in the interference graph.]
By definition of (1), we have $w[n_1] < w[n_2] < ... < w[n_N] < w[n_1]$, but this is conflicting to $w[n_1] \equiv w[n_1]$.
Hence, the supposition is false and the statement is true, namely there is no cycle in the graph; it is a DAG.

The depth-first search (DFS) and a stack (or last-in-first-out policy) are used together to realize the topological sort. We start from a random vertex n_1 and then recursively call the function of DFS for all its adjacent vertices $Adj[n_1]$, then push it into a stack. Note that the vertex n_1 can be pushed into the stack only when all of its $Adj[n_1]$ are already in the stack. Then the topological sorted sequence is the vertices popped out of the stack in the order. Since the time complexity of stack operation is $O(1)$, the time complexity of this topological sort is the same as DFS which is $O(\mathbf{V}+\mathbf{E})$, which is linear running time.

Topological sort is one of the sorting methods. The vertex order has a great influence on the next step, Vertices Grouping, and it is presented in Section 4.6, where we compare it with random sort, degree sort and bid sort. Therefore, our proposed auction is effective in gathering high bids together and thus further improves the revenue.

The spectrum use requirements from more than one base station may have a geographical conflict. A different order of the vertices produces a different grouping result. Previous bid sorting emphasizes the revenue and gathers high bids together, and topological sorting further incorporates the relationship between itself and the neighbour vertices.

4.4.2 Grouping

The vertex grouping rule is to guarantee that the vertices in a group, denoted as Ω_k, are independent in space and the controller needs to pick up independent vertex sets $\{\Omega_k\}$ (k=$\{1, 2, ...K\}$) from the graph, under the constraints of

$$\begin{cases} \forall(i,j) \in \mathbf{E}, & \{n_i, n_j\} \nsubseteq \Omega_k \\ \forall p, q, p \neq q, & \Omega_p \cap \Omega_q = \varnothing \\ \exists n_i \in \Omega_p, \exists n_j \in \Omega_q, & (i,j) \in \mathbf{E} \end{cases} \tag{4.4}$$

where K is the number of groups, and the vertices in the same group can access the same channels at the same time. Base stations that are organised in the same group have no interference with each other. Then the individual competition is transformed into group competition.

The grouping algorithm is described as Algorithm 1, where seq denotes the sorted vertices, $seq(1)$ denotes the first vertex in the sorted sequence and G denotes an interference graph.

4.4.3 Determination

This step is to select the winners from the auction. There are two rounds per base station to win in the auction: within a group and between groups. After grouping the vertices, the next step is to calculate the group-bid within a group. The group-bid defined in [59] is equal to the sum of all the bids and if this group wins, the buyers within the group will proportionally share the payment by their bids but it is not truthful. TRUST in [59] defines the group-bid as the lowest bid multiplied by the number of vertices in a group, $g(\Omega) = min\{\mathbf{b}\}|\Omega|$, where Ω denotes a group and $\mathbf{b}$ denotes its bid set. TAMES in [61] defines the group as the lowest bid in the group multiplied by the group size minus one, $g(\Omega) = min\{\mathbf{b}\}(|\Omega| - 1)$.

In LSAA, we propose another group-bid calculation method called Rank-bid to avoid low bids holding back the group-bid. Each bidder i has a rank-bid, which is defined as $rank(n_i) * b_i$, where $rank(n_i)$ is base station i's bid rank in its group. The group-bid should be the highest rank-bid, given by equation (4.5).

$$g(\Omega) = \max\{rank(n_i) * b_i\}, b_i \in \mathbf{b} \tag{4.5}$$

Algorithm 1 Vertices Grouping

```
procedure (input: seq, G)
    Group index initialization: k=0
    while ∑ G_ij > 0 do
        k++
        G'=(G'_ij) ← G=(a_ij)
        seq' ← seq
        while ∑ G'_ij > 0 do
            Put vertex seq'(1) into group Ω_k
            Delete vertex seq'(1)'s neighbours
            Update G'
            Update seq'
        end while
        Delete all the nodes in Ω_k from G and seq
        Update G
        Update seq
    end while
    return group set: Ω={Ω_1, Ω_2, ..., Ω_k}
end procedure
```

It is easy to show that sometimes there may be more than one maximum rank-bid in a group. Assume that all b_i that meet (4.5) form a set $\{b_{im}\}$. The winners in a group can be described as in equation (4.6).

$$winners = \{j \mid rank(n_j) \leq \max\{rank(\{n_{im}\})\}\} \tag{4.6}$$

where $g(\Omega)$ is a function to calculate the group Ω's group-bid and $rank(n_i)$ is a function to calculate the rank of bidder i in its group.

For example, in a 6-vertex group, assuming their bids are given as $\mathbf{b}$={60, 50, 50, 30, 30, 10} and accordingly their rank-bids are {60, 100, 150, 120, 150, 60}, then $g(\Omega)$=150 and $rank(\{b_{im}\})$ is $(3, 5)$, so each winner's rank should not be lower than $\max\{(3,5)\}$=5. As a result, the bidder that ranks 6 fails. For the groups, the group with the highest group-bid wins in the auction.

4.4.4 Payment

It is challenging to achieve truthfulness in the auction. In fact, the payment rule is coupled with group bid to achieve truthfulness, as shown in Fig.4.4. Even though a truthful scheme will lower spectrum revenue, it significantly contributes to resisting selfish bidding behaviours that can damage auction efficiency. If a buyer loses, it pays nothing. If Ω is the winning group, the winners in the group Ω will pay for their group-bid together and equally, as (4.7), where $|\Omega|$ denotes the number of base stations in the group Ω.

$$p_i = \begin{cases} \frac{g(\Omega)}{|winner_\Omega|}, & \text{base station } i \text{ wins}, i \in \Omega \\ 0, & \text{otherwise} \end{cases} \tag{4.7}$$

4.4.5 Channel Allocation

Fairness is the main concern in this section. Although all the base stations are homogeneous, their bids are different from each other as well as the groups that are formed based on their interference. Different groups should be allocated different numbers of channels. In the following we discuss three ways about how to determine the number of channels allocated to every group, when the number of channels is given as M. [108]

Assume that the number of channels that will be allocated to a group Ω_k is β_k and $M = \sum \beta_k$ denotes the total number of available channels. We define three allocation principles.

1. Equal Allocation (EA).

   The winning groups $\langle \Omega_1, \Omega_2, ..., \Omega_{\hat{K}} \rangle$ equally share the available channels in the networks regardless of their bid difference, so we have

   $$\beta_{\hat{k}} = \left\lfloor \frac{M}{\hat{K}} \right\rfloor . \tag{4.8}$$

   It is obvious from the equation above, the number of formed groups $\hat{K}$ can directly affect the number of channels in each group, while we have already considered it in the previous step, Vertices Grouping, in Algorithm 1.

2. Sum Weight Proportional Allocation (SWPA).

   In SWPA, we proportionally allocate the channels to every group according to their group traffic load, which is defined as the sum traffic load of a group, as

   $$w[\Omega_k] = \sum w[v_i], v_i \in \Omega_k \tag{4.9}$$

   and the number of channels one group can get is

   $$b_k = M \left\lfloor \frac{w[\Omega_k]}{w[\Omega_k] + \sum w[v_{-k}]} \right\rfloor , n_{-k} \notin \Omega_k \tag{4.10}$$

   where v_{-k} denotes the vertices do not belongs to Ω_k. Apparently if the group contains more users it can be allocated more channels; in that case the user's average spectrum resources are allocated fairly.

3. Maximum Weight Proportional Allocation (MWPA).

   We define the group traffic load as the maximum traffic load in a group in MWPA, as

   $$\omega[\Omega_k] = \max\{\omega[v_i]\}, v_i \in \Omega_k. \tag{4.11}$$

Then the channels will be proportionally allocated to these groups according to their group weight, as

$$b_k = M \left\lfloor \frac{\omega[\Omega_k]}{\sum_{i=1}^{K} \omega[\Omega_i]} \right\rfloor . \tag{4.12}$$

Because the vertices in a group are independent and share the same channels, the heaviest weighted vertex is chosen to be the group weight.

Finally, users within a base station will equally share the channels with the other group members. Therefore for the users under BS i coverage the spectrum resources per user can have is

$$\hat{b}_i = \frac{b_k}{w[v_i]}, v_i \in \Omega_k. \tag{4.13}$$

Note that in the proposed LSAA, we introduce "'bid' selection and "rank" calculation before winner determination, with computational complexity of node sorting as scale of N^2, which has the same scale of forming groups. Although under the same circumstances LSAA takes longer time than other schemes in the literatures, actually, it could be ignored. This is because, the time of winner determination process is so short (i.e. seconds) compared to the time interval of the auction, which is daily or hourly based. Furthermore, in the multi-seller-multi-buyer situation, LSAA could be repeatedly used until all sellers' spectrum blocks are sold. The number of sellers has a significant influence on the iteration of winner determination. Because the sellers' spectrum chunks need to be sold from the lowest price to the highest price. LSAA could be further extended to the double auction. How to match the buyers and the sellers is a problem about how to maximize the social welfare, which is the addition of sellers and buyers profits.

4.5 Truthfulness Proof

***Lemma 4.2*:** Under the LSAA mechanism, if one buyer increases its bid while the others remain unchanged, its group bid will be no less than before. Similarly, if one buyer decreases its bid while the others keep their bids unchanged, its group bid will be no more than before.

Lemma 4.2 can be described as equation (4.14).

$$g(\mathbf{b}) = \max\{b_{-x} * rank(b_{-x}), b_x * rank(b_x)\}, b_x, b_{-x} \in \mathbf{b} \tag{4.14}$$

where $\{b_{-x}\}$ denotes a bid set except buyer x's bid b_x, namely $\{b_{-x}\} = \mathbf{b} - \{b_x\}$. Buyer x is the one that bids untruthfully in the auction, leading to a change of group-bid. We just need to prove that (4.14) is a monotonically increasing function. Assume that buyer j is one of the winners and its rank is the highest so the group-bid is $g(\mathbf{b}) = b_j * rank(b_j)$. If buyer x changes its bid as $b'_x \geq b_x$, everyone's new rank absolutely belongs to {rank, rank+1}. We can prove this from the following two situations.

(a) When $b_x \neq b_j$. As we assume above, originally the group-bid is $g(\mathbf{b}) = b_j * rank(b_j)$. If buyer x raises its bid as $b'_x > b_x$ and the after-changing group bid set is $\mathbf{b}'$, it makes the others' ranks unchanged or increase it by one, so buyer j's new rank is $rank'(b_j) = rank(b_j)$ or $rank'(b_j) = rank(b_j) + 1$ after buyer x changes its bid, where we can see that buyer j's new rank-bid=$b_j * rank'(b_j)$ becomes no less than before. As the group-bid is the maximum rank-bid, regardless of what buyer x's rank-bid becomes, the new group-bid $g(\mathbf{b})$ can not be lower, i.e., $g(\mathbf{b}') \geq b_j * rank'(b_j) \geq b_j * rank(b_j) = g(\mathbf{b})$.

(b) When $b_x = b_j$. All the bids in a group are sorted as $\{b_1 \geq b_2 \geq ... \geq b_{j-1} \geq b_x \geq b_{j+1} \geq ... \geq b_n\}$, while $g(\mathbf{b}) = b_x * rank(b_x)$. When buyer x raises its bid as $b'_x > b_x$, the new sorted bid set should be $\{b_1 \geq b_2 \geq ... \geq b_x \geq ... \geq b_{j-1} \geq b_{j+1} \geq ... \geq b_n\}$, and buyer $(j-1)$'s new rank $rank'(b_{j-1})$ increases by one and is the same as $rank(b_x)$. Due to $b_{j-1} \geq b_x$, buyer $(j-1)$'s new rank-bid must be $b_{j-1} * rank'(b_{j-1}) \geq b_x * rank(b_x)$. As the group-bid is the highest rank-bid, no matter what others' rank-bids become, it is easy to get $g(\mathbf{b}') \geq b_{j-1} * rank'(b_{j-1}) \geq b_x * rank(b_x) = g(\mathbf{b})$.

From (a) and (b) we can get that for all $b'_x > b_x$, $g(\mathbf{b}') \geq g(\mathbf{b})$ always stands.

***Theorem 4.1*:** No one can obtain more utilization if bidding untruthfully in LSAA. We consider if buyer x wins the spectrum band by truthful b_x, the result is w_x and its utilization is u_x. Otherwise, if the buyer cheats by b'_x, the result and utilization are w'_x and u'_x. If it fails, its utilization is zero. We only need to prove that $u'_x \leq u_x$ is always true. We consider this from four cases.

1. $w_x = 0, w'_x = 0$. In this case, the buyer always fails, so $u_i = 0, u'_i = 0$.

2. $w_x = 1, w'_x = 0$. In this case, it is obvious that $u_x > 0$, while $u'_x = 0$. Due to individual rationality, it never happens.

3. $w_x = 0, w'_x = 1$. In this case, according to *Lemma 1*, it happens only if $b'_x > b_x$. Since b_x is the truthful value of a channel, $u'_x = b_x - b'_x < 0$, while $u_x = 0$.

4. $w_x = 1, w'_x = 1$. In this case, if a bidder wins in an auction cycle, it has to pay as much as the highest losing group-bid. Since the others keep their bids unchanged, then we can get $u_x = u'_x$.

From the analysis above, since u_x is always no less than u'_x, the Rank-bid calculation is truthful. Therefore any buyer under the LSAA mechanism has no motivation to bid untruthfully. ■

4.6 Simulation Results

The *buyer satisfaction* is introduced to avoid auction monopoly or manipulation. Because one cheating base station could report a large coverage that overlaps many other base station. If the cheating buyer wins, it is not very fair for the other small companies, which also violate the spectrum sharing purpose. In some degree, the buyer satisfaction can reflect how the spectrum mechanism satisfy the buyers. The *buyer satisfaction* is defined as

$$\mathbb{B} = \frac{\sum a_i}{N} \tag{4.15}$$

which is the ratio of the number of winners to the number of the total buyers.

4.6.1 Performance Comparison

Fig. 4.7 shows the results of the comparison between TRUST, TAMES and LSAA when there are different numbers of bidders in an auction. Since the TAMES's

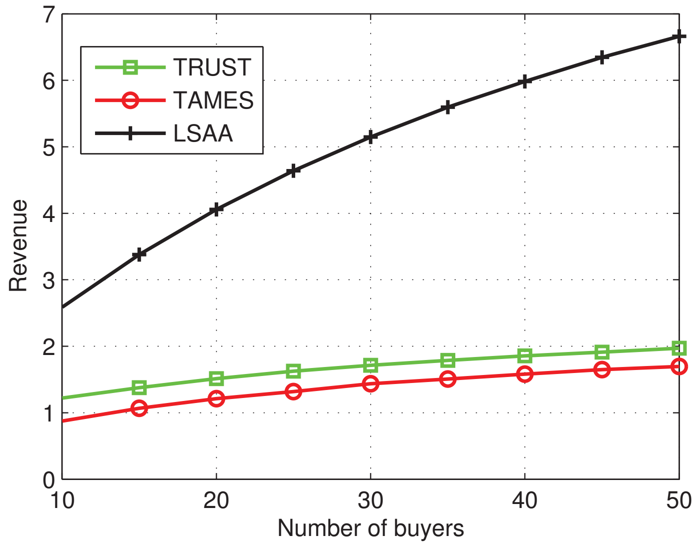


Figure 4.7: Incumbent revenue comparison between TRUST, TAMES and LSAA when the number of buyers varies between 10-50.

Table 4.1: Revenue in a weak interference network, interference range=0.1, (Revenue; Satisfaction).

	random	**degree**	**bid**
TRUST	1.444; 0.3740	1.451; 0.3730	1.533; 0.4904
TAMES	1.247; 0.4307	1.261; 0.4259	1.401; 0.5290
RANK	6.056; 0.3844	5.810; 0.3670	7.083; 0.4180

winner size is smaller, its revenue is lower than using TRUST and the performance of LSAA is much better than both of them. From the Fig. 4.8 we observe that as the number of buyers increases, buyer satisfaction gets lower. This is because more buyers make the auction competitive. LSAA also performs better in the aspect of buyer satisfaction than the other two approaches.

To further analyze the combination of different methods of independent set selection and group-bid calculation, we compare their performances in terms of revenue and satisfaction when there are 30 buyers. We compare three methods of group-bid calculation: TRUST, TAMES and our Rank, and three kinds of independent set selection: random, by degree and by bid. LSAA is the mechanism that combines the "bid" selection and "rank" calculation. From the Table 4.1 and Table 4.2 we can see that in both weak and heavy interference networks, LSAA performs better.

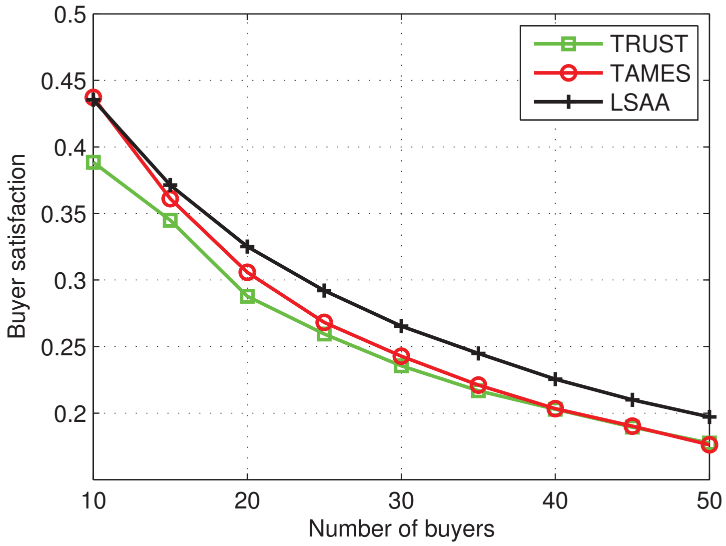


Figure 4.8: Buyer satisfaction comparison between TRUST, TAMES and LSAA when the number of buyers varies between 10-50.

Table 4.2: Revenue in a heavy interference network, interference range=0.5, (Revenue; Satisfaction).

	random	**degree**	**bid**
TRUST	1.615; 0.080	1.572; 0.070	2.114; 0.090
TAMES	0.952; 0.050	0.782; 0.040	1.309; 0.060
RANK	1.677; 0.075	1.557; 0.070	2.107; 0.088

4.6.2 Impact of the Sequence Order

We firstly demonstrate how the sequence order affects the fairness in the algorithm. In Fig. 4.9, the first column sub-figures $a1$, $b1$ and $c1$ are the means of number of channels allocated to each user and the second column sub-figures $a2$, $b2$ and $c2$ are their corresponding variances. The first row sub-figures show the simulation results of SWPA. Meanwhile, the second and third rows correspond to MWPA and EA respectively. In the first column the degree order seems to perform best under MWPA, SWPA and EA, but the variance is the biggest according to the second column. Even though the random order's variance is best in all of the four orders, it fails when compared with the average number of channels. From the overall performance, the topological sorted order perform better than the others.

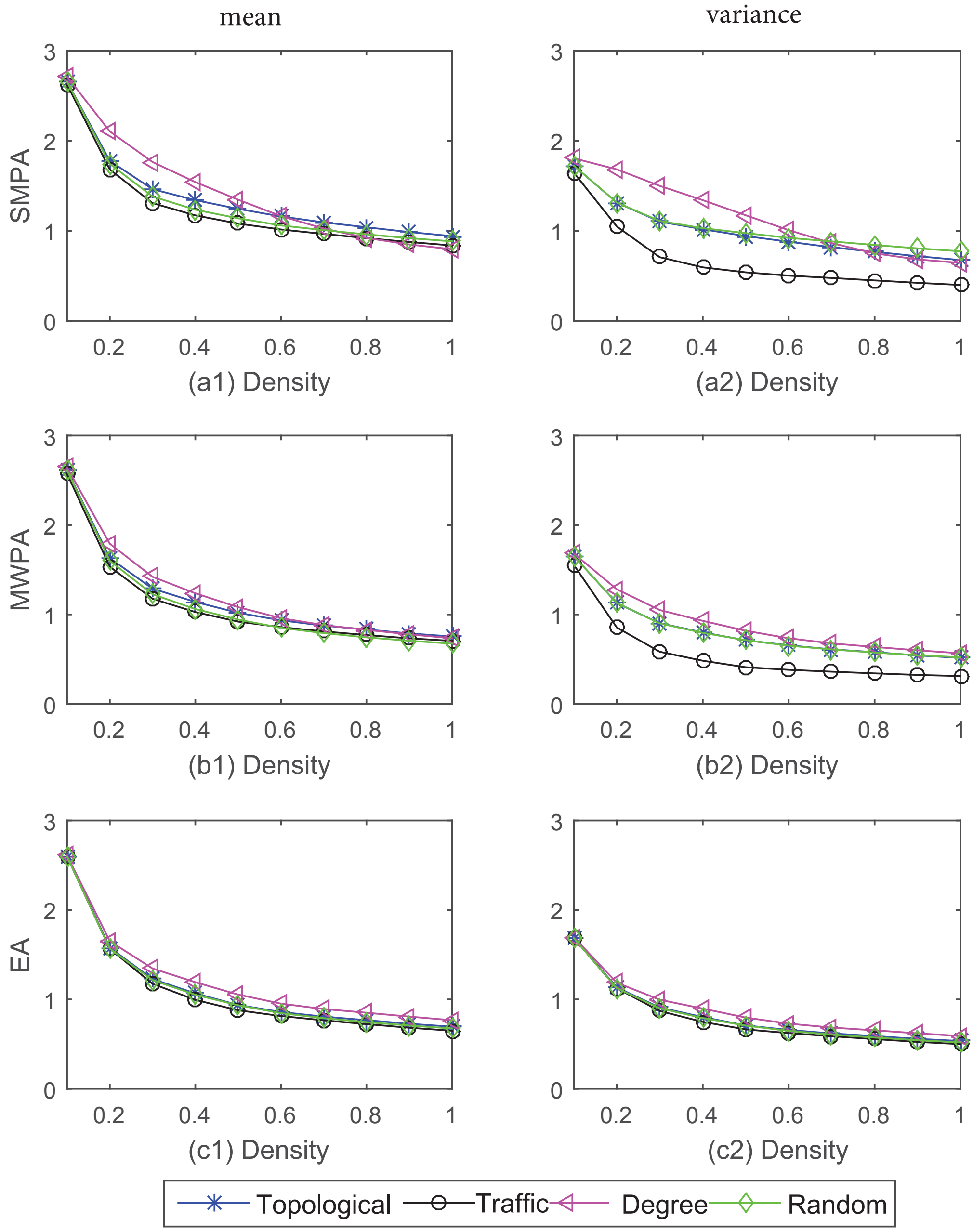


Figure 4.9: Mean and variance comparison of vertex sort by topological sort, traffic load, degree and random.

4.6.3 Impact of Bandwidth Allocation

Next we present how the bandwidth determination affects the spectrum allocation fairness. In Fig. 4.10, the first column is the average number of channels allocated to every user under different sequence orders, while the second column is their corresponding variances. Even though under the SWPA, the user can get a larger average number of channels in any sequence order, the variance is too high, which means not fair to all of the users in the network. For EA, it performs best in terms of variance but worst in terms of mean, while MWPA can balance both mean and variance.

Note that we only consider one seller in the LSAA mechanism and our target is to maximize the revenue of one spectrum block for multiple buyers. In the multi-seller-multi-buyer situation, LSAA could be repeatedly used until all sellers spectrum blocks are sold. LSAA could be further extended to the double auction. How to match the buyers and the sellers is a problem about how to maximize the social welfare, which is addition of sellers and buyers profits.

4.7 Summary

In this chapter, we present a fair and truthful auction mechanism for homogeneous base stations to operate within the LSA architecture. The establishment of LSA relies on Incumbents incentives to generate additional revenue as well as the urgency that wireless service providers want to offload their traffic. This proposal is to allocate Incumbents' idle spectrum to licensees for the purpose of commerce. It has been proved to guarantee that every licensee bids truthfully and the Incumbent can achieve a high revenue. We also give insights into spectrum allocation methods based on auction mechanisms to obtain high utilization for both Incumbents and Licensees. The proposed LSA Auction (LSAA) mechanism includes traditional auction techniques and new improvements, like vertex sorting and clustering by graph resolution and excluding lower bids. Our simulation results show that LSAA results in enhanced performance for Incumbent revenue and Licensee utilization, particularly in networks with heavy competition. We test the framework not only by comparing the average number of channels per user can get but also the variance to guarantee the fairness. In this framework, the scheme combining topological sort and maximum traffic load of base station contributes to keeping a better balance on the average number of channels and variance. Therefore, a fair spectrum sharing policy on the licensed band is more important among operators to break the

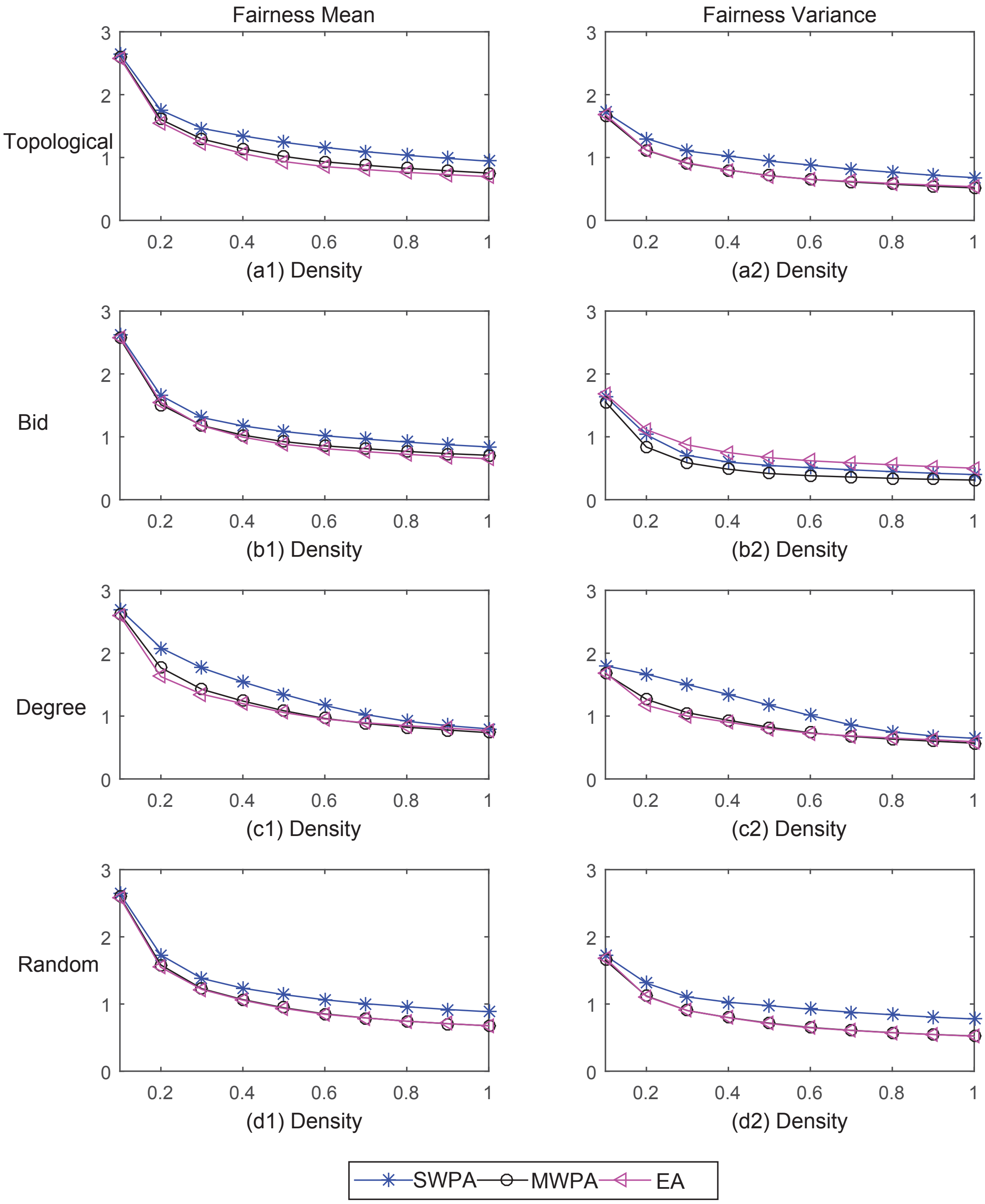


Figure 4.10: Mean and variance comparison of channel allocation principles, SWPA, MWPA and EA.

monopoly and inefficient spectrum allocation. Considering the spectrum can be spatially reused, an interference graph is adopted to avoid the interference between base stations of all the operators.

In the next chapter, considering the spatial efficiency of the heterogeneous base stations rather than the homogeneous ones, we enable them to customize their protection zones by submitting negotiable contours, hence make the auction mechanism more practical and further optimize the utilization of spectrum resources.

Chapter 5

Coverage Size Negotiable Auction for Spectrum Sharing

5.1 Introduction

To facilitate the interference coordination/negotiation at the auctioneer, a graph whose vertices represent bidders and edges represent interference between two vertices (i.e., can not co-exist) is often used (e.g., [58] [59] [61] [63] [67]). In such a graph, vertices/bidders of any independent set/group can simultaneously share the spectrum. However, the *undirected graph* which is used in all these existing works fails to model the interference among base stations who bid with a set of different coverage sizes. In fact, the mutual interference between any two bidders should be measured at multiple levels rather than only as a binary "yes" or "no" (using undirected graphs). To that end, we construct a *mixed graph* to facilitate the interference negotiation among bidders. We then prove that the winner determination problem in the formulated *multi-attribute auction* is in fact NP-hard. A heuristic winner and coverage range determination algorithm is then designed. Note that the most relevant prior work to ours is the joint power and channel allocation scheme in [109]. However, similar to all existing works, the authors in [109] failed to capture the interference among bidders with variable coverages but assumed a given conflict graph (for granted).

We incorporate the above into a spectrum sharing framework called **S**ize-**N**egotiable

Auction **M**echanism (SNAM). Taking the LSA architecture [19] [33] shown in Fig. 4.1 as a study case, spectrum allocation to all the base stations can be managed by a centralized calculator and then the result will be announced to all the base stations through the LSA Controller. In terms of the auction efficiency, coverage negotiation SNAM offers bidders a "second chance" to shrink their coverage areas to win a spectrum chunk. That helps to improve not only spectrum's spatial efficiency but also the seller revenue and the buyer satisfaction. Our major contributions in this chapter are as follows:

- We propose a novel economic tool, namely SNAM that exploits the unique feature of radio spectrum as a merchandise item: the bidder's ability to adjust its radio coverage. The tool allows the secondary bidders to simultaneously bid in an auction and negotiate their coverages for the spectrum chunks. Our negotiable auction mechanism is inspired by the empirical analysis and comparison of auction and negotiation in economics [68].

- To facilitate the negotiation of bidders in SNAM, we construct a mixed graph to better quantify the interference between spectrum licensees. To our best knowledge, this is the first effort to model the interference problem of spectrum auction using a mixed graph approach. Shrinking the coverage can improve the buyer satisfaction while not harming the seller revenue.

- SNAM is proved to be truthful and individually rational. Intensive simulations show that by better coordinating coverage regions of bidders, SNAM significantly improves the spectrum's spatial efficiency. That leads to dramatic improvement of the seller revenue and buyer satisfaction. The auction's truthfulness is achieved at the cost of the revenue. However, we design a novel grouping process that guarantees the truthfulness with a lower cost than [59] [61] [60].

- The winner determination and payment rule in SNAM relies on the bid per unit space and coverage area. This gives small bidder/firms who request small coverage areas a fair ground to compete with large bidders like Mobile Network Operators (MNOs).

The rest of the chapter is organized as follows. In Section 5.2, we present challenges in the spectrum sharing market, the problem formulation, and bid processing. In Section 5.3, we formally describe the details about SNAM. An example is illustrated in Section 5.4. The properties and complexity of SNAM are analyzed in Section 5.5. In Section 5.6, simulation results are shown and discussed. Conclusion is finally summarized in Section 5.7.

5.2 Preliminaries

5.2.1 Spatial Efficiency

Besides the economic properties, the spectrum auction should also consider the spatial efficiency. A conflict graph is often used to allocate spectrum, but the construction of a graph and the graph processing have significant influences on the allocation performance. An undirected graph fails to capture the heterogeneity in coverage sizes of spectrum bidders. Furthermore, the base stations can shrink/negotiate their coverage and to win in the auction ("gaining a smaller pie is better than losing everything"), thus improving the spectrum's spatial efficiency.

5.2.2 Problem Model

We consider a single-round sealed auction in which N base stations play as bidders who bid for a set of $\{1, 2, ..., M\}$ identical spectrum chunks from the auctioneer, i.e., spectrum sharing systems of LSA or SAS. Due to the privacy/security issue each buyer has no knowledge of the others, the auctioneer has to coordinate the interference between them. For that purpose, every base station should also report its geolocation. Let $(l_i, \boldsymbol{r}_i, b_i)$ denote bidder i's bid profile, where l_i is its location, $\boldsymbol{r}_i$ is the set of requested coverage ranges and b_i is the bid for each unit space (e.g., \$ per square meter).

SNAM is a single-round auction (saving overhead compared to multi-round auction), where buyers could customize the coverage sizes according to their preference, depending on how large an area they want to serve their customers, the RF planning of the area, and then adjust their bids and ranges in the next auction based on the business plan and other technical aspects. In its bidding profile, each base station registers K alternative coverage ranges, denoted as $\boldsymbol{r}_i = (r_{i1}, r_{i2}, \ldots, r_{iK})$. In existing works [9-23], K=1 and the interference status between any two bidders is modeled in a binary manner: "yes" (i.e., cannot simultaneously share a band) or "no" (i.e., can simultaneously share). To ease the exposition when K is large, we assume each bidder has two options for its requested coverages (i.e., K=2). Specifically, the owner of the base station can customize an alternative smaller interference-free range as a negotiable size if the original (large) coverage conflicts with others. Formally, $\boldsymbol{r}_i = \{r_{i1}, r_{i2}\}$, where $r_{i1} \geq r_{i2}$ and the ratio of these ranges is defined as

$$\theta_i = \frac{r_{i2}}{r_{i1}} \in (0, 1] \tag{5.1}$$

which captures the flexibility of bidders in negotiating their coverages. In two extreme conditions, when $\theta_i = 1$ (or $K = 1$), no bidder wants to negotiate its coverage, and when θ_i is close to 0 the bidder shrinks the range very much.

Note that in a region, the buyers could be uniformly or normally distributed/placed. A buyer does not have to bid for a large area when the buyers are concentrated in a small area. The requested coverage range set depends on the buyer's individual strategy and conditions. For the capacity, if additional spectrum chunks are made available, the base station's capacity can be nearly linearly expanded (w.r.t to spectrum bandwidth). Furthermore, the coverage area of a base station is determined via its transmit power which can be flexibly tuned with various power control mechanisms.

Let (m, γ_i, p_i) denote the determined result of bidder i, where p_i is the payment of spectrum chunk $m \in \{M\}$ and guarantee interference-free within range $\gamma_i \in \{0, r_{i1}, r_{i2}\}$. When $\gamma_i = 0$, bidder i loses with payment $p_i = 0$, and when $\gamma_i = r_{i1}$ bidder i can use the large coverage, while $\gamma_i = r_{i2}$, bidder i has to shrink its coverage range with a lower satisfaction, which is defined as

$$\eta_i = \left(\frac{\gamma_i}{r_{i1}}\right)^2 \in \{0, \theta_i^2, 1\} \tag{5.2}$$

After range determination the total bid of bidder i over the required area is

$$B_i = b_i \gamma_i^2 \pi \tag{5.3}$$

Assume that buyer i's true valuation of a spectrum chunk per unit space is v_i (e.g., \$ per square meter) that depends on its business efficacy and criticality of having the spectrum chunk (one may refer to [56] for the spectrum's value determination). Note that the true valuation v_i of bidder i, while using a winning spectrum chunk, is assessed on the bidder's *effective area/coverage* A_i. The effective coverage (private information) defines the maximum coverage over which a bidder can capitalize from using the spectrum chunk. Beyond this effective area, the valuation vanishes (i.e., $v_i = 0$) as additional coverage is neither profitable (e.g., deserts or jungles where no user/demand/traffic presents) nor possible (e.g., due to network planning or hardware/base-station or transmit-power regulation limit).

Then the buyer utility [59] [60] [61] is defined as the difference between the value capitalized by using a spectrum chunk and the buyer's payment. Let U_i denote buyer i's utility and it can be written as follows:

$$U_i(\boldsymbol{r}_i, b_i) = v_i \min(\gamma_i^2 \pi, A_i) - p_i \tag{5.4}$$

Let $\mathcal{M}$ denote the allocation mechanism, and we have

$$(m, \gamma_i, p_i) = \mathcal{M}(b_i, \boldsymbol{r}_i, l_i, b_{-i}, \boldsymbol{r_{-i}}, l_{-i}) \tag{5.5}$$

where $-i$ denotes all the bidders except bidder i. Spatially independent buyers will be further formed in groups under the mechanism $\mathcal{M}$. Each winning group will be allocated a spectrum chunk m out of the M available chunks (in Algorithm 3). Note that for the heterogeneous spectrum chunks, the auction could be realized by repeating a single auction or finding the optimal match between sellers and buyers [106]. Without loss of generality, SNAM mainly focuses on how to maximize the spectrum efficiency of one spectrum chunk. However, it still applies to heterogeneous spectrum chunks by dividing the heterogeneous spectrum chunks into identical smaller units.

In this chapter, the mechanism is evaluated from the following criteria:

1. *Individual rationality* [59] [60] [61]: under the allocation mechanism $\mathcal{M}$ the utility $U_i(b_i)$ of a bidder i should be non-negative, $U_i(b_i) \geq 0$.

2. *Truthfulness* [59] [60] [61]: any bidder cannot improve its utility by submitting a cheating bid, $U_i(v_i) \geq U_i(b_i)$.

3. *Spatial efficiency*: average total allocated area over each spectrum chunk. Note that this is what we originally introduce to measure the performance of a spectrum allocation algorithm in terms of the spatial coverage.

$$\mathbb{S} = \frac{\sum_{i=1}^{N} \gamma_i^2 \pi}{M} \tag{5.6}$$

4. *Buyer satisfaction*: [59] [61], is defined as the ratio of the number of winners to the total requesting buyers. It is used to measure how much a spectrum allocation mechanism can satisfy the buyers.

$$\mathbb{B} = \frac{\sum_{i=1}^{N} \eta_i}{N} \tag{5.7}$$

5. *Seller revenue* [59] [60] [61] [63] [106] [106]: is the capital gain of the spectrum owner for trading his/her spectrum, a concept used in both SAS and LSA.

$$\mathbb{R} = \sum_{i=1}^{N} p_i \tag{5.8}$$

We would like to emphasize that SNAM is derived from recently proposed spectrum sharing architectures by FCC and ETSI. The concept of coverage area in SNAM is inspired by the practical protection zone in LSA [19] and SAS [17], and used by SNAM to model the interference between base stations. Although the profit model is simple, it is sufficient for us to capture two facts. First, the utility function is the difference of the revenue and the cost of the spectrum over the granted coverage. Second, the revenue functions are non-decreasing w.r.t. spectrum and granted coverage area. In our work, to focus on the coverage negotiation (the major contribution of SNAM), we adopt that simple model from existing works in [59] [60].

The bid processing is similar to Fig. 4.3 in Chapter 4.

5.3 Detailed SNAM

5.3.1 Interference Levels

As aforementioned, unlike previous undirected graph based schemes [59] [61] [63] [60], the mixed graph in SNAM can quantify interference into five levels instead of two(“yes” or “no”). We model the coverage area as a circle and use the relative positions of the two circles to measure the interference conditions. By comparing the relationship between the sum of the radii and the distance between the centers of the circles, we can quantify the interference as one of five distinct levels, as shown in Table 5.1. For any two bidders i and j which are d_{ij} apart, their mutual interference is quantified from Level 1 to Level 5 using the below inequalities (5.9)-(5.13):

$$\text{Level 1:}\quad d_{ij} < r_{i2} + r_{j2} \tag{5.9}$$

$$\text{Level 2:}\quad r_{i2} + r_{j2} \leq d_{ij} < \min(r_{i1} + r_{j2}, r_{i2} + r_{j1}) \tag{5.10}$$

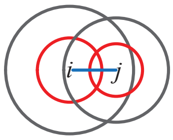
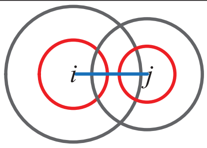
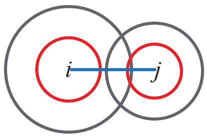
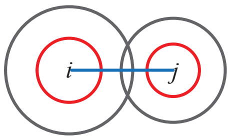
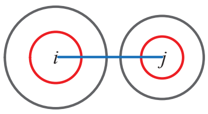
$$\text{Level 3:}\quad \min(r_{i1} + r_{j2}, r_{i2} + r_{j1}) \leq d_{ij} < \max(r_{i1} + r_{j2}, r_{i2} + r_{j1}) \tag{5.11}$$

$$\text{Level 4:}\quad \max(r_{i1} + r_{j2}, r_{i2} + r_{j1}) \leq d_{ij} < r_{i1} + r_{j1} \tag{5.12}$$

$$\text{Level 5:}\quad d_{ij} \geq r_{i1} + r_{j1} \tag{5.13}$$

From Level 1 to Level 5, the mutual interference decreases from extremely high to none. In Table 5.1, for Level 1, a plain line between the two nodes denotes that interference is so severe that even at their lowest transmit powers, both of them can not operate simultaneously. In Level 2, a double-headed arrow between the two nodes denotes that both of them have to make a concession if they want to win. If one node is pointed by a single-headed arrow, it has to make a concession, but the other one does not need to, as shown in Level 3. Two single-headed arrows denote that either of the base stations has to make a concession, as shown in Level 4. In this case, the winner is going to be further determined by comparing their overall area. In Level 5, if there is no edge between two nodes, it means that the two base stations can simultaneously share the same spectrum chunk using their large ranges.

Table 5.1: Five levels of interference.

Level #	Relative positions	Graph	Explanation
Level 1			Extremely High. Two BSs are too close to make any concession. $G_{ij} = 0, G_{ji} = 0$.
Level 2			Simultaneous concessions. BS i and j have to make concessions at the same time. $G_{ij} = -1, G_{ji} = -1$.
Level 3			Only one concession. BS i uses a small interference-free area while BS j uses a large one. $G_{ij} = -1, G_{ji} = 1$.
Level 4			Either concession. The one with higher degree has to make a concession. $G_{ij} = 1, G_{ji} = -1$; or $G_{ij} = -1, G_{ji} = 1$.
Level 5			No concessions. BS i and j are far away from each other. They can share the same spectrum. $G_{ij} = 1, G_{ji} = 1$.

Note that this distance-based interference model is only used for the purpose of constructing the mixed interference graph. In practice, our major contribution of the work is SNAM that can adopt any mixed interference graph as the input, regardless of which interference model is used.

5.3.2 Constructing a Mixed Graph

The auctioneer generates a mixed graph $\mathcal{G}$ by using the above definition of bidders' mutual interference levels. Every interference level corresponds to either a directed or an undirected edge. Each element G_{ij} in the adjacency matrix $\mathbf{G}$ adopts a value in $\{0, 1, -1\}$. Specifically, $G_{ii} = 1$ to capture the fact that a node adjacent to itself and does not interfere with itself by using a large range. Additionally, every node has three possible interference statuses to the others ($j \neq i$): $G_{ij} = 1$ denotes that base station i can use a large range relative to that of base station j; $G_{ij} = -1$

denotes that base station i should use a small one relative to that of base station j; $G_{ij} = 0$ denotes that base station i interferes to base station j seriously. Table 5.1 specifies how the auctioneer maps the five levels of mutual interference to the adjacency matrix $\mathbf{G}$.

Additionally, Level 4 still needs a further judgement, depending on their area summation. If

$$r_{i1}^2 + r_{j2}^2 \geq r_{i2}^2 + r_{j1}^2 \tag{5.14}$$

then bidder i will use the large area while bidder j uses the small area. Note that even when K is greater than 2, the key point is to maximize the overall coverages of the two buyers. The algorithm for mixed graph construction is described in Algorithm 2 and its complexity is stated as follows.

Theorem 5.1: For N bidders of which each submits K coverage ranges, the complexity of constructing their corresponding mixed interference graph is $O((KN)^2)$.

Proof: In Algorithm 2, it first needs to determine all possible interference levels between two bidders (the "switch" loop), resulting $O(K^2)$ complexity. There are two outer "for" loops that explore all bidders with complexity of $O(N(N-1)/2) = O(N^2)$. Hence, the combined complexity of the 3 loops to construct the mixed interference graph is $O((KN)^2)$. ■

This complexity grows quadratically w.r.t the number of the bidders N and the number of the requested coverage K. Hence its complexity is manageable.

5.3.3 Winner Determination

An ideal auction mechanism should simultaneously maximize the revenue and maintain its economic robustness. Assuming that the bidders are truthful in revealing their valuations of the spectrum, the spectrum allocation problem is to assign the spectrum to independent nodes so that the revenue is maximized while no two bidders mutually interfere with each other. We first show that finding the independent nodes to form groups is NP-hard.

Theorem 5.2: The spectrum allocation problem that maximizes the total revenue in (5.8) under interference constraints is NP-hard.

Algorithm 2 Construct a mixed graph

Require: Bid profiles of N bidders

Ensure: Interference Mixed Graph: the adjacency matrix $\mathbf{G}$

for i=1:N **do**
  $G_{ii} \leftarrow 1$
  for j=$(i+1)$:N **do**
    Check the interference *Level* between base station i and j by (5.9) - (5.13).
    Switch *Level*
    case 1: $G_{ij} \leftarrow 0, G_{ji} \leftarrow 0$
    case 2: $G_{ij} \leftarrow -1, G_{ji} \leftarrow -1$
    case 3: $G_{ij} \leftarrow$1,$G_{ji} \leftarrow$-1 or $G_{ij} \leftarrow$-1,$G_{ji} \leftarrow 1$
    case 4: $G_{ij} \leftarrow \mp 1, G_{ji} \leftarrow \pm 1$ determined by (5.14)
    case 5: $G_{ij} \leftarrow 1, G_{ji} \leftarrow 1$
  end for
end for
return G

Proof: We assume that the above spectrum allocation problem is not NP-hard. Hence, for the special case $\theta = 1$ in which the mixed graph that we constructed becomes an undirected graph, there exists a polynomial time solution to maximum weighted independent set of the undirected graph [110]. That contradicts the fact that maximum weighted independent set is an NP-hard problem [111]. ■

Not only does the NP-hardness of the spectrum allocation problem make the winner determination challenging but also the strategic actions of the bidders who may not be truthful in revealing their valuations. However, to achieve the revenue maximization and truthfulness simultaneously is impossible, because to guarantee the truthfulness the pricing should be independent of its own bid but based on the harm they cause to other bidders [112] [113]. For example, in the second price auction, the highest bidder pays as much as the second highest bid, and the difference between the highest bid and second highest bid is the loss to guarantee the truthfulness. In the following, we propose a winner determination mechanism that aims

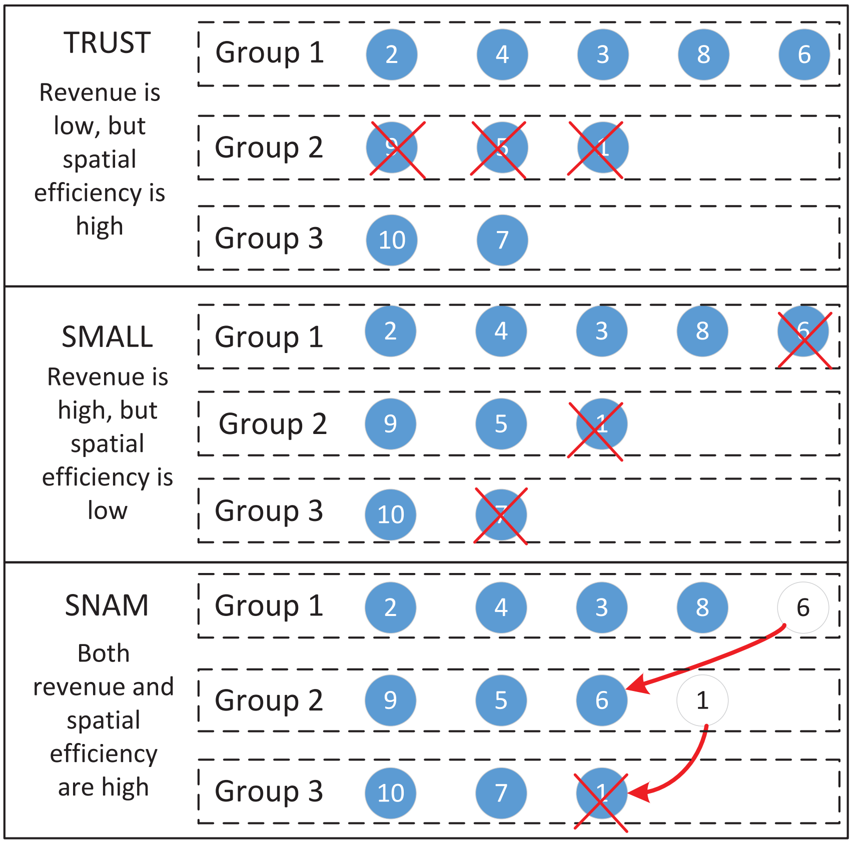


Figure 5.1: In TRUST, winners pay as the second highest group bid, the revenue loss is the difference between the 1st and 2nd highest group bid. In SMALL, winners equally share the group bid, but the minimum bid in the group will be sacrificed and the nodes' space is wasted. In SNAM, in every iteration the minimum bid is not sacrificed but *moved* into next iteration.

to find a better trade-off between revenue maximization and auction truthfulness.

Unlike conventional merchandise, spectrum can be reused simultaneously by a group of bidders who do not interfere with each other. Such a group of bidders corresponds to a group of vertices of which any two nodes x_i, $x_j \in \mathcal{V}$ have no edge between them. Each group will be treated as a super bidder in the following spectrum allocation; then the immediate questions are (i) how to group these nodes, (ii) how to determine the group bid, and (iii) how much to charge each member in a group. Notationally, the nodes are grouped as $\Omega_1, \Omega_2, \ldots, \Omega_L$, and let Ω_l^B denote the group bid of group l.

To facilitate the truthfulness of bidders in an auction, the winning buyer's payment should be made independently from its bids [114]. Therefore, we abandon the minimum bidder (the dependent bidder), also known as benchmark node. Now all

Figure 5.2: The bidder i's range will be forced to shrink.

the ones left have to make a payment that depends on the benchmark node but not on their own bids. However, we observe that either abandoning the minimum bidders in all the groups e.g., [60] or abandoning the entire group with the lowest group bid e.g., [59] would cause a large loss in both revenue and spectrum's spatial efficiency. Hence, instead of removing them completely, we "recycle" the benchmark nodes by putting the loss into each iteration, and then put the minimum ones to the next iteration. Finally, only one bidder is sacrificed, as shown in Fig. 5.1. This is also the key novelty of the chapter and main contribution to improve the system performance. The following are three steps to iteratively form groups and the algorithm is shown in Algorithm 3.

Step 1: Dropping seriously interfering bidders.

First of all, to make sure all the bidders in a group can coexist, the node that $G_{ij} = 0$ should be dropped iteratively. Those bidders who seriously interfere (in Level 1) to the others are dropped from the mixed graph and the higher degree will be dropped first. For example, if an edge $G_{ij} = (x_i, x_j)$ is 0, and bidder i's degree $deg(x_i)$ is higher than bidder j's $deg(x_j)$, bidder i is dropped. This is because a bidder with higher degree interferes to more neighboring bidders. Those dropped nodes will be put forward to the next iteration.

Step 2: Interference-free area judgment.

After above processing, it is possible that bidder i can use a large range to bidder j but has to use a small range to base station k, namely $G_{ij} = 1, G_{ik} = -1$. Consider the overall friendly sharing environment, one has to adopt the small range to all the neighboring bidders. For example, in Fig. 5.2, G_{ij} is forced to be -1. Therefore the determined range of bidder i is $\gamma_i = r_{i2}$, if $\exists j$, $G_{ij} = -1$; and otherwise, $\gamma_i = r_{i1}$, if and only if $\forall j$, $G_{ij} = 1$.

Step 3: Group bid calculation.

Since the ranges of bidders are determined, then the total bid of bidders in the group is easy to get. If there are n nodes in a group $\hat{\Omega}_l$ and let $\{B_1^l, B_2^l, \ldots, B_n^l\}$ denote their

Algorithm 3 Winner Determination

Require: Adjacency matrix $\mathbf{G}$, number of available spectrum chunks M and bids $\{b_i\}$

Ensure: Groups$\{\Omega_l\}$, payments$\{p_i\}$, determined ranges$\{\gamma_i\}$

$l = 0$
while $0 \in \mathbf{G}$ or $|\mathbf{G}| > 1$ **do**
  $\mathbf{G}' \leftarrow \mathbf{G}$
  $l \leftarrow l + 1$
  while $0 \in \mathbf{G}'$ **do**
    delete the higher degree node from $\mathbf{G}'$
  end while
  for $i = 1 : |\mathbf{G}'|$ **do**
    if $\exists j$ with $G'_{ij} = -1$ **then**
      $\gamma_i \leftarrow r_{i2}$
    else if only if $\forall j, G'_{ij} = 1$
      $\gamma_i \leftarrow r_{i1}$
    end if
  end for
  put the remaining nodes in group $\hat{\Omega}_l$
  find out the minimum bid in group $\hat{\Omega}_l$: $B^l_\alpha \leftarrow \min(B^l_1, B^l_2, \ldots, B^l_n)$ (using (5.3))
  abandon the minimum bid in group: $\Omega_l \leftarrow \hat{\Omega}_l \backslash \alpha$
  calculate the bid of group l: $\Omega^B_l = |\Omega_l| B^l_\alpha$
  remove Ω_l from $\mathbf{G}$
end while
pick up the M highest group-bid (Ω^B_l) groups as winning groups and allocate each group with one spectrum chunk m
the bidders in the same winning group Ω_l will equally share the group bid Ω^B_l, as much as $p_i \leftarrow B^l_\alpha$
set the losers' payment $p_i = 0$, $\gamma_i = 0$
return $\{\Omega_l\}$, $\{p_i\}$, $\{\gamma_i\}$, m

total bids, and minimum total bid in the group is $B_\alpha^l = \min(B_1^l, B_2^l, \ldots, B_n^l)$. All the nodes are independent and can coexist and the minimum bidder will be treated as the benchmark B_α^l but will be abandoned. The remaining nodes automatically form a group $\Omega_l = \hat{\Omega}_l \backslash \alpha$, and the group bid is:

$$\Omega_l^B = |\Omega_l| B_\alpha^l \tag{5.15}$$

where $|\Omega_l|$ is the size (number of nodes) of the group. All the nodes that are abandoned (in Step 1 and 3) will be moved into the next iteration of the group formation. The next group will be formed by repeating Step 1, 2, and 3. The grouping process continues until only one node is left.

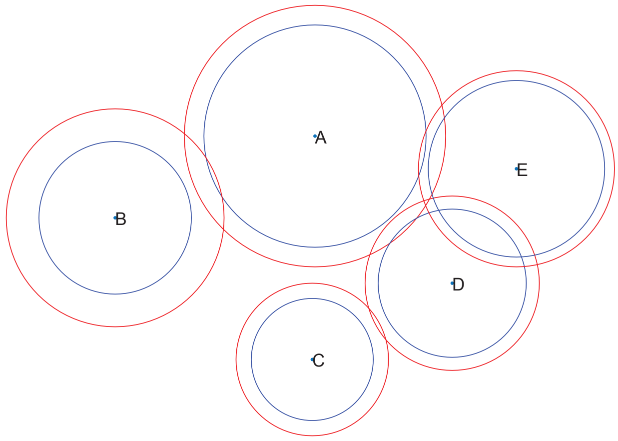
Step 4: Final winner determination.
After all the nodes are formed into groups $\Omega_1, \Omega_2, \ldots, \Omega_L$, the M highest groups win and each member in the same group will equally share their own group bids. Specifically, for buyer i in a winning group Ω_l, its payment p_i is given as:

$$p_i = \Omega_l^B / |\Omega_l| = B_\alpha^l. \tag{5.16}$$

Note that if $M > L$, then bidders who are in need of additional spectrum can join another auction for the rest of $M - L$ spectrum chunks. Moreover, auctioning with heterogeneous spectrum is considered in the literature [106]. In fact, SNAM can also accommodate the case of heterogeneous spectrum chunks. Multi-radio buyer can be seen as two who have the same requirements with the same valuations for the radio. Additionally, although SNAM is a single-round auction with multiple (M) identical spectrum chunks, it can also accommodate the case of heterogeneous spectrum chunks. In such a case, we can simply set the number of available chunks $M = 1$ (i.e., trading with one chunk at a time). The following chunks are then traded in the next auctions.

5.4 An Example

In this section we provide a simple example to demonstrate SNAM. Assume that one seller registers an available spectrum chunk in the geolocation database in a



(a) Five base stations' requirements for license areas.

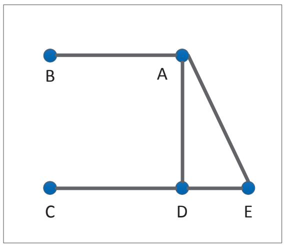
	A	B	C	D	E
bid/unit	0.8	0.5	0.7	0.8	0.9
r_1	12	10	7	8	9
r_2	10.2	7	5.6	6.8	8.1
ratio	0.85	0.7	0.8	0.85	0.9
B_i, $\gamma=r_1$	361.73	157	107.7	160.77	228.91
B_i, $\gamma=r_2$	261.35	76.93	68.93	116.15	185.41

(b) Bid profiles of five base stations

Figure 5.3: A simple example

region, where there are five buyers $\{A, B, C, D, E\}$ with bids and negotiable ranges listed in Fig. 5.3. In this example, we compare the significant differences between SNAM and the undirected graph based approaches TRUST [59] and SMALL [60].

In Fig. 5.4, we present how these five nodes are formed in groups under TRUST and SMALL. The conflict graph in Fig. 5.4(a) is modeled as all the base stations using large ranges. Under TRUST, the group bid is defined as the lowest bid multiplied by the group size, $|\Omega_l| \min(\Omega_l)$. TRUST's payment rule is that the winning groups will pay as much as the highest losing group. For instance, the winning group is {B D} in this example, and they altogether pay 228.91 as much as group {E}. Since there are two winners out of five bidders, the buyer satisfaction under TRUST is 40%. On the other hand, SMALL's group bid is defined as the lowest bid multiplied by the group size minus one, $(|\Omega_l| - 1) \min(\Omega_l)$, and the payment rule is that winners will equally share the group bid. The revenue, spatial efficiency and buyer satisfaction are given is Fig. 5.8.



(a) Undirected graph.

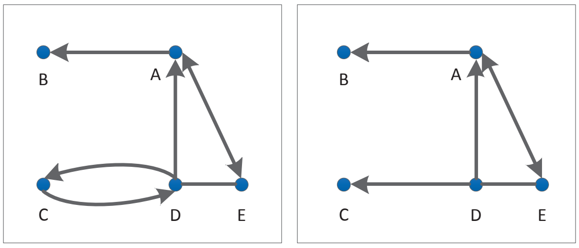
TRUST			
Group	Min bid	Group bid	Winner(s)
AC	107.7	215.40	
BD	157	314	BD
E	228.91	228.91	

(b) Allocation result under TRUST

SMALL			
Group	Min bid	Group bid	Winner(s)
AC	107.70	107.70	
BD	157	157	D
E	228.91	0	

(c) Allocation result under SMALL

Figure 5.4: Allocation results of the approaches based on undirected graph.



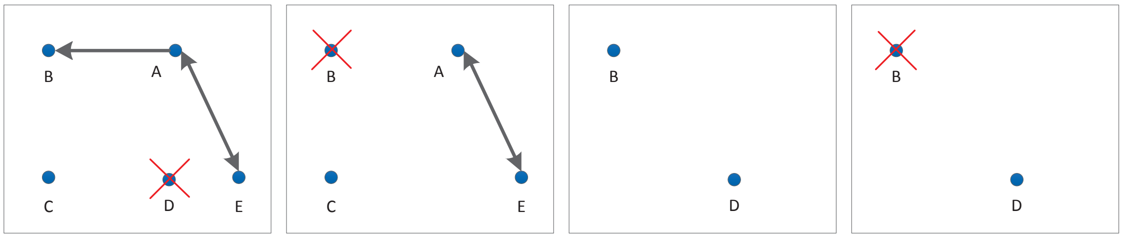
(a) (b)

$$\mathbf{G}= \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \end{array} \begin{array}{c} \begin{array}{ccccc} A & B & C & D & E \end{array} \\ \begin{bmatrix} 1 & 1 & 1 & -1 & -1 \\ -1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 0 \\ -1 & 1 & 1 & 0 & 1 \end{bmatrix} \end{array}$$

(c)

Figure 5.5: Construction of a mixed graph. The pointed nodes needs to shrink while the pointing nodes can use large range. (a) the edge between any two nodes can be constructed as Table 5.1; (b) For nodes C and D in Level 4, a further decision is needed by (5.14); (c) adjacency matrix $\boldsymbol{G}$.

SNAM lets each base station have a different negotiable range ratio as shown in row “ratio” in Fig.5.3(b). Fig. 5.5 shows the mixed graph and its adjacency matrix for the bidders. The initial mixed graph is shown as Fig. 5.5 (a), then for node C and D, according to the further determination of the Interference Level 4 in (5.14), the mixed graph turns into Fig. 5.5(b), because of $r_{C1}^2 + r_{D2}^2 < r_{C2}^2 + r_{D1}^2$ node C uses small range. Fig. 5.6 provides the SNAM's grouping process, Fig. 5.7 lists the calculation of group bid, and Fig. 5.8 visually shows the comparison of the allocation results. The pink circle is the benchmark node, green circles are winners, and particularly, dark green circles are shrinking areas.



(a) (b) (c) (d)

Figure 5.6: Group formation: (a) Group 1: Dropping seriously interfering and high degree bidder D; (b) Group 1: Benchmark node B is sacrificed; (c) Group 2: The dropped node D and benchmark node B are moved into a second iteration. (d) Group 2: The last benchmark node B is sacrificed.

Buyer	b_i	γ_i	B_i
A	0.8	10.2	261.3
B	0.5	7.0	76.9
C	0.7	7.0	107.7
E	0.9	8.1	185.4

(a)

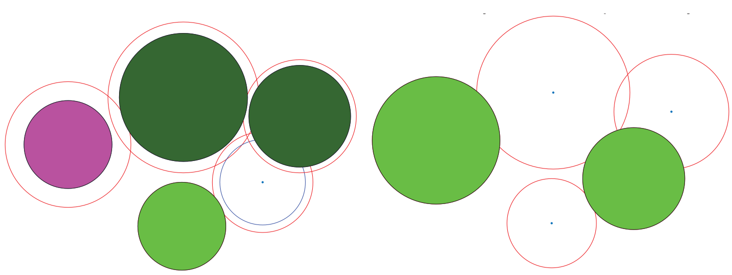
Buyer	b_i	γ_i	B_i
B	0.5	10.0	157.0
D	0.8	8.0	160.8

(b)

Figure 5.7: Group bid calculation: (a) Group 1: $\{A, C, E\}$ form a group, and the group bid $\Omega_1^B = 76.9 * 3 = 230.7$; (b) Group 2: $\{D\}$ itself forms a group. The last node B is sacrificed, and the group bid is $\Omega_2^B = 157 * 1 = 157$. Therefore, the winning group is group 1: $\{A, C, E\}$.

	SNAM	TRUST	SMALL
Spatial Efficiency	0.27	0.21	0.08
Buyer Satisfaction	51%	40%	20%
Seller Revenue	230.79	228.91	157

(a)



(b) (c)

Figure 5.8: Comparison of allocation results of SNAM and undirected graph based approaches. (a) Performance comparison; (b) Allocation result under SNAM; (c) Allocation result under undirected graph based approach.

5.5 SNAM Properties

5.5.1 Individual Rationality

Theorem 5.3: SNAM is individually rational, i.e. $U_i \geq 0$.

Proof: We have two cases: (a) If bidder i is a winner, its payment is p_i and is equal to the benchmark payment B_α^l that is the minimum bid in group Ω_l, i.e., $B_i > B_\alpha^l$. Recalling the utility function (5.4) we have:

$$\begin{aligned} U_i &= v_i \min(\gamma_i^2 \pi, A_i) - B_\alpha^l \\ &= v_i \gamma_i^2 \pi - B_\alpha^l \\ &= B_i - B_\alpha^l > 0 \end{aligned} \tag{5.17}$$

(b) If bidder i is a loser, it is obvious that $U_i = 0$.

Therefore, SNAM is individually rational. ■

5.5.2 Truthfulness

In the bid profile $(l_i, \boldsymbol{r}_i, b_i)$ of bidder i, the bidder may manipulate its bid per unit space b_i, its location, or its requested range of coverages to maximize its utility (defined in (5.4)). In the sequel, we prove that SNAM provides a truthful auctioning mechanism in which buyers have no incentive or are unable to cheat on the above information.

Theorem 5.4: SNAM is truthful for all the bidders.

Proof: We first show that buyers should be truthful in its coverage range. Note that each bidder has its own choice to set its requested ranges, depending on the area over which it can capitalize from using the spectrum (defined above as the effective coverage area) as well as its own justification of the risk of being rejected due to a large coverage request. Hence, all requested ranges that are within the effective coverage area are considered truthful and part of the bidder's strategy. However, the buyers may still cheat on the requested coverage range in two cases:

Case 1: A buyer requests a small coverage to win the spectrum then uses the spectrum over a larger coverage. Under both LSA and SAS, regulations and spectrum enforcement mechanism are assumed to be in place to enforce bidders to abide by its requested coverages (e.g., using the environment sensing capability ESC in SAS [1], [115]). Interested readers are also referred to [116] [117] for similar spectrum monitoring approaches. Hence, a bidder cannot manipulate its geolocation or use the winning spectrum outside its granted range γ_i.

Case 2: A buyer i inflates its requested ranges $\boldsymbol{r}'_i = \{r'_{i1}, r'_{i2}\}$ beyond its effective coverage area, i.e., ${r'}^2_{i1}\pi \geq {r'}^2_{i2}\pi > A_i$. If the buyer wins the auction either with r'_{i1} or r'_{i2} coverage, from the utility function in (5.4), we have:

$$U'_i(\boldsymbol{r}'_i, b_i) = v_i A_i - p_i \tag{5.18}$$

However, by bidding truthfully (i.e., within the effective coverage area) with requested ranges $\boldsymbol{r}_i = \{r_{i1}, r_{i2}\}$ where $r_{i1} = r_{i2} = \sqrt{A_i/\pi}$, the buyer can attain the same utility as above $U_i = U'_i$ *with a larger likelihood*. This is because the range/coverage inflation leads to higher risk of interfering with others, hence increasing the risk of being removed in Step 1. On the other hand, if the buyer loses the auction with the requested range $\boldsymbol{r}'_i$ we have: $U'_i = 0$ or $U_i \geq U'_i$ (due to the individual rationality property). Hence, regardless of losing or winning the auction, inflating the coverage requests beyond the effective coverage area results in inferior utility, compared with a truthful coverage bid.

Next, we prove that for all strategic bidders in SNAM, their best strategy is to reveal their true type of spectrum valuation v_i. To that end, we first have the following lemmas.

Lemma 5.1: If a bidder wins a spectrum chunk, the bidder's granted range γ_i is independent of its own bid b_i.

Proof of Lemma 5.1: For any winner in a group, its granted coverage range is adjusted in Step 1 and Step 2 of the grouping process. In Step 1 and Step 2, when there is a conflict between requested coverages, the bidders' coverages are adjusted for the coexistence with more neighbors. This criterion is only related to the bidders' locations and their requested coverage but not their bids. ■

Lemma 5.2: For any winner i, its utility is a step function of its bid b_i (or B_i) (as shown in Fig. 5.9).

Proof of Lemma 5.2: For any winner i in the winning group Ω_l, its utility

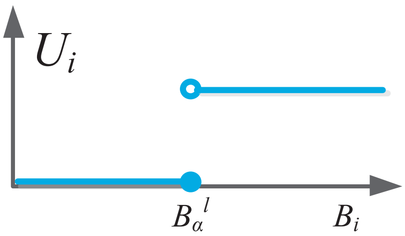


Figure 5.9: The remaining bidder i's utility is a step function of its bid b_i.

$U_i = v_i \min(\gamma_i^2\pi, A_i) - p_i$ depends on its payment $p_i = B_\alpha^l$ and granted range γ_i. If bidder i is retained, then the benchmark payment is B_α^l. After a set of nodes are formed in a group, their ranges are determined and fixed. When bidder i increases its bid b_i, even though the bidder i's total bid B_i increases, its payment (set by the benchmark bidder) does not change. On the other hand, if bidder i decreases its bid which is lower than the benchmark, then it will be the benchmark and be dropped and put forward to the next iteration. The grouping process in Step 3 continues. At the last iteration, if the bidder wins, its payment is then again independent of its bid (set by the benchmark bidder in this iteration/group); if not, its payment is 0. ■

Now, let's assume that if buyer i bids truthfully by $b_i = v_i$ its utility is U_i with granted coverage γ_i and payment p_i. If it cheats by bidding $b_i' \neq v_i$, its utility is U_i' with granted coverage γ_i' and payment p_i'. We have four cases:

(a) $|\gamma_i| = 0, |\gamma_i'| = 0$: In this case, bidder i loses regardless of cheating or not, and $U_i = U_i' = 0$, and there is no motivation for buyer i to cheat.

(b) $|\gamma_i| = 0, |\gamma_i'| > 0$: We first have $U_i = 0$. According to steps 1, 2, 3 in the winner determination process, a bidder can only become a winner (from a loser) by increasing its bid, i.e. $B_i' > B_i$ *and* if and only if the bidder happens to be a benchmark (with truthful bid), i.e., $B_i = B_\alpha$ (see *Lemma 5.2*). By reporting a bid b_i', the new benchmark will be the second lowest bid B_{-2} (in the case with truthful bid) that is greater than B_i. The bidder i with its bid b_i' needs to pay $p_i' = B_{-2} > B_i$. We have:

$$U_i' = v_i \min(\gamma_i'^2\pi, A_i) - B_{-2} \tag{5.19}$$

Recalling *Lemma 5.1*, to win with bid b_i', the granted range/coverage is determined independently of their bids, i.e., the granted coverage γ_i' would be the same as that if the bidder wins by bidding with b_i. Hence, we have:

$$B_i = v_i {\gamma'}_i^2 \pi \geq v_i \min({\gamma'}_i^2 \pi, A_i) \tag{5.20}$$

From (5.19), (5.20), and $B_{-2} > B_i$, we have $U_i' < 0$ which is smaller than $U_i = 0$.

(c) $|\gamma_i| > 0$ and $|{\gamma'}_i| > 0$: In this case, the cheating bid does not change the granted coverage (see *Lemma 5.1*) and the benchmark payment B_α stays the same, so does the payment $p_i' = p_i = B_\alpha$. Then we have $U_i' = U_i$.

(d) $|\gamma_i| > 0$ and $|{\gamma'}_i| = 0$: It is obvious that in this case $U_i > 0$ and $U_i' = 0$, the bidder prefers to bid truthfully.

From the above analysis, $U_i \geq U_i'$ always stands, so cheating can not make the bidder obtain more utility. ■

5.5.3 Group Formation

Theorem 5.5: Along with the group formation process, (1) group size and (2) group bid become smaller statistically.

Proof: (1) With the group formation running, the number of remaining nodes becomes less after each iteration, therefore the group size is no larger than the previous group statistically.

(2) The bids are uniformly distributed, so the expectations of bids are the same. In addition, the group bid is defined as group size multiplied by the minimum bid in equation (5.15). Therefore, if the expectations of minimum bids in every group are the same, then the group bid is mainly contributed by the group size. So the group bid of a smaller group is lower. ■

This is illustrated in Fig. 5.13 in Section 5.6.3.

5.5.4 Complexity Analysis

Theorem 5.6: For N bidders, and K levels of coverage, the complexity of SNAM is $O((K^2 + N^2)N^2)$.

Proof: SNAM consists of Algorithm 2 and Algorithm 3. According to *Theorem 5.1*, the complexity of constructing a mixed interference graph is $O((KN)^2)$. Algorithm 3 first aims at finding the auction winners with three loops (two *while*s and one *for*) whose combined complexity is bounded by $O(N^2(N^2+N^2))$. Therefore, the overall time complexity of SNAM is bounded with $O((K^2+N^2)N^2)$. ■

Note that $O((K^2+N^2)N^2)$ is a polynomial w.r.t. the network size N and the number of requested ranges K. SNAM is hence scalable with N and K. Additionally, SNAM is a single-sided auction. The whole process includes the bid submitting and winner determination with the complexity of $O((K^2+N^2)N^2)$ could be completed or calculated out in time scale of a second or less. Hence, a time constraint may not be necessary in practice.

5.6 Simulation and Discussion

In this section, we evaluate the performance of SNAM through simulation and compare it to the undirected graph based approaches [59] [60].

5.6.1 Simulation Setup

The simulation setting of this chapter is similar to those in [59] [61] [60]. We consider a certain region where heterogeneous base stations (in terms of bid and range) uniformly (buyers are uniformly placed) or normally (most buyers are placed at the centre of a region and less buyers are at the edge) scatter in the normalized area of 1x1. Buyer's range is randomly distributed in [0.07,0.14]=$[0.1/\sqrt{2}, 0.1\sqrt{2}]$, and the bid/valuation of the spectrum is randomly distributed in [b_0,1]. Here, b_0 is a variable and reflects the dynamic range of bid, and b_0 is studied in subsection 5.6.5. To mitigate the impact of randomness, we run SNAM for 10000 times in MATLAB to evaluate its performance.

5.6.2 Comparison to the Existing Works

At first, one visual allocation result is shown in Fig. 5.10, and the number of base stations is N=50. The pink circle denotes the deleted benchmark node for truthfulness guarantee; and the light green circles denote the nodes without any concession, and the dark green circle denotes the shrinking area. It is obvious that the overall allocated area under SNAM is larger than that under the undirected graph auction. So SNAM can improve spatial efficiency because of the concession mechanism. Besides the spatial efficiency, making a concession also allows more base stations to access extra shared spectrum, which means a higher revenue and buyer satisfaction.

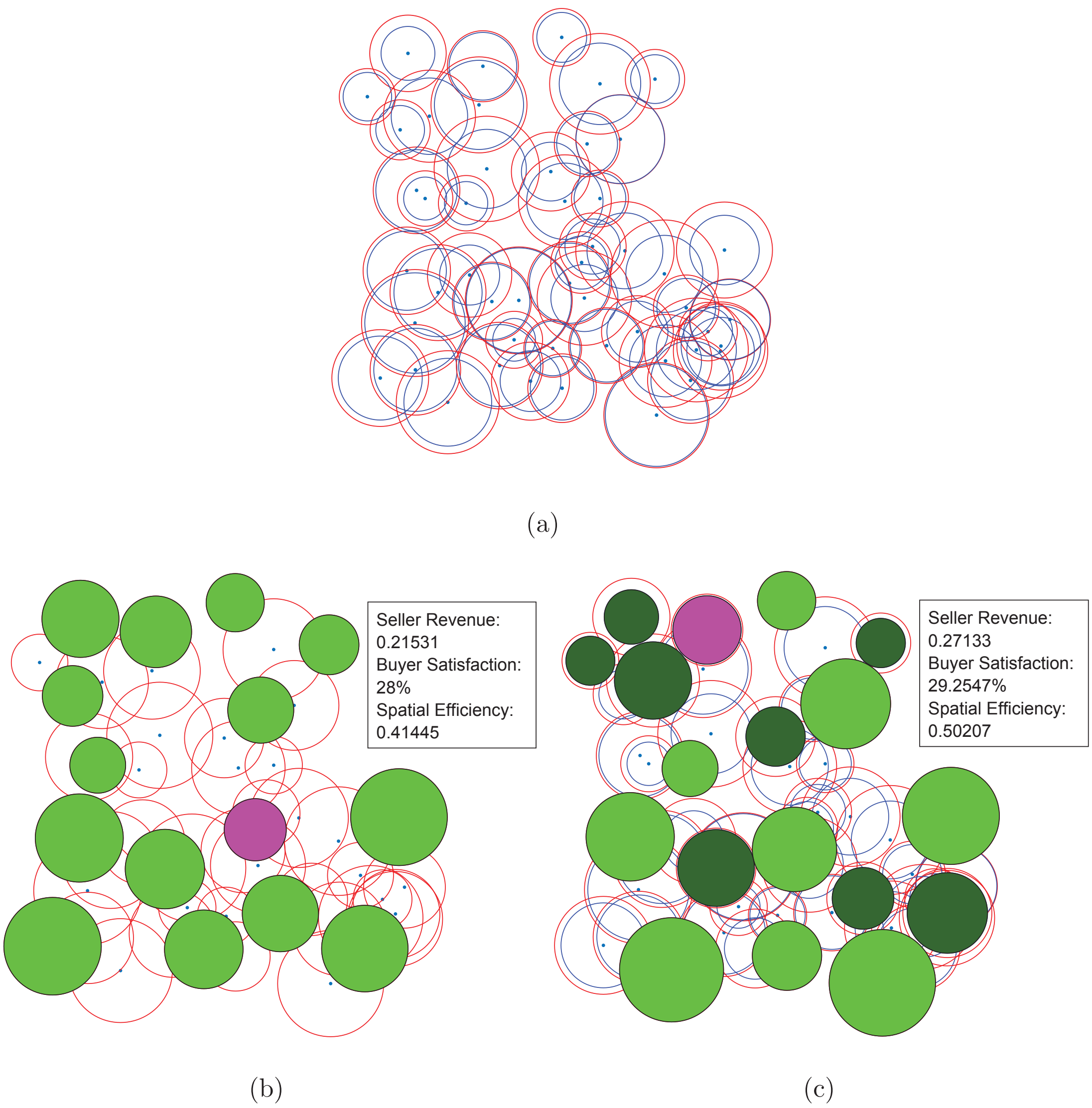


Figure 5.10: A visual allocation result comparison. (a) Coverage requirements: each base station has two options of interference-free ranges; (b) allocation result based on SMALL [60]: the pink circle is the sacrificed node; (c) SNAM' allocation result: the light green nodes are the winners that can use large ranges, and the dark green nodes are the winners that can use small ranges.

We then compare SNAM with the Pure Allocation (PA) algorithm. Due to its

NP-hardness, we run PA on scenarios with a decent number of bidders 10, 15, and 20 so that the exhaustive search method can be affordable. Note that although PA can provide the highest revenue, it is extremely time-consuming and generally not affordable for a large number of bidders. As can be seen in Fig. 5.11, SNAM can achieve more than 87% revenue of PA. Moreover, SNAM yields slightly higher buyer satisfaction over PA. It is worth noting that under SNAM the spectrum's spatial efficiency is dramatically improved, compared with PA. This is thanks to the negotiations of bidders in adjusting their coverages, thus improving the spatial efficiency and accommodating more buyers. The advantage of the ability to shrink coverage is more obvious in a heavily congested network.

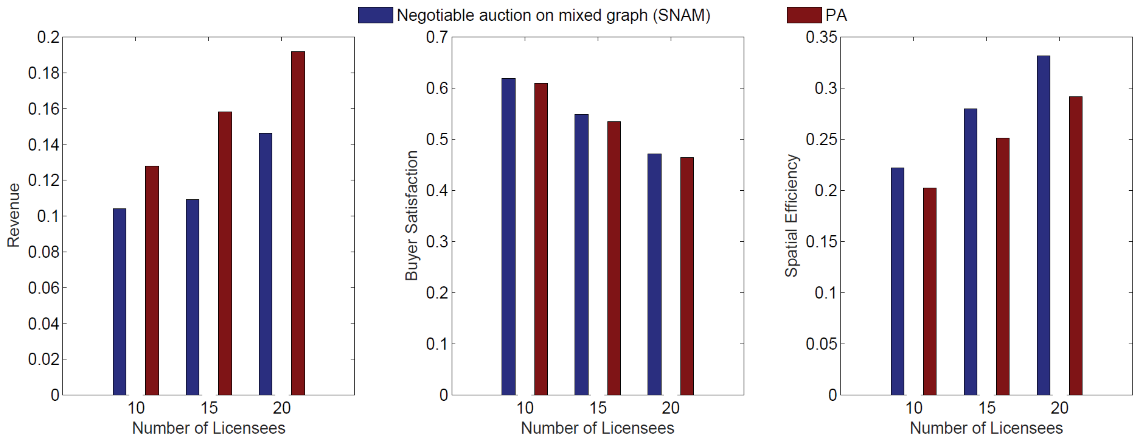


Figure 5.11: Comparison of SNAM's performance with PA.

We also compare SNAM to the existing work TRUST [59] and SMALL [60]. We let all the bidders randomly set their range ratio between $[\theta_0, 1]$, and for the SMALL and TRUST the ratio is always 1. θ_0 is the lower bound of coverage ratio as equation (5.1) and reflects the dynamic range. When θ_0 varies from 0.1 to 1, the comparisons are shown in Fig. 5.12. Setting the shrinking ratio too small is neither practical nor beneficial. When the ratio is set greater than 0.8, SNAM performs better than SMALL and TRUST in terms of spatial efficiency, buyer satisfaction and seller revenue. This is because if the ratio is small, the total bid of a bidder is also small and it will always be treated as the benchmark and be abandoned in the group formation iteration.

Note that the loss of the revenue is related to the payment rule. Everyone's payment depends on the benchmark of the group, therefore, the difference between their total bid B_i and benchmark bid B^l_α is the revenue loss.

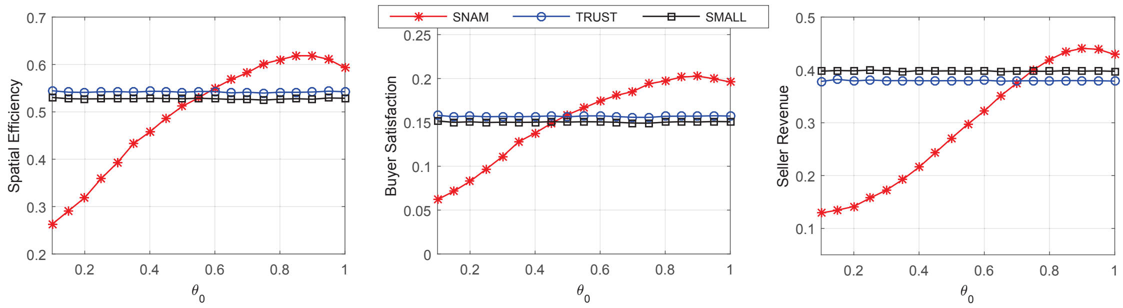


Figure 5.12: When the ratio is set from $[\theta_0,1]$, SNAM performs best over $\theta_0 \in[0.8,1]$. This is because too much shrinking the coverage makes bidder's total bid low and leads to losing in a group. If shrinking ratio is set greater than 0.8, the buyer satisfaction can be improved and so are spatial efficiency and revenue.

5.6.3 The Group Formation

The feature that allows the bidder with an alternative range makes the groups formed under SNAM accommodate more bidders. As an important step in the auction, group formation directly affects the performance. Since the bid, location and range are distributed in the same domain, we have the same total bids' expectations as

$$E[B_1] = E[B_2] =, \dots, = E[B_n] \tag{5.21}$$

Hence, recall the group bid definition (5.15), then the group size becomes the only key to winning. However, during the grouping process as shown in Fig. 5.13, we also find the size of the first formed group is no smaller than the later ones in both uniform and normal bidder distribution, which also proves *Theorem 5.5*. It is worth noting that the number of groups under SNAM is less, which means that the grouping process ends up quickly, therefore, the group formation speed of SNAM is faster than TRUST and SMALL who use the same grouping scheme. However, SMALL has the lowest spatial efficiency, because the minimum bid is sacrificed in each group under SMALL. Comparison of spatial efficiency can also be observed in Fig. 5.12, Fig. 5.14 and Fig. 5.16.

As a result, in a congested spectrum market, when the number of available spectrum chunks M is small ($M \ll N$), the spatial efficiency, seller revenue and buyer satisfaction under SNAM are better than TRUST or SMALL. Along with the increment of M, the difference between them becomes smaller, and finally the revenue turns equal, as shown in Fig. 5.14.

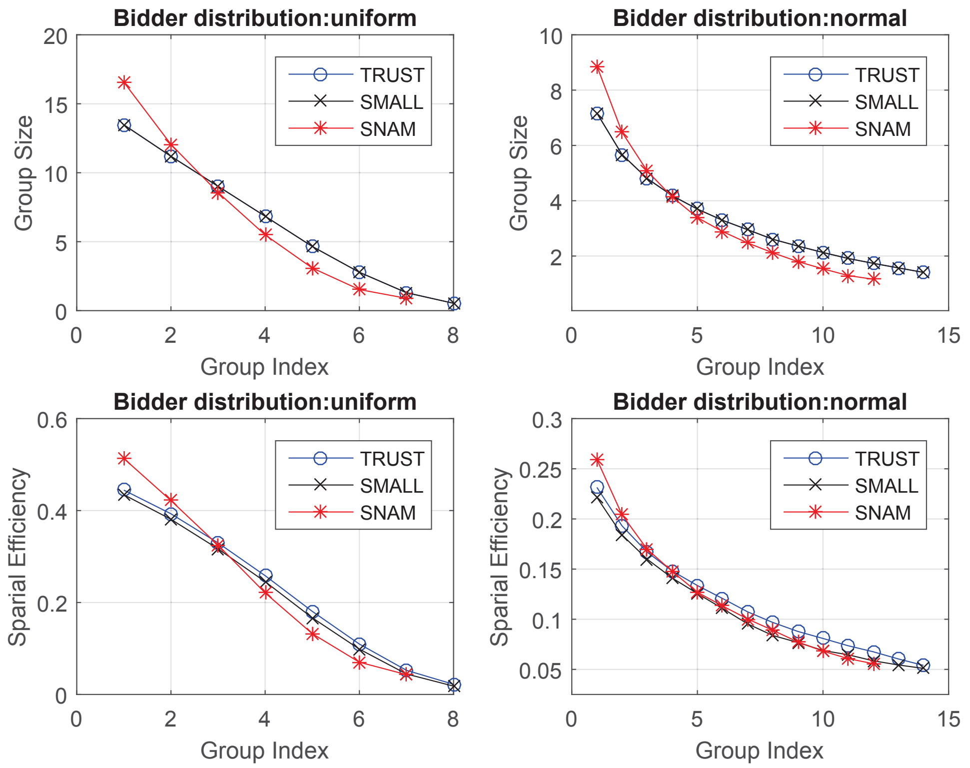


Figure 5.13: The first few groups formed under SNAM are bigger than those under TRUST/SMALL in both uniform and normal distributions.

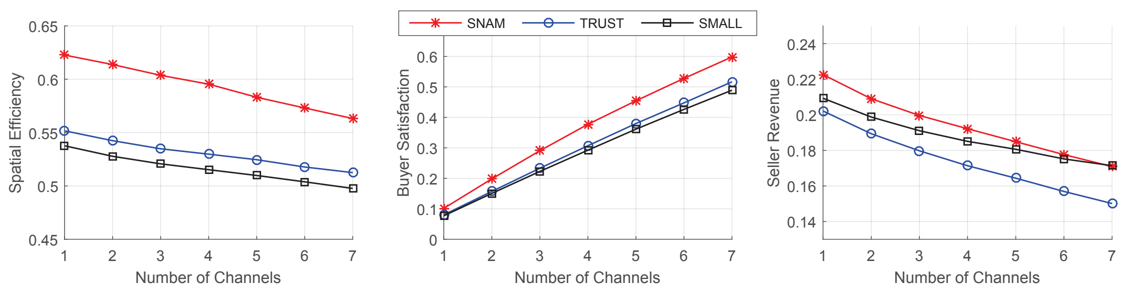
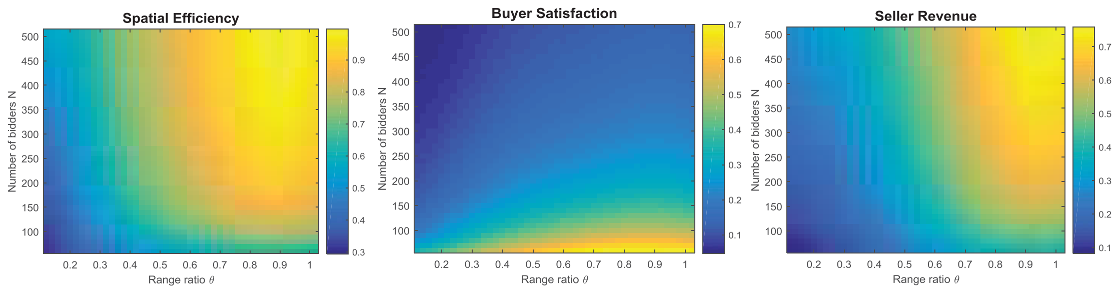


Figure 5.14: Impact of number of available spectrum chunks. SNAM has a more obvious advantage when the number of available spectrum chunks is less.

5.6.4 Impact of Network Density and Range Ratio

Next, we examine the performance of SNAM in different kinds of networks in single-unit ($M = 1$) auction when the number of bidders varies from 50 to 500 and ratio varies from 0.1 to 1, as shown in Fig. 5.15. Here we try to find out the best ratio while varying the bidder density. It is obvious that no matter how many bidders participate in the auction, setting the ratio between [0.85 0.95] is the dominant strategy for the bidders, which means that the bidders can achieve highest buyer satisfaction and for sellers, they can get highest revenue.



(a) (b) (c)

Figure 5.15: Impact of network density and range ratio. Network density and range ratio are jointly observed that the best ratio is around [0.85, 0.98], regardless of the network density.

5.6.5 Impact of the Bid Distribution

Bid distribution is defined as in [59] [61] to capture the heterogeneity of the bids made by all buyers. Our model can adopt any bid distribution (not necessarily uniform). However, without losing the generality, in the chapter, we assume the bid distribution is uniform across all bidders. From the payment rule in equation (5.15), we can find that how much one winner pays depends on the minimum bid/benchmark in a group. To examine how the bid distribution effects the revenue, we set the bid distribution is over $[b_0, 1]$. When b_0 is small, the dynamic bid range is large. This is because when the dynamic range of bid becomes smaller, the difference between the minimum bid and the other bid in a group becomes smaller. As shown in Fig. 5.16, SNAM's degradation over SMALL and TRUST becomes smaller when b_0 is less than 0.4 in terms of revenue, but the revenue becomes higher and higher from 0.4 to 1. However, SNAM's spatial efficiency and buyer satisfaction are always much better than SMALL and TRUST.

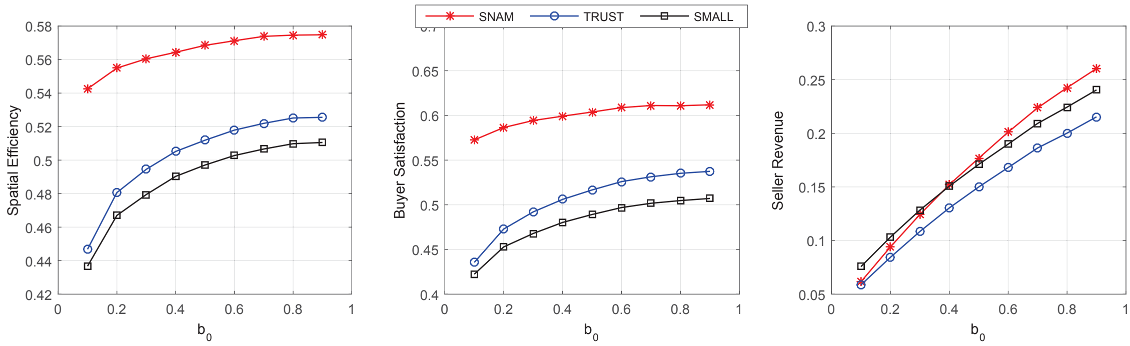


Figure 5.16: The impact of bid distribution. If the dynamic range of bid distribution is large, then the minimum bid will hold back the group bid, so the revenue loss to guarantee the truthfulness is more.

5.7 Summary

We presented a hybrid approach of auction and negotiation for spectrum sharing, namely SNAM. Unlike all existing auction-based spectrum sharing models in the literature that stifle the communications between the seller and buyers, SNAM provides a channel for the seller and its buyers to further negotiate their coverages. Considering the spatial efficiency in a licensed shared spectrum scenario, the mixed graph lets base stations from different operators make concessions when interference happens. Merging the area shrinking into the grouping process can reduce the number of iterations and also improve the spatial efficiency and buyer satisfaction, thus contributing to a higher revenue. This is the main difference from the existing works that form bidder groups only based on the undirected interference graph. As a result, our approach can accommodate more base stations thus providing a fair competition environment for small firms competing with large firms for spectrum. Based on the analysis of the simulation results, the importance of the large to small range ratio of the interference-free coverage can be observed. We also prove that the proposed auction mechanism preserves the economic properties of individual rationality and truthfulness. Overall in the heterogeneous networks, the proposed mechanism performs better than the undirected graph based auction in terms of spatial efficiency, seller revenue and buyer satisfaction.

In the next chapter, we will study the tiered spectrum sharing from the perspective of entire system's performance. We present a game theoretical analysis of PA and GAA band selection and propose to form pair coalitions to reduce utility loss that is caused by the operators' non-cooperation.

Chapter 6

Game Theoretic Analysis of PA and GAA Band Selection

6.1 Introduction

In addition to providing simply faster speeds, 5G wireless networks target more flexible and efficient spectrum allocation approaches. The spectrum regulators have the unenviable task of keeping both licensed and unlicensed users happy when it comes to dividing up spectrum resource across the competing industries. The Federal Communications Commission (FCC) has been developing the architecture of the Spectrum Access System (SAS) that serves three hierarchical users [17], and European Telecommunications Standardization Institute (ETSI) also proposed a similar system called Licensed Spectrum Access (LSA) [30]. The core of the sharing rules of the systems is that a certain spectrum will be used as a common pool and assigned to tiered users with the help of a spectrum-geographic database, from where we can see that a sublicense scheme based on a smaller scale in terms of time duration and geographical space becomes more feasible.

In this chapter, we provide a case study of sublicensing in SAS for two types of bands, namely Primary Access License (PAL) band and General Authorized Access (GAA) band. SAS is a spectrum sharing platform and provides entrants more flexibility of different tiered accesses. A potentially interested holder of a PAL could be anyone, like conventional Mobile Network Operators (MNOs) or public venues owners of a stadium or shopping malls. However, if the portion of the band is not licensed by anyone, then it will be used as the GAA band for free but without Quality of Service (QoS) guarantee. Additionally, PAL is based on census tracts in the space domain and renewable every three years in the time domain [17]. Based on the up-to-date SAS architecture we further propose to sublicense PALs on a smaller scale, e.g., the base station coverage in the space domain and days or hours in the time domain.

In a local region, there are multiple operators with different subscriber masses, i.e., the number of the subscribers, and they will interfere with each other if run in the same frequency band. One operator may temporarily request a PAL sublicense of a block of the spectrum from the SAS when the interference is too heavy. However, how to share the spectrum between the competing operators and how to benefit from ordering a PAL sublicense is a challenging problem and not fully studied yet. In this chapter, we focus on PAL and GAA band selection in a common spectrum pool between different operators.

A challenging problem in the joint sharing and exclusive network is to optimize a general utility function with only partial knowledge of the network and operators. In such a case, game theory can provide a mathematical model that describes the interactions between various players who try to maximize their payoffs. To that end, we follow the capacity models in [118] and then formulate a decision making process as a non-cooperative Sublicensing Game, in which operators are assumed to be selfish.

The available spectrum portion in the common pool is shown in Fig. 6.1. The incentive of a PAL sublicense holder is having the exclusive use in this portion of the band. However, in the GAA band it has no interference protection. As the exclusive usage is guaranteed in the PAL band, we assume that it is a centralized (or complete information) network operating in these PAL sublicensed portions. On the other hand, it is a randomly distributed (or incomplete information) network in the GAA portion. The operators have to select one of the two access methods to maximize their own payoffs.

The main contributions of this chapter are as follows.

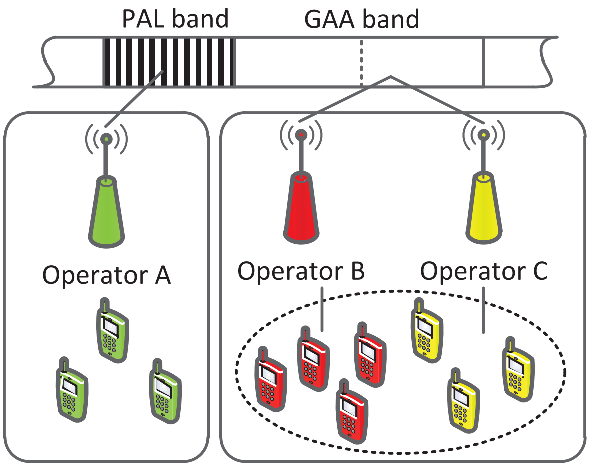


Figure 6.1: Spectrum common pool in SAS: an operator can sublicense a block of spectrum from the common pool, otherwise the spectrum block will be used as the GAA band.

- To the best of our knowledge, this non-cooperative Sublicensing Game has not been proposed before to study the problem of PAL and GAA band selection for the purpose of enabling commercial spectrum sharing.
- By presenting the analysis of pure and mixed-strategy Nash equilibria, we provide the operators with a reference for the selection of the PAL or GAA band in SAS.
- Simulation results show that the operators with fewer subscribers are more likely to order a PAL sublicense. However, if the price of the sublicense is set too high, operators will move to select the GAA band. In addition, we also find that the variance of subscriber masses is the major factor in the overall utility loss.

The rest of the chapter is structured as follows. In Section 6.2, the system model and problem formulation are provided. In Section 6.3, we present Nash equilibrium analysis for the Sublicensing Game. We also provide the characterization of the Nash equilibrium in Section 6.4. By using a local centralized coordinator, we also provide a pair coalition scheme to reduce utility loss in Section 6.5. Finally, Section 6.6 concludes our findings.

6.2 Preliminaries and Game Formulation

An operator can order a spectrum portion as a PAL band. In the PAL band, the operator has a full exclusive right of the spectrum, and no one else can use that spectrum. However, if the spectrum portion is not ordered by anyone, it will be used as the GAA band without interference protection.

6.2.1 Licensed Shared Spectrum

The architecture of spectrum sharing between different tier users is technically achievable [33]. However, before it is widely accepted and used a spectrum trading analysis will extract its potential business value and accelerate the development [119]. Although spectrum sharing is not a new idea, most of it is still based on the theoretical analysis without any prototype [120] [121]. Congestion or queuing cost, fairness and being interference-free are the main key aspects of spectrum sharing [106] [122]. Recently, more spectrum sharing models with an economics perspective for the newly proposed systems, such as SAS and LSA have been discussed and investigated [123]. There is a vast literature on spectrum economics, but most of it relies on general theoretical auction [43] and contract-based models [124]. In this chapter, we focus on practical spectrum sharing between licensed and unlicensed users in a spectrum common pool, particularly for SAS or LSA.

To realize the sublicensing scheme between different hierarchical accesses, a game theoretical analysis is recognized as an important tool in spectrum allocation [125]. A game is a description of a strategic interaction that includes the constraints on the actions that players can take and the players' interests. The three basic components of a game are the set of *players*, set of *strategies* available for each player and set of *payoffs* for each player. In a word, in the Sublicensing Game, operators will sublicense different PALs from the shared band, otherwise they will access the shared band as GAA.

6.2.2 Game Formulation

The *players* are a set of operators, denoted by a finite set $\mathcal{K} = \{1, 2, ..., K\}$. In this work, we consider that the number of PALs is enough for the operators, who sublicense PAL bands from a limited spectrum $\mathcal{B}$. All the PAL bands are identical as α, and the remaining band is δ. Therefore, if $n(n \leq K)$ operators order PALs, we have $n\alpha + \delta = B$. The players are different from each other in terms of the subscriber mass (equal to the number of the subscribers). Let m_k denote the number of subscribers of player k. Initially, the GAA access fee is free and the operators prefer to stay in the GAA band. However, with the increasing number of other operators' subscribers, the overall performance may drop in the GAA band because of interference and congestion. Then, some player may move to play the PAL band to seek a better band. The *strategy* of each player $k \in \mathcal{K}(K)$ is to decide to access the PAL band or the GAA band.

All the players have the same *strategy* set denoted by $s_k \in \{0, 1\}$. Let $s_k = 1$ that operator k orders a PAL while $s_k = 0$ denote operator k does not order a PAL. The remaining portion of the spectrum will be shared without interference protection as the GAA band by all the operators who have $s_i = 0$.

The *payoff* of player k is a function of its own strategy s_k and other players' strategies $\mathbf{s}_{-k} = \{s_i | i \neq k, i \in \mathcal{K}\}$. In the PAL band, a player has an exclusive right of the band and coordinates all its subscribers in a centralized manner, while in the GAA band all the players are decentralized to share the spectrum resource. The payoff of player k is denoted by $u_k(s_k, \mathbf{s}_{-k})$, which will be defined later in the next section.

Therefore, the Sublicensing Game for the operators and the corresponding Nash equilibrium are defined as follows.

Sublicensing Game $\mathbf{G} = (\mathcal{K}, \mathbf{s}, \mathbf{u})$:

- *Players: the set $\mathcal{K}$ of operators*;
- *Strategies:* $\mathbf{s} = s_1 \times ... \times s_k$, *and* $s_k \in \{0, 1\}, \forall k \in \mathcal{K}$;
- *Payoffs:* $u_k(s_k, \mathbf{s}_{-k}), \forall k \in \mathcal{K}$.

Definition 6.1. *A Nash equilibrium of the Sublicensing Game on operator k is a profile* $\mathbf{s}^* = \{s_k, \forall k \in \mathcal{K}\}$ such that for each player $k \in \mathcal{K}$,

$$u_k(s_k^*, \mathbf{s}_{-k}^*) \geq u_k(s_k, \mathbf{s}_{-k}^*), \forall s_k \in \{0, 1\}. \tag{6.1}$$

This Nash equilibrium means that no player can gain more payoff by moving differently when all the other stay the same.

Note that we assume that one player can only order one PAL. In practice, if an operator needs more spectrum, for example two PALs, we can see it as two players with halved subscribers in this game. In addition, the total spectrum is limited and fixed, if a certain portion is not licensed, it will be used as the GAA band.

6.2.3 Payoff Definition

We assume that some mechanism is in place to achieve the fairness for all the subscribers, for example, listen-before-talk in the GAA band. Over a sufficiently long period, we can see that the spectrum resource is equally shared by the subscribers in the same access method (i.e., the PAL or GAA band). To capture how the decision affects the payoff of player k we estimate the average capacity of the wireless network as a function of the subscriber mass similar to [118]. To see how the subscriber mass affects the decision and observe the payoff, we consider that the average data rate of subscriber is proportional to the spectrum resource α (or δ), i.e, the more spectrum an operator can provide, the higher data rate its subscriber can obtain.

We assume that in the PAL band, the license holder (i.e., player k) has the full knowledge of the network and every subscriber under player k has interference protection. The average spectrum resource per subscriber in the PAL band that can be achieved is defined as follows.

Definition 6.2. *In a centralized or complete information network, i.e., the PAL band, the average capacity is a function of the number of subscribers m and spectrum resource α as* [118]

$$C^P(m, \alpha) = \frac{\alpha}{\sqrt{m}}. \tag{6.2}$$

On the other hand, in the GAA band, we assume that the subscribers from different operators are independent and unknown to each other. We also assume that all the subscribers are homogeneous, i.e., all transmissions employ the same power range. The average spectrum resource per subscriber in the GAA band is defined as follows.

Definition 6.3. *In a distributed or incomplete information network, i.e., unlicensed band, the average capacity is a function of the subscriber mass m and spectrum resource δ as* [118]

$$C^G(m,\delta) = \frac{\delta}{\sqrt{m \log m}}. \tag{6.3}$$

Since $C^P(m,\alpha) > C^G(m,\delta)$ always holds when the number of subscribers m and the spectrum resource stay unchanged $\alpha = \delta$ as shown in Fig. 6.2, we can see that the average capacity of a centralized PAL band is higher than that in the GAA band. However, there is a cost of licensing a portion of spectrum for exclusive use.

Next, we separately present the definitions of the payoff when player k plays

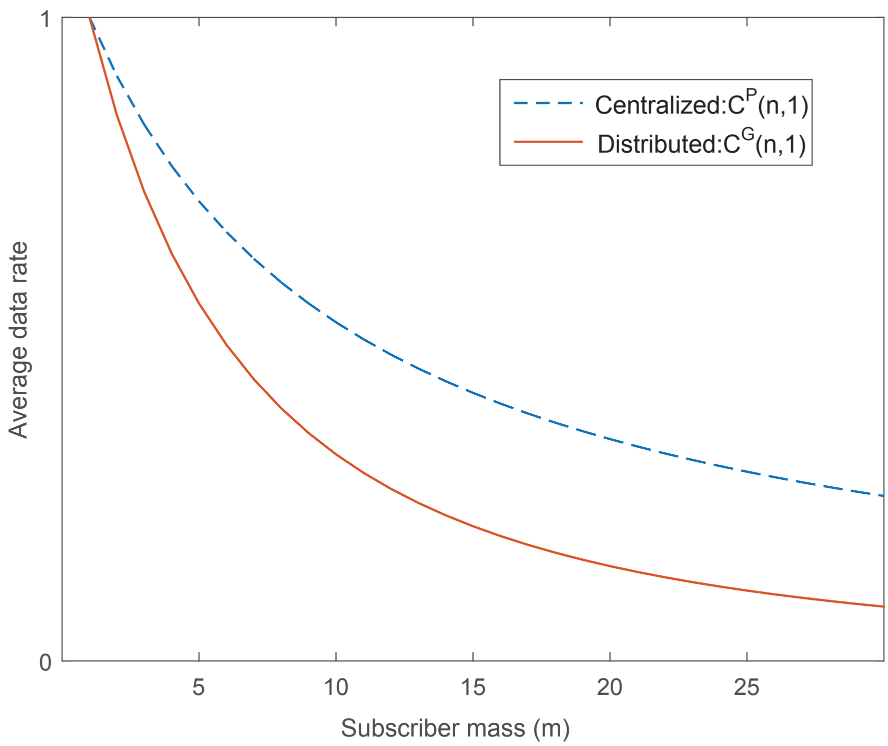


Figure 6.2: Average capacity in two different networks.

different strategies. When player k orders a spectrum portion as the PAL band $s_k = 1$, the payoff is some percent of revenue of the overall capacity, as

$$\begin{aligned} u_k(1, \mathbf{s}_{-k}) &= m_k C^P(m_k, \alpha) r - c \\ &= \alpha \sqrt{m_k} r - c \end{aligned} \tag{6.4}$$

where r and c are the profit rate and cost of PAL in terms of money and they are constants, and $\mathbf{s}_{-k}$ is the others' strategies. Therefore, the spectrum resource used for the GAA band is

$$\delta = \mathcal{B} - \alpha \sum s_k \tag{6.5}$$

where $\sum s_k$ is the number of players that order the PAL bands including player k. This portion of spectrum resource δ will be shared by all the players who play the GAA band. Let $\hat{M}$ denote the total number of subscribers from all the operators, then we have:

$$\hat{M} = \sum m_k (1 - s_k) \tag{6.6}$$

Substituting (6.5) and (6.6) in (6.3), we have the player k's payoff of playing the GAA band $s_k = 0$ as

$$\begin{aligned} u_k(0, \mathbf{s}_{-k}) &= m_k C^G(M, \delta) r \\ &= \frac{(\mathcal{B} - \alpha \sum s_k) m_k r}{\sqrt{\sum m_k (1 - s_k) \log \sum m_k (1 - s_k)}} \end{aligned} \tag{6.7}$$

Note that if player k orders a PAL, it leaves less spectrum resources for the GAA band. However, on the other hand, if player k does not order a PAL, i.e., plays the GAA band, its payoff is a function of the other players' strategies $\mathbf{s}_{-k}$, because it has to share the GAA band with other operators who also play the GAA band.

6.3 Nash Equilibrium Analysis

In non-cooperative games, a Nash equilibrium (NE) is an operating point at which no player can improve its payoff by unilaterally changing its current strategy.

6.3.1 Mixed Strategies

The strategies of buying or not buying a PAL are *pure strategies*. In general, a player may be able to select each pure strategy with a certain probability, which is the basis of the concept of *mixed strategy*. For a given player, a mixed strategy consists of a number of possible pure strategies of which each is associated with a probability. Essentially, a mixed strategy is a set of probabilities under which a given pure strategy is executed.

Specifically, given the above pure strategy game, for each player k we define $\mathbf{x}$ as the set of probabilities over its set of pure strategies $\mathbf{s}$. A probability $x_k(s_k) \in \mathbf{x}$ of player k is the probability that action $x_k \in \mathbf{s}$ is selected. Consequently, the payoff for a mixed strategy corresponds to the expected value of the pure-strategy profiles in its support. Let x_k denote the probability of player k if it plays the PAL band, and $1 - x_k$ is the probability if it plays the GAA band. Then we have the expected spectrum resource used as the GAA band

$$\hat{\delta} = \mathcal{B} - \alpha \sum x_k. \tag{6.8}$$

Similarly, the expected number of subscribers in the GAA band is given as:

$$\hat{M} = \sum m_k(1 - x_k). \tag{6.9}$$

Therefore, for player k the payoff expectation is

$$u_k(x_k, \mathbf{x}_{-k}) = x_k u_k(1, \mathbf{s}_{-k}) + (1 - x_k)u_k(0, \mathbf{s}_{-k})$$

which can also be written as

$$\begin{aligned} u_k(x_k, \mathbf{x}_{-k}) = {} & x_k(\alpha\sqrt{m_k}r - c) \\ & + (1 - x_k)\frac{(\mathcal{B} - \alpha \sum x_k)m_k r}{\sqrt{\sum m_k(1 - x_k)} \log \sum m_k(1 - x_k)} \end{aligned} \tag{6.10}$$

according to (6.4), (6.7), (6.8) and (6.9). Then we can have the definition of a mixed-strategy profile.

Definition 6.4. *A mixed-strategy profile* $\mathbf{x}$ *is a mixed-strategy Nash equilibrium if, for each player* $k \in \mathcal{K}$ *and for each* $s_k \in \mathbf{s}$*, we have:*

$$u_k(x_k^*, \mathbf{x}_{-k}^*) \geq u_k(s_k, \mathbf{x}_{-k}^*). \tag{6.11}$$

where x^* is the mixed equilibrium profile.

The mixed Nash equilibrium can be obtained by using the best response function which is the best strategy of one player given others' strategies. Given the other players' strategies $\mathbf{x}_{-k}$, the best response of player k is defined as

$$\mathcal{BR}(\mathbf{x}_{-k}) = \arg\max_{x_k}(u_k(x_k, \mathbf{x}_{-k})) \tag{6.12}$$

To ease discussion and focus on u_k and x_k, we further rewrite (6.10) only in terms of x_k instead of $\sum x_k$, as

$$\begin{aligned} u_k(x_k, \mathbf{x}_{-k}) &= x_k(\alpha\sqrt{m_k}r - c) \\ &+ (1 - x_k)\frac{(\mathcal{B} - |\mathbf{x}_{-k}|\alpha - x_k\alpha)m_k r}{\sqrt{[\mathbf{m}_{-k}\mathbf{x}_{-k} + m_k(1 - x_k)]\log[\mathbf{m}_{-k}\mathbf{x}_{-k} + m_k(1 - x_k)]}} \end{aligned} \tag{6.13}$$

where $|\mathbf{x}_{-k}|$ is number of other players who select PAL, and accordingly $\mathbf{m}_{-k}\mathbf{x}_{-k}$ is the number of their subscribers. The common way to achieve the maximum value of a function is to solve

$$\frac{\partial u_k(s_k)}{\partial x_k} = 0 \tag{6.14}$$

However, solving the above set of equations to obtain Nash equilibrium is not straightforward and a numerical method is required. In this chapter we use *Nelder-Mead* direct search method [126] to obtain the Nash equilibrium. We formulate an optimization problem with the objective defined as follows

$$\text{Minimize:} \sum |x_k - \mathcal{BR}_k(\mathbf{x}_{-k})| \tag{6.15}$$

That is, we want to minimize the difference between decision variables x_k and the corresponding best response function. Note that, the minimum value of the objective function is zero if the algorithm reaches the Nash equilibrium.

6.3.2 Existence of Nash Equilibrium

Theorem 6.1 The Sublicensing Game has at least one (mixed) Nash equilibrium.

Proof: Nash proved that a finite game always has at least one Nash equilibrium [127]. Here "finite" means two things: a finite set of players and each of them has a finite set of strategies. In our game formulation, each operator has two action profiles: select the unlicensed band or the licensed band. Moreover, the number of players in this game is also finite. Therefore this game is a finite game with a finite number of players, so according to the Nash theorem, we have the existence of a Nash equilibrium.

6.4 Characterization of Sublicensing Game

We assume that two players want to consider whether to order licenses. We will see explicitly how to find the set of Nash equilibrium for a two-player game where each player has a strategy space containing two actions. After setting up the analytical framework and deriving some general result for such a game, we will apply this to multi-player games in Section 6.5.

6.4.1 Payoff of Players

We can address all the possible combinations of the two players in a payoff matrix as shown in Fig. 6.3.

We assume that in a two-player game, the subscriber masses of player 1 and

I \ II	PA	GAA
PA	$u_1(s_1{=}1, s_2{=}1), u_2(s_2{=}1, s_1{=}1)$	$u_1(s_1{=}1, s_2{=}0), u_2(s_2{=}0, s_1{=}1)$
GAA	$u_1(s_1{=}0, s_2{=}1), u_2(s_2{=}1, s_1{=}0)$	$u_1(s_1{=}0, s_2{=}0), u_2(s_2{=}0, s_1{=}0)$

Figure 6.3: Payoff matrix of a two-player game, in which player 1 (column) has strategies $s_1 = 0, s_1 = 1$ and player 2 also has the same strategies $s_2 = 0, s_2 = 1$.

player 2 are m_1, m_2 respectively. If a player plays the PAL method, the payoff is

$$\begin{aligned} u_1(1, s_2) &= \alpha\sqrt{m_1}r \\ u_2(1, s_1) &= \alpha\sqrt{m_2}r \end{aligned} \tag{6.16}$$

If player 1 plays the GAA method the payoff is

$$u_1(0, s_1) = \begin{cases} \dfrac{m_1}{\sqrt{(m_1+m_2)\log(m_1+m_2)}}, & s_2 = 0 \\ \dfrac{(1-\alpha)m_1}{\sqrt{m_1 \log m_1}}, & s_2 = 1 \end{cases} \tag{6.17}$$

When $s_2 = 0$, the whole band will be used for the GAA band. However, when player 2 plays the PAL method $s_2 = 1$, then the spectrum resource for the GAA band will be reduced by α, which is played by player 2. Although the spectrum resource GAA band is reduced, so is subscriber mass in the GAA band, we can neither tell if $u_1(0, 1) > u_1(0, 0)$ nor $u_1(0, 1) < u_1(0, 0)$, and this will be discussed later.

6.4.2 Nash Equilibrium

Following the definitions of mixed equilibrium, we look into more details of the two-player game. Given the pure strategy profile $\mathbf{s} = (s_1, s_2)$ and the probability set $\mathbf{x} = (x_1, x_2)$ if they play the PAL band, we consider the expected payoff of player 1 as follows.

If player 1 orders a PAL sublicense with probability x_1, it has an expected payoff of

$$u_1(x_1, 0) = x_1 u_1(1, 0) + (1 - x_1) u_1(0, 0)$$

when player 2 does not order a license, and

$$u_1(x_1, 1) = x_1 u_1(1, 1) + (1 - x_1) u_1(0, 1)$$

when player 2 orders a PAL sublicense. Similarly, for player 2 we have its expected payoffs as

$$u_2(x_2, 0) = x_2 u_2(1, 0) + (1 - x_2) u_2(0, 0)$$

and

$$u_2(x_2, 1) = x_2 u_2(1, 1) + (1 - x_2) u_2(0, 1).$$

To illustrate how the two players approach pure or mixed Nash equilibrium, we roughly plot the payoff polygon of player 1 and player 2 as shown in Fig. 6.4, where PG (GP) denotes player 1 chooses the PAL (GAA) method while player 2 chooses the GAA (PAL) method, and PP (GG) denotes they both choose the PAL (GAA) methods. However, we can not immediately determine the value of $u_1(1,0/1), u_1(0,0), u_1(0,1)$ and $u_2(1,0/1), u_2(0,0), u_2(0,1)$; we find that whether Nash equilibrium is pure or mixed, unique or multiple depends on the relationship among them. Next, we further determine the pure or mixed Nash equilibrium under different combinations.

For ease of discussion, we consider them in four cases as follows. For player 1, the relationship between $u_1(1,0), u_1(0,1), u_1(0,0)$ can be one of the following four conditions:

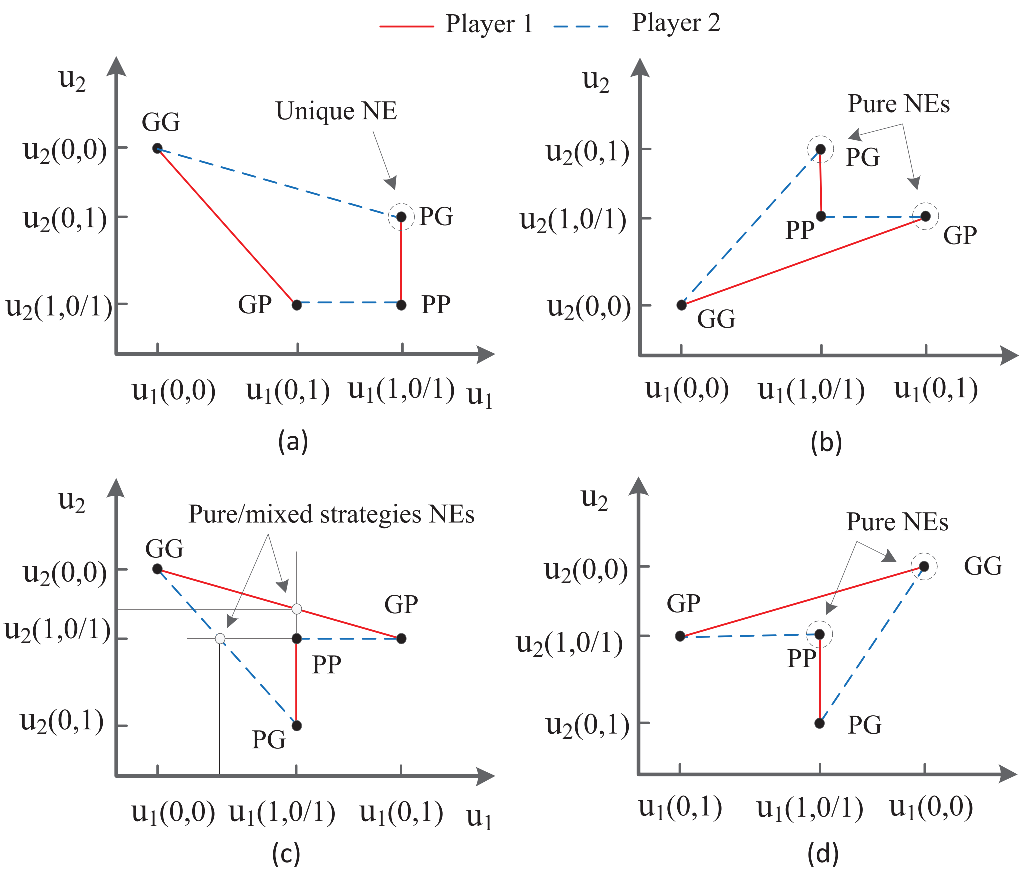


Figure 6.4: The payoff polygon of two players.

$$u_1(1, x_2) \geq \max\{u_1(0, 0), u_1(0, 1)\} \tag{1a}$$

$$u_1(1, x_2) \leq \min\{u_1(0, 0), u_1(0, 1)\} \tag{1b}$$

$$u_1(1, x_2) \in (u_1(0, 0), u_1(0, 1)), u_1(0, 0) < u_1(0, 1) \tag{1c}$$

$$u_1(1, x_2) \in (u_1(0, 1), u_1(0, 0)), u_1(0, 1) < u_1(0, 0) \tag{1d}$$

Similarly, for player 2 we have

$$u_2(1, x_1) \geq \max\{u_2(0, 0), u_2(0, 1)\} \tag{2a}$$

$$u_2(1, x_1) \leq \min\{u_2(0, 0), u_2(0, 1)\} \tag{2b}$$

$$u_2(1, x_1) \in (u_2(0, 0), u_2(0, 1)), u_2(0, 0) < u_2(0, 1) \tag{2c}$$

$$u_2(1, x_1) \in (u_2(0, 1), u_2(0, 0)), u_2(0, 1) < u_2(0, 0) \tag{2d}$$

Case (i): If player 1 is located in (1a), playing the licensed access is its best response. Then for player 2, player 1's strategy is fixed and no matter what condition player 2 is in, it will pick the greater one from $\{u_2(0, 1), u_2(1, 1)\}$. A ***unique pure Nash equilibrium*** exists in this case. Condition ($1a$) and condition ($2b$) are demonstrated in Fig. 6.4 (a).

Case (ii): If player 1 is located in (1b), playing the unlicensed method is its best response. Similarly, for player 2, player 1's strategy is fixed and it will pick the greater one from $\{u_2(0, 0), u_2(1, 0)\}$. A ***unique pure Nash equilibrium*** exists in this case.

Case (iii): If player 1 is located in (1c), we can immediately tell the player's best move if player 2 is either located in (2a) or (2b), referring to the discussion in Case (i) and Case (ii). However, if player 2 is also located in (2c), for both of them the best responses are in the pair of PG and GP which means that they prefer to move differently, then they reach the equilibrium. Therefore, there are ***two pure Nash equilibria*** under these two conditions, as shown in Fig. 6.4 (b).

Additionally, if player 2 is located in (2d), there is no pure Nash equilibrium for both of them simultaneously. One of them reaches the equilibrium with ***a pure strategy*** while the other reaches the equilibrium with ***a mixed strategy***, as shown in Fig. 6.4 (c).

Case (iv): If player 1 is located in (1d), the discussion is similar to Case (iii) above. Note that if player 2 is also located in (2d), for both of them the best responses are in a pair of GG or PP, which means they prefer to stay in the same band, then we have **two pure Nash equilibria**, as shown in Fig. 6.4 (d). If player 2 is located in (2c), the discussion is the same as Case (iii) about the combination of (1c) and (2d).

Coalition Formation

We observe that the utility loss is mainly derived from the difference of the subscriber masses, so to conquer we further enable SAS to form a pair coalition for the operators with fewer subscribers. A number of coalition formation algorithms have been developed to determine which of the potential coalitions should actually be formed [128] [129]. To do so, they typically calculate a value for each coalition, know as the *coalition value*, which provides an indication of the expected outcome that could be derived if that coalition was formed. Then, having computed all the coalition values, the decision about the optimal coalition to form can be taken. The way this value is calculated depends on the problem under investigation, and the complexity of this calculation varies correspondingly from linear to exponential. How the coalition formation is described in Algorithm 4.

Note that in the spectrum sharing model, considering the privacy issue, we only allow two operators to form a pair coalition. This is because forming too many operators in a coalition would cause a complicated security and privacy problem among operators. The coalition value is the payoff of two operators, and the two operators with the fewest number of subscribers will be formed in a pair coalition. The algorithm of coalition formation is presented as follows.

6.4.3 A Local Centralized Coordinator

Price of Anarchy

We first study the efficiency of the Nash equilibrium by checking the Price of Anarchy (PoA), which is widely used to measure how efficiency of a system degrades

Algorithm 4 Formation of the Pair Coalition

Initialization: $\mathbf{m} \leftarrow \text{sort}(\mathbf{m})$, $v_0 \leftarrow \text{variance}(\mathbf{m})$, $i \leftarrow 1$, $coalition \leftarrow \varnothing$
while *true* **do**
  merge pair $(i, i+1)$ by $\mathbf{m}.append \leftarrow \mathbf{m}_i + \mathbf{m}_{i+1}$
  calculate the new variance: $v_1 \leftarrow \text{variance}(\mathbf{m}_{(i+2):end})$
  if $v_1 > v_0$ **then**
    break
  else
    put merging pair $(i, i+1)$ into *coalition*
    update: $i \leftarrow i+2$, $v_0 \leftarrow v_1$
  end if
end while
return *coalition*

due to selfish behaviour in a non-cooperative game. The PoA is defined as the ratio between the “centralized” (complete information) solution and the “worst” (incomplete information market) equilibrium.

Since local optimization is always dominated by global optimization, decentralizing operations usually results in a loss of efficiency. We can define a subset $\mathbf{s}^* \subseteq \mathbf{s}$ to be the set of strategies in equilibrium, then the PoA is defined as follows.

$$PoA = \frac{\max Welf(\mathbf{s})}{\min Welf(\mathbf{s}^*)} \tag{6.18}$$

6.5 Simulation Results and Numerical Analysis

In this section, we start with performing numerical experiments for a simple two-player game. Then we further carefully discuss the Nash equilibrium and the Price of Anarchy of the non-cooperative game.

6.5.1 Game Setup

Profit rate r is normalized as 1, while the cost of PAL c is set as a variable between 1 and 10. According to the latest FCC document [17], the bandwidth of PAL is a

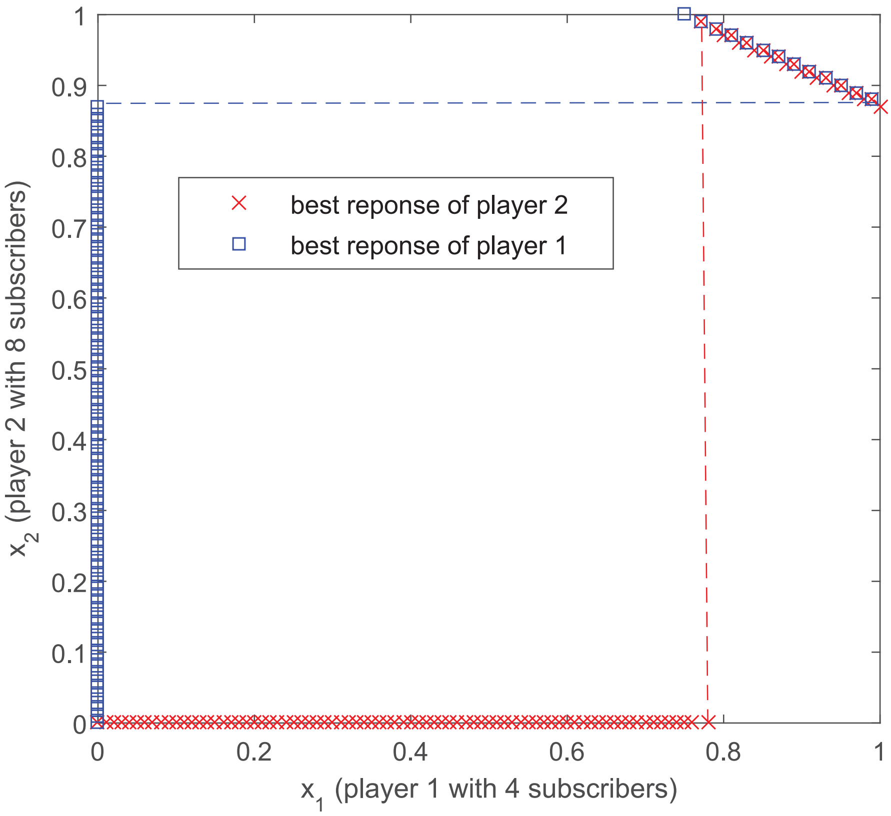


Figure 6.5: The best responses of two players, given their subscriber masses as $m_1 = 1, m_2 = 8$.

constant at 10 MHz , and there are up to 7 PALs in a census tract.

6.5.2 Nash Equilibrium in a Two-player Game

We first demonstrate the mixed-strategy Nash equilibrium of a two-player game, as shown in Fig. 6.5. Given the subscriber masses of two players as $m_1 = 4, m_2 = 8$, and the cost of PAL $c = 5$, we present the simulation result of their best response in Fig. 6.5. Player 2 always plays the GAA band ($x_2 = 0$) until player 1's probability grows approximately greater than $x_1 > 0.8$. On the other hand, player 1 stays in the GAA band ($x_1 = 0$) until player 2's probability is approximately $x_2 > 0.9$. Hence, a player with fewer subscribers is more likely to move compared with the player who has a larger number of subscribers. Overall, there are multiple Nash equilibria in this setup, including one pure Nash equilibrium at $\mathbf{x} : (x_1 = 0, x_2 = 0)$ and multiple mixed equilibria at around $\mathbf{x} : (0.8 \leq x_1 \leq 1, 0.9 \leq x_2 \leq 1)$.

From the simulations, we can say that with the dynamic change of the network, the players with more market share or high subscriber mass are more sensitive to changes in their strategies, while the players with a less market share or subscriber mass are reluctant to change.

We then demonstrate the mixed-strategy Nash equilibrium of a two-player game with varying subscriber mass, as shown in Fig. 6.6. To observe the relationship between the subscriber mass and the trigger of the strategy switch, we introduce another "puppet" player, who has subscriber mass as m_0 and only access to the GAA band. Given $m_1 = 20$ and $m_2 = 30$, with the growing of puppet player' subscriber mass, both player 1 and player 2 tend to access the PAL band. However, player 1 approaches to the PAL band faster than player 2 does (player 1 reaches the strategy $s = 1$ at $m_0 = 6$ while player 2 reaches the strategy $s = 1$ until m_0 increases to 12). The reason is that the number of player 2's subscribers is more than player 1's and it can stand more interference from others. Therefore the probability that player 2 wants to access the PAL band is lower than player 1 in the beginning then it turns stable and the same as player 1.

The mixed-strategy Nash equilibrium also indicates that all the players will make the sharing band go in a balanced direction. Under some conditions of puppet player's subscribers, players' partial subscribers will select the GAA band and partial subscribers will select the PAL band, which makes the average payoff converge.

6.5.3 Impact of the Cost of PAL

As the negative part in the utility function, the cost of PAL plays a significant role in the Sublicensing Game. We first study how the cost of PAL affects the player's move. Note that the two y-axes Fig. 6.7 shows the utility and response of an operator, when the cost of the PAL sublicense varies from 1 to 10. When the PAL sublicense cost increases, the operator will move from the PAL band $x_i = 1$ to the GAA band $x_i = 0$. This is because we can observe that if the PAL sublicense cost keeps going up, the operator can no longer afford it and has to move to the free GAA band.

Additionally, when the subscriber mass m varies from 2 to 16, we can also observe that an operator is reluctant to change the strategy until the sublicense cost is high

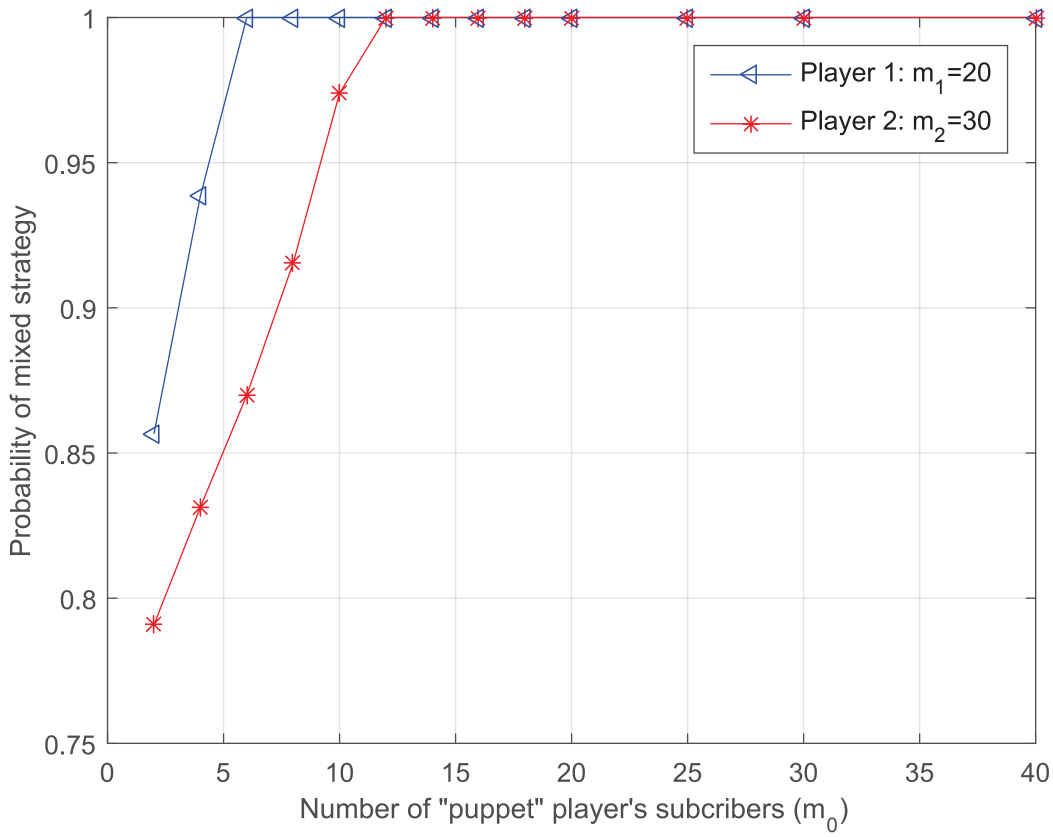


Figure 6.6: The interfering subscribers from a third ("puppet") player have a significant influence on the mixed-strategy Nash equilibrium in a game.

enough. Similarly, the reason is that an operator can afford the sublicense cost when it has a large number of subscribers.

6.5.4 Price of Anarchy

We examine Price of Anarchy (PoA) and the subscriber mass standard deviation. This is to quantify the amount of dispersion of the set subscriber mass $\mathbf{m}$. We can observe that if the subscriber masses are spread out over a wider range, the PoA and utility loss is larger. If a centralized coordinator is placed in the spectrum sharing, this non-cooperative game transforms into a cooperative game. Furthermore, the PAL cost does not contribute to utility loss very much.

Assume that there are $K = 7$ players in the game and given the subscriber masses randomly distributed in $m_k \in [2, 16]$, we run all the strategy profiles and find the Nash equilibrium, as shown in Fig. 6.8. We find that the difference of their

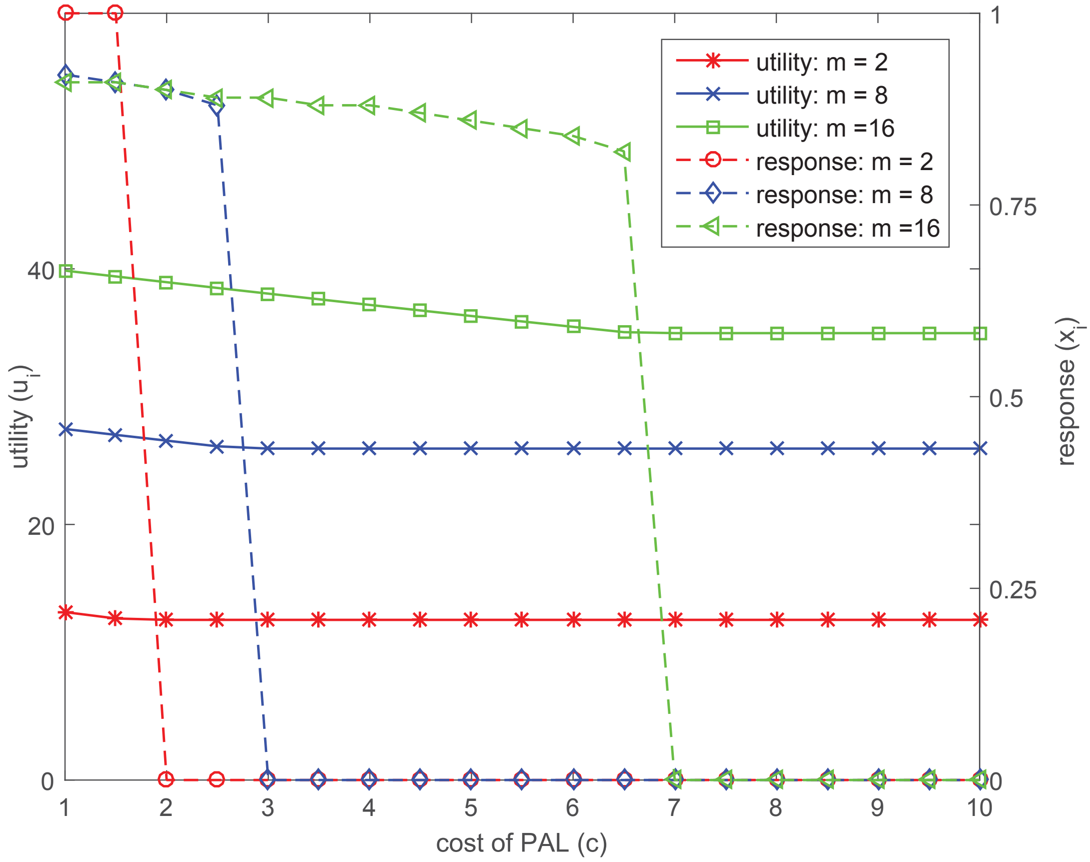


Figure 6.7: Impact of the PAL's cost on player's utility and response.

subscriber masses is the key impact of utility loss. With the increasing of the variance of the operators' subscriber masses, the utility loss becomes larger. However, the change of PAL cost does not affect the utility loss very much. Therefore, for small operators if they can unite, then the utility loss will be reduced, as shown in Fig. 6.8(b). The overall utility loss is reduced by 5%-10% if a centralized coordinator is placed to form pair coalitions for the operators. Therefore, the centralized system in SAS can further coordinate the players and let them form nearly equal coalitions, thus avoiding utility loss.

6.6 Summary

In this chapter, we considered a Sublicensing Game for operators who play two types of access methods: PAL and GAA in the SAS. Employing the game theoretical tool, we have studied the feasibility of PAL and GAA based spectrum allocation and

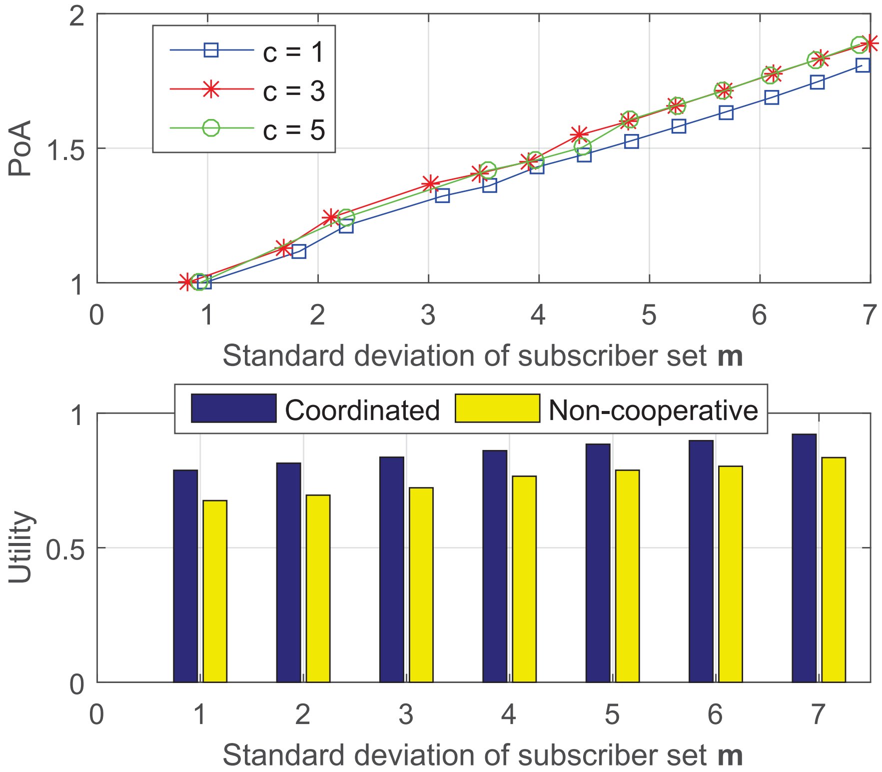


Figure 6.8: PoA and utility loss.

sublicensing in SAS. In this finite game, all the players can reach unique or multiple Nash equilibria. We find that the market share plays a significant role for a player to make the decision. The operators who have fewer subscribers are more likely to stay in the GAA band. Additionally, the cost of the PAL sublicense is another key aspect for an operator to order a portion of the spectrum for exclusive use. We find that the differences in the number of subscribers lead to utility loss. Hence, employing a centralized coordinator to enable small operators to join together and make the stakeholders equal contributes to a higher overall utility without harming anyone.

Chapter 7

Conclusions and Future Work

This thesis focuses on the short-term sublicensing with economic awareness for dynamic spectrum sharing. We have conducted research into short-term sublicensing to incorporate policy, technology and business, which provides critical technical foundations for a number of applications based on the online spectrum auction. Due to time constraints, this thesis still leaves some valuable research topics for future work. In this chapter, we summarize the innovations of this thesis in Section 7.1, then we point out the directions for future work in Section 7.2.

7.1 Research Summary

Rather than being another 'next generation', 5G has already been under way and it will be a better integration of old and new technology. As one of the primary aspects of the combination of evolution and revolution, spectrum sharing solutions will enable a full scalable service experience on demand. Figuring out how to best utilize available spectrum resources simultaneously engages complex multidisciplinary technical, business, and policy issues that strain the skills and knowledge of domain experts. Keeping abreast of emerging technical innovations, changing regulations and legacy frameworks, and rapidly changing spectrum market is difficult. Engaging these issues is often exceedingly daunting but the issues are sufficiently important and with implications across the internet and wireless economy that we need to broaden the basis of engagement.

The major innovations of this thesis are presented as follows.

7.1.1 Enabling Base Station as a Bidder

The scalable service experience in 5G will be realized by gradually breaking the concepts of operator and long-term license. Enabling base station as a bidder can tailor the system to extremely diverse use cases in order to meet specific performance requirements. A uniform service experience can still be achieved in most use cases by tighter coupling base stations and spectrum flexibility. In addition, as a direct service access point, a base station can dynamically require extra spectrum resource from local spectrum sharing platforms, such as LSA and SAS according to the changing traffic requirements along with time. The contour based protection zone is easy and flexible to apply and at the same time guarantees interference-free operation among multiple base stations.

7.1.2 Short-term Online Auction

Short-term sublicensing is the basis of future spectrum sharing. The increase in achievable data rates for 5G cannot be achieved without reducing the cell size and license duration. Over the next few years this trend will accelerate as the use of data-hungry applications rises. Ultimately, the need for small cells will be one of the triggers for 5G. The key to meeting these requirements is to bring the access point closer to the users, with smaller cells gaining more spectrum resources through online auction via a local centralized platform instead of manual auction. This will also substantially reduce the radio round trip time for lower latency and increase overall network efficiency by creating sub-networks to handle a proportion of the traffic locally. The short-term online auction can achieve the innovation of spectrum sharing based on the heterogeneous small cells. The proposed LSAA performs better than existing works in terms of revenue and fairness and also has the properties of truthfulness and individual rationality.

7.1.3 Negotiable Size Auction

Mobile communications have relied on spectrum licensing on a per-operator basis within a geographical area. Emerging spectrum sharing in a common pool will remain the foundation for mobile communications in the 5G era, allowing multiple operators to provide high-quality connectivity in a controlled-interference sharing environment like LSA and SAS. Allowing negotiation during an auction can improve spectrum spatial efficiency and ensure interference protection. Additionally, this mechanism can well serve directly on the current LTE network without any changes of the infrastructure. The ability to provide a customized negotiable sublicense will benefit many industries around the world, enabling them to bring new products and services to market rapidly and adapt to fast-changing demands while continuing to offer and expand existing services.

7.1.4 Containerized Spectrum Sharing Systems

Dedicated spectrum for exclusive use is still the gold standard preferred to meet the expected demand from future 5G networks, but it is also vital to use the available unlicensed spectrum as efficiently as possible. New regulatory regimes will be needed to allow more flexible, shared spectrum allocation. The fact that spectrum sharing increases interference requires a clear definition of interference and any associated mutual benefits, like different tiered access methods. However, letting the player choose licensed or unlicensed accesses in manner of distribution forms non-cooperative spectrum sharing that harms the overall utility. If a centralized spectrum sharing system is placed to coordinate the players' constraints, performance can be improved.

7.2 Future Work

Spectrum management has been raised as one of the main challenges of current mobile communications, especially in the context of constant evolution. However, spectrum holders usually have not been enthusiastic in supporting spectrum sharing.

Thus, understanding the incentives to the spectrum holder will play an important role when implementing new spectrum regimes. Introducing economic awareness for spectrum sharing is considered as an effective solutions.

Next-generation 5G networks will cater for a wide range of new business opportunities some of which have yet to be conceptualized. Technologies like Software Defined Network (SDN), Cloud Radio Access Networks(CRAN) and virtualization are enabling a drastic change to take place in the network architecture allowing traditional structures to be broken down into customizable elements that can be chained together pragmatically to provide just the right level of connectivity with each element running on the architecture of its choice. This will make the short-term sublicensing much easier to be realized in a novel way of on-demand resource. This is the concept of network slicing that will enable core networks to be built in a way that maximizes flexibility.

To deploy an online auction in reality, several practical issues must also be addressed. First, the sublicense protection is assumed as a self-report contour yet in practice it has not been fully studied. Second, in the negotiable auction each bidder is provided with multiple options of the discrete coverage sizes, but it is the bidder rather than the seller that decides the size of interference-free area. In practice, who and how to define the license area is still an open question. Moreover, taking consideration of the bidder's situation, some could prefer a continuous way to shrinking the coverage sizes, but some may prefer a discrete way because of geographical issues.

Another important design principle for 5G is to decouple operator's functionality and spectrum sublicenses. The latter includes the provisioning spectrum information; that is, the availability and procedures needed for a device to access the system. Such a decoupling will allow separate scaling of base station capacity and basic system control functionality. For example, user data may be delivered by a dense spectrum sharing platform, while system information is only provided via an operator's primary layer on which a device also initially accesses the system. Then it is easy for the system to be capable of mapping service requirements to the best suitable combinations of spectrum resources and base station geographically, instead of the operator.

Appendix A

Visualization Interface

To better understand this economic-aware sublicensing scheme, we have simulated, developed and visualized this work with Matlab. The software architecture is depicted in Fig. A.1 and described as below.

Network Settings

Setup the sensor networks in a regular grid or Poisson distribution, and deploy a certain number of base stations.

- Base stations: set the number of base stations N and their geographic distribution in a region.
- Sensor networks: set the sensor resolution ρ and distribution.
- Geolocation: N base stations are depicted in a geolocation map.

Bid Profile

The bid profiles are shown in a table, where (x, y) denotes the location, *radius* denotes the interference-free range and *bid* denotes the bid over unit space.

Group Formation

The group formation methods are listed and the text box below "Groups" is to show the grouping result.

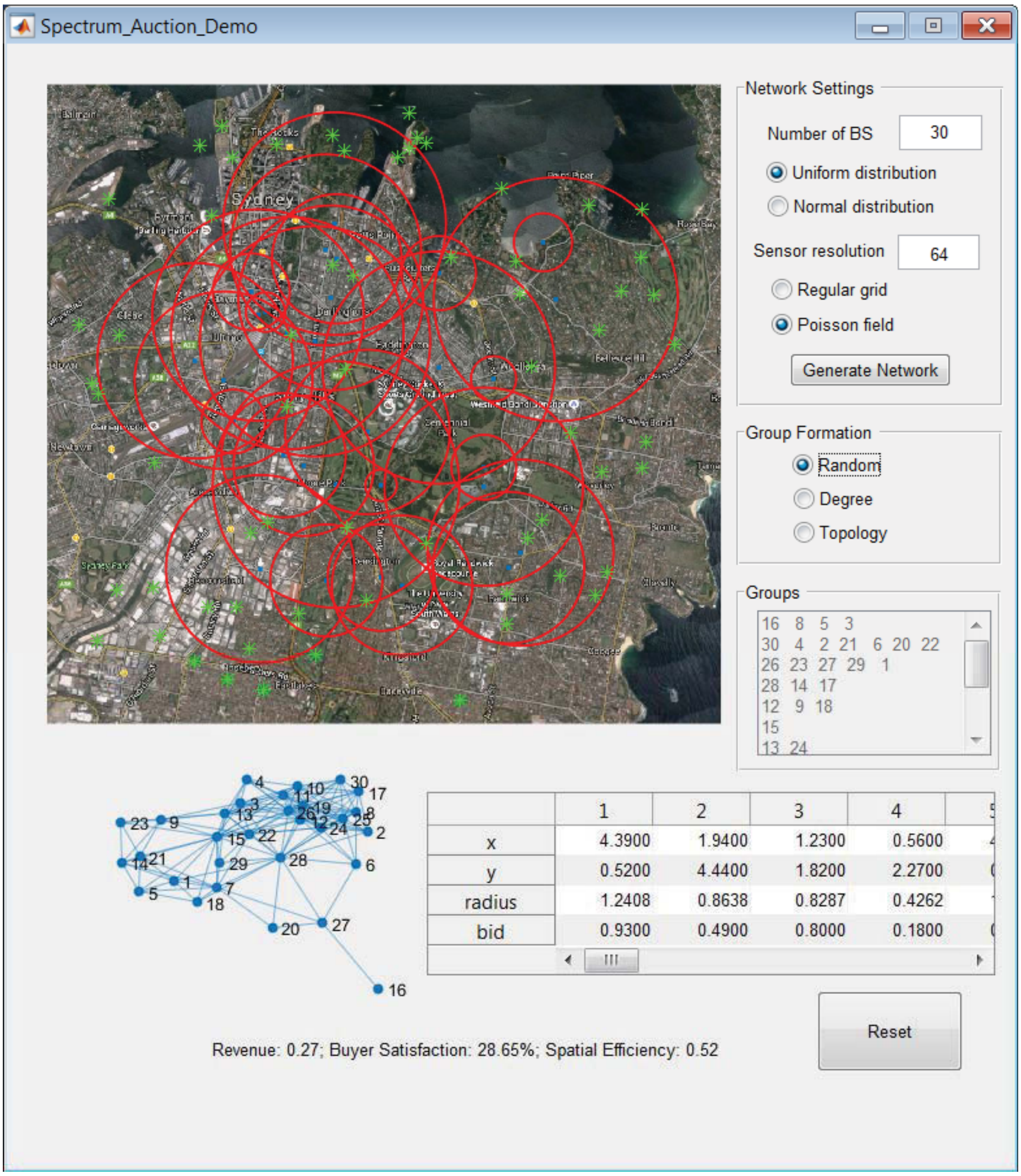


Figure A.1: A visualization interface.

Interference Graph

The corresponding interference graph is shown at the bottom left.

Simulation Result

The revenue, buyer satisfaction, and spatial efficiency are finally given.

Abbreviations

5G The 5th generation mobile networks

ACMA Australian Communications and Media Authority

AP Access Point

BS Base Station

CEPT European Conference of Postal and Telecommunications Administrations

CRAN Cloud Radio Access Networks

CSAT Carrier-Sensing Adaptive Transmission

DAG Directed Acyclic Graph

DFS Depth First Search

DSA Dynamic Spectrum Access

DSS Dynamic Spectrum Sharing

EA Equal Allocation

ECS Electronic Communications Services

EIRP Effective Isotropic Radiated Power

EPC Evolved Packet Core

ESC Environmental Sensing Capability

ETSI European Telecommunications Standardization Institute

FCC Federal Communications Commission

FM Frequency Management

GAA General Authorized Access

ICT Information and Communications Technology

IMS IP Multimedia Subsystem

IoT Internet of Things

LSA Licensed Shared Access

LSAA Licensed Spectrum Access Auction

LTE Long Term Evolution

MFCN Mobile/Fixed Communications Network

MNO Mobile Network Operator

MWPA Maximum Weight Proportional Allocation

NE Nash Equilibrium

NPRM Notice of Proposed Rule

NRA National Regulation Administration

NUM Network Utility Maximization

OAM Operation, Administration and Maintenance

PA Priority Access

PAL Priority Access License

PoA Price of Anarchy

PT Project Team

QoS Quality of Service

RAN Radio Access Network

RSPG Radio Spectrum Policy Group

RRS Reconfigurable Radio Systems

SAS Spectrum Access System

SDN Software Defined Networking

SNAM Size Negotiable Auction Mechanism

SPAL Secondary Priority Access License

SWPA Sum Weight Proportional Allocation

TCP Transmission Control Protocol

TS Technical Specification

VCG Vickrey-Clarke-Groves

WBB Wireless Broadband

WG Working Group

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