GAME THEORY BASED DYNAMIC SPECTRUM SHARING FOR NEXT-GENERATION MOBILE NETWORKS

by

Ahsan Saadat

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Department of Engineering
Faculty of Science and Engineering
Macquarie University
Sydney, Australia

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STATEMENT OF CANDIDATE

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been written by me.

In addition, I certify that all information sources and literature used are indicated in the thesis.

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Ahsan Saadat

To my family

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I am extremely fortunate to have experienced the love, care and selfless devotion showered on me by my parents; I hope today I have become a reason for their pride. My sister and brothers who have stayed by my side in all my highs and lows have an immeasurable contribution in my success. Finally, I thank my wife for her patient support throughout this journey.

ABSTRACT

Next-generation mobile networks need to ensure flexible and efficient utilisation of the radio spectrum to keep pace with the rapid growth of mobile services and applications in recent years. This thesis presents novel game-theoretic frameworks for enabling dynamic spectrum sharing to achieve spectral efficiency in next-generation mobile networks, and proposes novel ideas for dynamic allocation of spectrum resources among participating networks, while ensuring reliable quality of service (QoS) for all users through appropriate sharing rules, protocols and architectures. The spectrum-sharing schemes proposed in this thesis are categorised as power-control games for femtocell-based networks and games based on Licensed Shared Access (LSA).

The main contributions of this thesis include formulating equal-priority and multi-priority non-cooperative power-control games for femtocell-based networks to achieve interference mitigation such that the QoS of the users served by the femtocells is not compromised. During the game, each femtocell, serving either the primary users or the secondary users of the spectrum, dynamically adjusts its transmit power until the transmit power is stabilised, adapting to its interference measurement and traffic. It is shown that the existence and uniqueness of the Nash equilibrium of the non-cooperative game can be achieved by carefully selecting the game parameters, which are designed to determine the priority status of the femtocells. Furthermore, the real-time signalling overhead is minimised

between the networks through a novel dual-mode solution.

Another key contribution of this thesis is the application of game-theoretic principles for dynamic spectrum sharing using LSA. A two-layer LSA-based evolutionary game is proposed which ensures demand-driven allocation of spectrum resources to LSA licensees. The scheme also incorporates dynamic price-adjustment strategies adopted by incumbents to ensure an improved total gain for the incumbents. The stability of the proposed evolutionary algorithm is proved using Lyapunov stability criteria. Furthermore, a practical scenario of LSA-based spectrum sharing is considered, and the LSA architecture is modified to enable mobile network operators acting as domestic licensees to provide an enhanced QoS in border areas, for minimising the effects of cross-border interference.

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- **Publication 1:** A. Saadat, G. Fang, and W. Ni, “A two-tier evolutionary game theoretic approach to dynamic spectrum sharing through licensed shared access ”, *in 15th IEEE International Conference on Computer and Information Technology (CIT-2015)*, pp. 6-11, 26-28 October 2015, Liverpool, UK.

- **Publication 2:** A. Saadat, G. Fang, E. Dutkiewicz, M. Mueck and S. Srikanteswara, “Enhanced QoS for domestic licensees in border areas through game theory based licensed shared access”, *in 16th International Symposium on Communications and Information Technologies (ISCIT-2016)*, pp. 44-47, 26-28 September 2016, Qingdao, China.

- **Publication 3:** A. Saadat, W. Ni, R. Vesilo and Q. Cui, “ Errata to the paper “An evolutionary game theoretic framework for femtocell radio resource management”,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 8610-8612, Dec. 2016.

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Chapter 1

Introduction and Motivation

With smart devices becoming increasingly ubiquitous, the demand for mobile services has undergone a rapid increase in recent years. Mobile users increasingly demand on-the-go connectivity, be it for location-based services, high-definition video streaming, or networked multi-player video games. Such real-time services have resulted in an unprecedented rise in mobile data traffic. According to a report by Cisco [1] the total global mobile data traffic has increased 4,000-fold over the past decade, with an increase of 74% in 2015 alone. The total global mobile data traffic was recorded as 3.7 exabytes per month at the end of 2015; to cope with the increase in capacity, approximately 51% of the total traffic in 2015 was offloaded onto the fixed network using small cells (femtocells) or Wi-Fi. Moreover, 563 million new mobile devices and connections were seen in 2015. Mobile video streaming appeared to be the key contributor in this trend, consuming up to 55% of the total mobile data traffic. The exponential growth in traffic is expected to continue over the next decade, with the accumulated global mobile data traffic for the period 2016 – 2021 expected to reach 1,600 exabytes. 9100 million mobile subscriptions are expected in 2021 [2].

Mobile users now require unprecedented mobile data speeds that existing mobile technologies are unable to cope with. If mobile service providers are to keep up with the demands of their users, there is a dire need for next-generation mobile networks and wireless technologies. In this regard, fifth-generation mobile network technology (5G) has been a much-investigated topic among academic researchers and the mobile industry in recent years [3–5]. 5G promises to satisfy the anticipated explosion in user demand. Specifically, the expectation from 5G technologies is to be able to deliver data with a delay of no more than a couple of milliseconds [6], compared with the approximate 70 ms delay expected from 4G networks, and to ensure peak download speeds of up to 20 Gb/s, which is twenty times greater than the current maximum under 4G networks [7]. For instance, users of the current 4G mobile technology expect to wait for at least thirty minutes to download a typical ninety-minute, 1080p-resolution movie; 5G promises to bring the downloading time to a few seconds [8]. Furthermore, while it is expected to speed up currently available mobile services, the 5G vision extends far beyond higher data rates; it is envisioned to become an enabling technology for novel, mission-critical services, for example autonomous vehicles, virtual reality, and remotely controlling medical procedures or personal property with the Internet of Things [3], by supporting their real-time connectivity and reliability requirements [7].

However, next-generation mobile networks are not expected to be deployed in this decade; the first commercial 5G network is expected to debut in the early 2020s [7]. Currently, 5G technologies are very much in the planning phase, with academic and industry researchers and engineers working towards establishing standards and implementation schemes. At the present, some examples of the enabling technologies for 5G implementation under consideration include small cells, millimetre waves, and massive MIMO.

1.1 Next-Generation Spectrum Requirements

The development and implementation of next-generation technologies is the only viable solution for mobile network services to keep pace with the recent boom in mobile data traffic. However, next-generation mobile applications are bandwidth-hungry, and have raised a dramatically increased demand for radio spectrum [9, 10] to serve the additional capacity needs of Mobile Network Operators (MNOs). With the explosion in the number of connected devices and increasingly bandwidth-hungry applications, the demand for spectrum will only increase – and rapidly so. Thus, legacy spectrum allocation approaches, based on rigid allocation of spectrum bands that cannot be shared, will fast become obsolete as they fail to meet the rising demand. There is a dire need to roll out a new approach to spectrum allocation, where spectrum can be flexibly shared among all categories of networks, be it satellites, military networks, or wireless internet and mobile service providers, according to the need of the hour. This understanding has increasingly led governments, academia, and the industry to collaborate on designing new dynamic spectrum-sharing solutions and draft policies to facilitate such a paradigm shift. Solving the problem of artificial spectrum scarcity, therefore, is an urgent need of our time to enable worldwide adoption of fifth-generation technology for a better user experience [9].

1.1.1 Creating New Spectrum Resources

The allocation of radio spectrum is regulated by national regulatory bodies such as the Federal Communications Commission (FCC) in the USA. Licensed spectrum users, also known as *primary network users*, are assigned spectrum bands by the FCC on a long-term basis for large geographical regions. Intuitively, it appears that it should be possible to meet the need for additional spectrum simply by creating additional spectrum bands which can be licensed out to new users as well as existing primary network users with expanding needs. Unfortunately, in the radio-frequency zones, only a very limited number of spectrum bands are available, which are not enough to meet the next-generation spectrum demands of MNOs. As the existing spectrum allocation is rigid, i.e. the licensed bands can not be shared among MNOs, and more bands are simply not available, this has put a limitation on the capacity that the MNOs can offer, resulting in slow or at worst dropped connections in peak-traffic scenarios. One solution for creating new spectrum resources is to move beyond the current radio spectrum to exploit frequency ranges that have not been used for mobile services before. In this regard, millimetre waves, currently used by satellite operators and radar systems, are being proposed for mobile data transmission. Under this approach, transmission frequencies would lie in higher bands (30 to 300 GHz) as compared to the current radio frequencies (below 6 GHz) [7], resulting in ample new spectrum to meet the higher capacity needs of next-generation networks. However, although experiments are underway to use millimetre waves for cellular communication, a practical deployment is far from becoming a reality, as it involves major changes to current hardware and software infrastructure. Moreover, millimetre waves suffer from their own drawbacks, such as low penetration in urban environments.

1.1.2 Efficient Use of Existing Spectrum Resources

A more realistic solution emerges from the fact that portions of the spectrum exclusively dedicated to primary network users often remain unused, resulting in inefficient usage of the spectrum for the times when it is not being used by the primary networks. This under-utilisation of the spectrum results in an artificial spectrum scarcity for the secondary networks [11]. To mitigate this, there is a need for the development of *dynamic spectrum access* techniques that can allow unlicensed spectrum users, known as *secondary network users*, to access the white spaces present in the dedicated, licensed spectrum of primary network users. The idea of dynamically sharing spectrum resources has been discussed in the context of two paradigms: a *property rights* model under which the primary owners of particular spectrum bands can allow secondary users temporary access to parts of the band under certain agreements in exchange for a fee, and a *commons* model which regards spectrum as a shared resource that can be openly shared among interested users [12].

Property Rights Model

The property rights model allows the individual owners of particular spectrum bands to utilise, trade, sell, rent or lease their licensed spectrum [13]. The exclusive ownership and subsequent rights that the owners (i.e. the primary network users or licensed spectrum users or incumbents) possess, enable them to experience seamless connectivity and achieve their desired quality of service (QoS) without any uncertainty. Each incumbent can buy a licence to access a particular frequency spectrum band by paying the prescribed fee, which allows the incumbent to utilise the band exclusively for its operation, thus achieving its desired QoS. Since no other network can utilise the band licensed to a particular incumbent without approval, this model guarantees that the licensed spectrum users (incumbents) experience no interference from other network operations. However, this model often results in under-utilisation of the spectrum [12]. According to spectrum occupancy statistics reported in [14], 13% to 87% of the licensed spectrum remains idle at different times of the day.

Commons Model

According to the commons model (also known as spectrum commons), the frequency spectrum is treated as a common resource and is subject to open sharing among interested access systems, i.e. it is shared among all interested parties [15,16]. For example, wireless services such as bluetooth or Wi-Fi can access the unlicensed industrial, scientific, and medical (ISM) radio band. Although this model allows the systems to access the spectrum without rigid spectral boundaries, the coexistence of multiple systems makes it challenging for the users to meet their QoS requirements [12].

With the boom in demand for radio spectrum, spectrum management bodies and regulatory authorities have been considering the merits of both models, i.e. the property rights model and the commons model [17, 18], while the industrial community has emphasised the importance of flexible spectrum-access mechanisms [19, 20]. While MNOs have traditionally preferred the property rights model as incumbents to ensure full control over their portion of the spectrum, in recent times they have shown a keen interest in enabling dynamic access to additional spectrum (originally licensed to other incumbents) in order to meet the increased capacity demand [21]. Currently, MNOs can utilise their exclusively licensed spectrum bands to anchor connections and ensure that their target QoS is achieved, but at the same time they would benefit greatly from the ability to access additional spectrum (not originally licensed to them) in a flexible manner based on the variation in demand during peak traffic times in order to meet additional capacity needs. With 5G in its inception stage, to cope with booming traffic demands dynamic sharing of the frequency spectrum is the right way forward as an efficient way to solve the spectrum scarcity problem for next-generation networks [22, 23]. Dynamic spectrum sharing, on one hand, improves the spectral efficiency, and on the other hand ensures provision of additional capacity for users who need more spectrum for their 5G applications [23]. Thus, the spectrum regulatory authorities in the European Union (EU) [24, 25] and the USA [26, 27] are promoting the development of innovative spectrum-sharing schemes that ensure efficient spectrum utilisation, while maintaining the quality of service of both primary network users and secondary network users.

1.2 Spectrum-Sharing Techniques and Challenges

Among the techniques that have been studied in the context of enabling dynamic and flexible spectrum sharing, some of the key schemes are cognitive radio, femtocells, and licensed shared access.

1.2.1 Cognitive Radio

Cognitive radio technology is a widely researched technique to enable spectrum sharing and avoid spectrum under-utilisation. A cognitive radio is able to intelligently acquire necessary information from its environment and select channels for transmission in an under-utilised licensed band. Based on an analysis of channel characteristics such as transmission frequency, bandwidth, power, or modulation, it can identify the best channels available for secondary users to access. A cognitive radio must be reconfigurable in order to instantly adjust the operational parameters to ensure interference-free, optimal performance for the secondary users. However, there is a need to develop useful spectrum-sharing schemes for cognitive radio technology, especially in situations where primary and secondary users coexist. For instance, the idea of power control has been proposed to mitigate the interference resulting from the coexistence of multiple networks, where each user is required to control its transmit power according to a set of rules to avoid unacceptable interference to other users.

1.2.2 Femtocells

Femtocells, also known as small cells, are expected to play a vital role in future spectrum-sharing schemes as they can provide better coverage for MNOs, who can use them to offload mobile data traffic from macrocells using the available spectrum resources [28, 29]. Femtocells are low-power, low-cost, portable miniature base stations, which can be deployed within half a kilometre of each other in areas with high data traffic, for example a commercial building or shopping centre. When installed in a group in a dense area, these cells act like relays, receiving signals from the main base stations and passing them on to users; thus, femtocells help maintain user connectivity in situations where it may otherwise have been intermittent and unreliable owing to the heavy load. To support 5G networks, MNOs have the option to completely overhaul their infrastructure, or utilise the benefits provided by femtocells (to avoid complete overhaul) as femtocells are easily mountable on power poles and atop buildings. This flexible network structure can ensure targeted and efficient use of the MNO's spectrum in next-generation mobile networks [7]. However, the placements of these cells, the distances between them, and their power budgets need to be carefully selected, so that cells using the same frequencies are either placed far apart or allowed to control their transmit power to limit interference.

In fact, the primary challenge for femtocell-based spectrum sharing is to overcome inter-tier and intra-tier interference to avoid performance degradation [30]. Traditionally, there are two modes of femtocell deployment: separate-channel deployment and co-channel deployment [31]. Under separate-channel deployment, the femtocell operation is carried out in a specific separate channel which is not being used by the macrocells. Thus, inter-tier interference is avoided in this setting. When the femtocells share the spectrum with the macrocells, this arrangement is called co-channel deployment which is often preferred by the MNOs. However, this setting introduces the challenge of inter-tier interference; to mitigate this, complex coordination among all cells is required. Thus, in both cases interference management is essential [31].

1.2.3 Licensed Shared Access

Licensed Shared Access (LSA) schemes have recently gained popularity as a solution for efficient utilisation of spectrum resources [24]. LSA is a dynamic spectrum-sharing framework, where the unused spectrum of *incumbents* (licensed spectrum users or primary network users) can be shared with *licensees* (unlicensed spectrum users or secondary network users) to provide mobile services [32]. According to the European Conference of Postal and Telecommunications Administrations (CEPT), LSA is a recognised spectrum-sharing solution for the introduction of Mobile/Fixed Communications Networks (MFCN) in the 2.3 GHz band without affecting the existing utilisation of the frequency band by the relevant incumbents [21, 33].

Under an LSA-based spectrum-sharing regime, the frequency spectrum can be shared based on predefined conditions [34]. Unlike cognitive radio, LSA does not require the transmitting devices to be equipped with the capability to sense spectral availability, as the available spectrum that can be leased is advertised through out-of-band signalling [35]. Furthermore, LSA addresses key spectrum-sharing issues such as uncertainties about long-term spectrum availability for the secondary users (LSA licensees). Successful implementation of LSA-based technologies involves the challenges of ensuring a reliable quality of service for participating incumbents and licensees through sharing agreements and suitable communication protocols [24, 25]. Specifically, an LSA system allows licensees to achieve their target QoS by providing them with spectrum resources with an agreed availability guarantee. Thus, major wireless-industry manufacturers such as Intel, Qualcomm, Nokia, etc. are leading 5G research on implementation of LSA schemes for MNOs [20,36].

1.2.4 Spectrum Sharing Challenges

The coexistence of primary network users and secondary network users while sharing available spectrum resources poses a number of challenges. Firstly, this arrangement must not degrade the QoS of the primary network users, i.e. the secondary network operation must not cause harmful interference to the primary network operation [28]. As a solution, effective interference management and power-control schemes are needed to achieve the objective of maintaining the QoS of the primary network users, while allowing the secondary network users to exploit the surplus network capacity [29]. Secondly, contemporary spectrum-sharing schemes require coordination between network users, to enable information exchange and ensure enforcement of spectrum-sharing rules [9]. Thus, any information exchange between the systems must avoid an excessive signalling overhead to avoid real-time delays. Thirdly, for enabling spectrum sharing, sufficient intelligence features need to be incorporated in dynamic spectrum-access systems so that they can observe the radio-frequency (RF) environment and adapt their transmission parameters accordingly without the compulsion of cooperating with each other [37]. While spectrum sensing is particularly important for secondary networks [38], the ability of learning and adapting to the RF environment is equally important for both primary and secondary networks so that they can avoid causing interference, while minimising the signalling overhead.

1.3 Thesis Organisation

1.3.1 Thesis Objectives

This research aims to investigate novel dynamic spectrum-sharing methods to improve spectral efficiency for next-generation mobile networks. The research goals include investigating such methods, which can perform dynamic allocation of the radio-frequency spectrum to unlicensed spectrum users (secondary network users or LSA licensees), without affecting the QoS of the licensed spectrum users (primary network users or incumbents). The desired solution is expected to guarantee increased spectral efficiency and ensure a reliable QoS for all users through appropriate sharing rules, agreements, protocols and architectures.

This thesis applies game-theoretic principles on dynamic spectrum-sharing models, and provides performance analysis. The proposed dynamic spectrum-sharing schemes cover two aspects of spectrum sharing. Firstly, spectrum-sharing schemes for femtocell-based networks are presented to achieve the targets of interference mitigation, minimising signalling overhead during information exchange, and improved QoS for network users. Secondly, game-theoretic principles are applied to LSA-based spectrum-sharing scenarios, enabling the licensees to achieve improved QoS under an agreed set of spectrum-sharing rules.

The key objectives of this thesis are listed below:

1. To investigate novel dynamic spectrum-sharing techniques, ensuring that the quality of service of all the users participating in the spectrum-sharing process is maintained or improved by proposing appropriate solutions to ensure interference mitigation and minimising signalling overhead.

2. To investigate suitability of various contemporary spectrum-sharing frameworks for our analysis and selecting appropriate techniques and scenarios.

3. To formulate a mathematical model for representing spectrum sharing in selected scenarios, and to design appropriate adjustable system parameters and functions, which can be adjusted to facilitate the analysis of the performance of the network users under study in selected spectrum-sharing frameworks.

4. To identify appropriate game-theoretic approaches to facilitate analysis of dynamic spectrum sharing in proposed system models, and to identify the resources to be allocated, e.g. power for downlink transmission or bandwidth.

5. To investigate novel spectrum-sharing requirements, and proposing novel spectrum-sharing frameworks which can enable unlicensed spectrum users to achieve improved

gains by getting the right to access the licensed spectrum under an agreed set of conditions.

6. To formulate a mathematical model for representing game-theoretic spectrum sharing, and to design appropriate sharing rules, protocols and architectures to facilitate performance analysis.

1.3.2 Thesis Contributions

Throughout this thesis, novel game-theoretic approaches are presented to enable dynamic spectrum sharing for next-generation mobile networks. The key contributions in this regard are as follows:

1. A game-theoretic framework to enable spectrum resource management for next-generation heterogeneous mobile networks is proposed, which considers the coexistence of a set of femtocells, belonging to multiple networks, in a coverage area where all cells have an equal priority for accessing the spectrum. A non-cooperative transmit power-control game is formulated, in which all the femtocells share the spectrum by adjusting their transmit powers, based on measured interference, until the transmit power is stabilised. By designing appropriate game parameters, such as a static price coefficient, the existence and uniqueness of the Nash equilibrium of the proposed non-cooperative power-control game is ensured. Furthermore, a dual-mode solution is presented to minimise the signalling overhead for any information exchange during the game.
   (Supported by Publication 3 and Publication 4)

2. A multi-priority game-theoretic spectrum-sharing framework for next-generation mobile networks is proposed, where the primary network shares the spectrum resources licensed to it with the secondary network in a non-cooperative power-control

game. The proposed scheme guarantees that the primary network users can maintain their desired QoS during the spectrum-sharing process. The proposed game considers the coexistence of a set of femtocells in a coverage area, and allows the network nodes to adjust their transmit powers, based on measured interference, until the transmit power is stabilised. By designing appropriate game parameters, such as a dynamic price coefficient, which is used to give the primary network nodes priority over the secondary network nodes, the existence and uniqueness of the Nash equilibrium of the non-cooperative game is ensured. A modified dual-mode solution is presented to minimise the signalling overhead for any information exchange during this multi-priority game.

(Supported by Publication 5)

3. A two-layer evolutionary game for dynamic spectrum sharing using Licensed Shared Access (LSA) is formulated, ensuring demand-driven allocation of spectrum resources to LSA licensees, and guaranteeing spectrum availability for licensees, unlike previous spectrum-sharing techniques. The incumbents are allowed to charge a price for their spectrum, and the evolutionary game is further extended by modelling the dynamic price-adjustment strategies adopted by incumbents, achieving an improved total gain for the incumbents. The stability of the proposed evolutionary algorithm is proved using Lyapunov stability criteria, and the convergence of the average licensee payoff to an equilibrium point is shown.

   (Supported by Publication 1)

4. An LSA-based spectrum-sharing scenario is considered, where game-theoretic principles are applied to formulate a non-coordinated LSA model which enables MNOs acting as domestic licensees to provide an enhanced QoS in border areas. The proposed spectrum-sharing model introduces backup strategies for the domestic

licensees, enabling them to maintain their QoS in border areas. An LSA-based game-theoretic algorithm is proposed, and the convergence of this game-theoretic algorithm to an equilibrium point after a finite number of iterations is proved. **(Supported by Publication 2)**

1.3.3 Thesis Outline

In this chapter, a brief overview of the motivation behind dynamic spectrum sharing as a solution to the spectrum-scarcity problem to meet 5G traffic demands is provided. Chapter 2 provides the background and motivation of the proposed research on dynamic spectrum sharing by presenting a literature review focussing on applications of game theory in spectrum sharing. The chapter also covers the basics of relevant game-theoretic techniques, which are used to formulate the proposed game-theoretic spectrum-sharing schemes in later chapters. In Chapter 3, an equal-priority power-control game for spectrum sharing in femtocell-based networks is formulated and a throughput performance analysis is presented. This non-cooperative power-control game enables spectrum sharing among a set of femtocells by awarding equal priority for accessing the spectrum to all the network nodes. Building on the work presented in Chapter 3, a multi-priority game-theoretic spectrum-sharing framework is presented in Chapter 4 for dynamic spectrum sharing among a set of femtocells. The femtocells, serving either the primary network users or the secondary network users, participate in a non-cooperative power-control game, where the primary network users are rewarded for sharing their spectrum as they are enabled to achieve improved throughput. Chapter 5 proposes a two-layer evolutionary game for dynamic spectrum sharing using LSA to serve the additional capacity needs of MNOs. The proposed game ensures demand-driven allocation of spectrum resources to LSA licensees, and converges to an equilibrium point. Chapter 6 presents a non-coordinated LSA model through backup strategy-based dynamic spectrum sharing for domestic licensees in border areas. The proposed solution ensures that the domestic licensees are equipped to provide enhanced QoS in border areas by reacting efficiently to the interference caused by foreign incumbent operations. Chapter 7 concludes the thesis by summarising the contributions of the thesis regarding dynamic spectrum sharing using game theory, and highlighting future work ideas. The thesis outline is illustrated graphically in Figure 1.1.

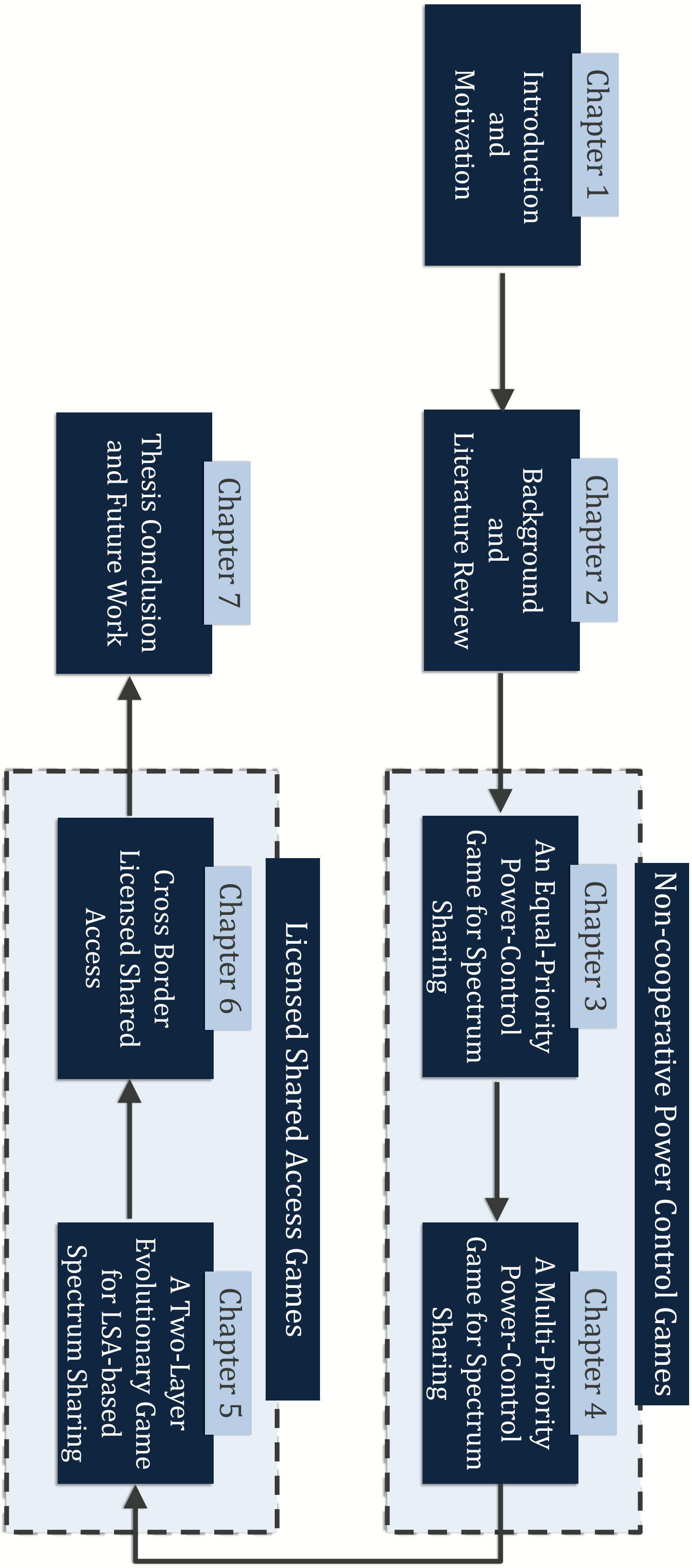

Figure 1.1: Thesis outline.

Chapter 2

Background and Literature Review

2.1 Introduction

This chapter provides an overview of the promising features of 4G (Fourth-Generation Mobile Networks) and modern mobile technologies, as well as an account of traditional and contemporary spectrum-sharing techniques and the recent initiatives taken to solve the spectrum scarcity problem for next-generation mobile networks. Some basic terminology is presented which will be referred to in this thesis with regards to game-theoretic spectrum-sharing approaches. Lastly, a literature review regarding the application of game theory in spectrum sharing is provided.

2.2 Current and Future Mobile Networks

Over the years, mobile networks have undergone remarkable technological advancement to keep pace with growing user demand. This progressive growth has been governed through development of standards. The most recent standardised generation of mobile networks is 4G. Salient features of current and next-generation mobile networks are outlined in the following sections.

2.2.1 Fourth-Generation Mobile Networks (4G)

The fourth generation of mobile networks (4G) refers to technologies which are compliant with the International Mobile Telecommunications Advanced (IMT-Advanced) requirements. Unlike 3G, this generation is a dedicated packet-switching based technology, benefiting from the flexibility provided by the Internet Protocol (IP). The most primary specification of an IMT-Advanced compliant technology is to ensure the capability of offering peak data rates of up to 1 Gbps in a static environment and up to 100 Mbps for high-speed mobile environments. Overall, the key characteristics of 4G include [39]:

- Support for high mobility;
- Support for data rates of up to 100 Mbps (high mobility), or 1 Gbps (low mobility);
- Cooperation between different networks/access systems, with a unified architecture;
- Network detection and network selection (uses the concept of ABC: Always Best Connected);
- Independence from technology and topology.

One technology that qualifies as 4G is LTE-Advanced, which meets the IMT-Advanced requirements on mobility, transmission bandwidth and data rates, and maintains the backward compatibility with LTE systems [40]. For wider adoption, the backward compatibility of LTE-Advanced with earlier 3GPP releases is ensured. LTE-Advanced can achieve high data rates using carrier aggregation of different spectrum portions. In carrier aggregation, each portion of the spectrum, termed “component carrier”, can be allocated flexibly to different users. Moreover, these component carriers can be flexibly aggregated to support varying high data rates and large bandwidth to suit application requirements [40]. Overall, the following five features are generally considered to be the distinguishing aspects of LTE-Advanced, from its predecessors [41]:

- Carrier aggregation (increased spectrum bandwidth);
- Higher-order MIMO (increased capacity and data rate);
- Heterogeneous networks and relay nodes (better coverage and capacity at cell edges);
- Enhanced inter-cell interference coordination (interference management and mitigation procedure);
- Coordinated multipoint (CoMP) transmission for better utilisation of system resources/ better user experience.

2.2.2 Fifth-Generation Mobile Networks (5G)

To go beyond 4G, not only do the requirements set up by IMT-Advanced need to be surpassed significantly, but there is also a need to ensure cost-effective, spectrally-efficient and energy-efficient advancements in technology for a wider adoption [42–44]. Thus, 5G must have the flexibility to utilise the benefits available in previous-generation technologies, but at the same time, provide a paradigm shift for worldwide mobile technological adoption.

The fifth generation (5G) of mobile networks has been a topic of keen interest among academic researchers and the mobile industry in recent times [45–48]. Table 2.1 summarises the key performance indicators (KPIs) for 5G proposed by different organisations [6]. However, in order to meet these high data rates and 5G requirements, the spectrum requirements for next-generation mobile networks need to be estimated. Thus, the ITU-R has taken a leading role in Europe to predict the future spectrum demand for international mobile telecommunication (IMT) [6].

Table 2.1: Selected 5G KPIs Proposed by Different Organisations.

KPI	**4G ITU Requirement**	**METIS (Europe)**	**5G Forum (Korea)**
Peak data rate	1 Gb/s	10-100 Gb/s	50 Gb/s
Cell edge user data rate	6 Mb/s	6-600 Mb/s	1 Gb/s
User plane latency	10 ms	2 ms	1ms

In general, a 5G terminal must meet the following requirements [39]:

- It must support the capability to access and choose between different wireless/mobile technologies using environment knowledge;
- It will be required to include more adaptors based on access networks selected for transmission (WLAN, 3G, 2G, etc. adaptors);
- It should support switching on various technologies during the same session – i.e. until the terminal makes a final selection about the access system, the supported technologies must provide user mobility;
- It must be capable of combining and distinguishing between different streams coming from multiple technologies;
- It must deliver higher performance through enhanced modulation and error-correction schemes.

Furthermore, a subset of the requirements being discussed for 5G from the OSI (Open Systems Interconnection) layer perspective are listed below [39]:

- The type of technology selected by the terminal will define the functionality of the first and second layers;
- The third layer will constitute a total IP integration;

- The terminal will have a single fixed address and multiple temporary care-of-addresses (CoA), to facilitate the connected and unconnected access networks;
- The network layer will include three sub-layers: a sub-layer to handle CoA address, a sub-layer for performing address translation to IPv6 fixed address, and a sub-layer utilising the fixed terminals IPv6 address;
- The information about the transport protocols, from a transport-layer perspective, will be provided by the wireless technology being accessed;
- The application layer will be responsible for ensuring intelligent QoS management over all supported networks.

2.3 Spectrum-Sharing Techniques and Initiatives

This section provides an account of traditional and contemporary spectrum-sharing techniques and the recent initiatives taken to solve the spectrum scarcity problem for next-generation mobile networks.

2.3.1 Cognitive Radio

In order to utilise the congested radio-frequency (RF) spectrum efficiently, one of the most researched technologies is cognitive radio, a software defined radio based technique for spectral efficiency. Under this technique, unused portions of the radio spectrum allocated to primary or licensed spectrum users can be utilised by secondary or unlicensed spectrum users. A cognitive radio based secondary network is able to efficiently observe and estimate the characteristics of the spectrum of the primary network to identify spectrum white spaces, which can then be used for the secondary users' communication. Cognitive radio schemes should ensure that the communication quality of the primary users must not be degraded due to interference from secondary users. It needs to be ensured that the interference experienced by the primary networks remains under a predefined threshold.

2.3.2 Licensed Shared Access

Licensed Shared Access, or LSA, is a promising future technology for efficient RF spectrum utilisation. LSA is an initiative regarding next-generation standardisation efforts in Europe, and in [49] the Radio Spectrum Policy Group (RSPG) has defined LSA as *"A regulatory approach aiming to facilitate the introduction of radiocommunication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the Licensed Shared Access (LSA) approach, the additional users are authorised to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorised users, including incumbents, to provide a certain Quality of Service (QoS)"*.

The significance of LSA-based solutions as a 5G contender cannot be overlooked, as the primary goal is to maintain a reliable QoS for all participating users through sharing agreements and suitable communication protocols [24,25]. Under LSA, the primary users to which a portion of the RF spectrum is originally licensed are called *incumbents*, and secondary users who wish to share the incumbents' spectrum are called *licensees*. LSA can enable dynamic spectrum sharing by sharing idle incumbent spectrum with licensees so that they can meet their additional capacity needs to provide mobile services [32]. LSA is different from previous spectrum-sharing techniques such as cognitive radio as it does not require the procedure of spectrum sensing and guarantees long-term spectrum availability. The licensees are informed of the available spectrum during their agreement with the incumbents, and the spectrum availability at run-time is advertised through out-of-band signalling [35]. While the primary objective of LSA-based sharing is to allow licensees to use the idle spectrum of incumbents, it has also been proposed that sharing agreements should be designed to allow coexistence between licensees and incumbents, provided that the licensee operation does not cause interference to the incumbent operation.

The LSA system includes an LSA controller, LSA repository and LSA regulator [50]. The functions of these elements are outlined below and depicted graphically in Figure 2.1.

1. LSA repository: The LSA repository is essentially a database containing a list of the available frequency bands to be shared under the LSA-based sharing agreements. As these frequency bands can be used by the incumbents or the licensees, the repository also maintains information about usage details of incumbents, such as usage time and geographical location. The conditions under which the spectrum is to be shared are also provided to the repository. Generally, the input data in the repository comes from the incumbents and the LSA controller, according to the rules set by the LSA regulator.

2. LSA controller: The LSA controller is the front-end of licensees for accessing the available spectrum using LSA. Thus, the LSA controller enables the licensees to access the spectrum, using the usage details and sharing conditions contained in the LSA repository.

3. LSA regulator: The spectrum-sharing conditions of an LSA sharing agreement, negotiated between the LSA licensee, the regulator and the incumbent, are provided by the LSA regulator to the LSA repository. These rules only need to be provided at the time of the LSA agreement, and they remain valid throughout an LSA-based sharing process. The LSA agreement (also referred to as the "sharing framework") usually contains information about the duration of the agreement, incumbent usage details, the required evacuation time set by the incumbent and the protection criteria laid out by each incumbent.

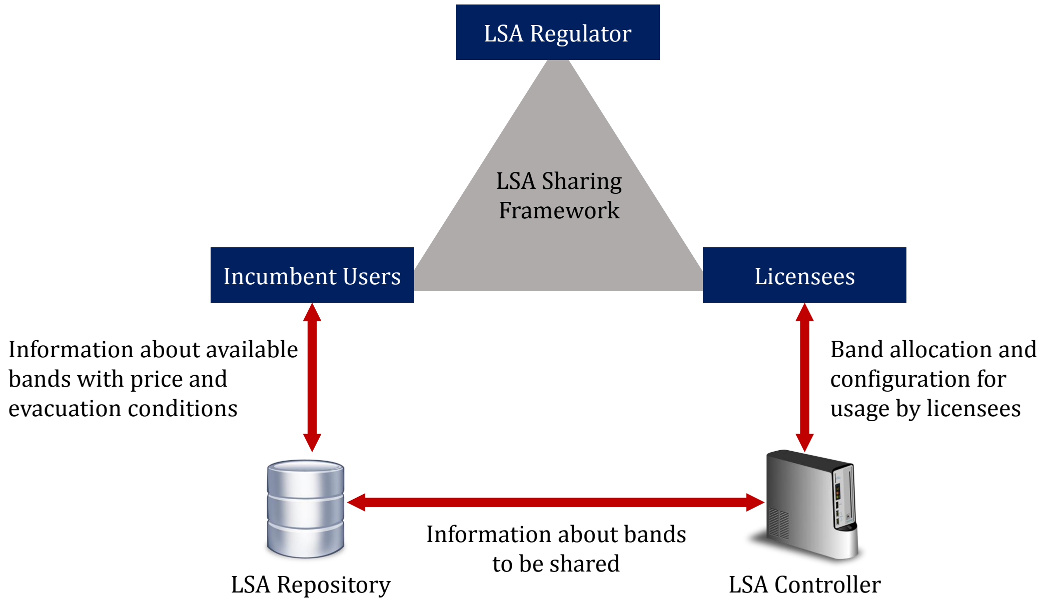

Figure 2.1: A general overview of the LSA system architecture.

2.3.3 Spectrum-Sharing Initiatives in the USA

In [9], a comprehensive overview of recent initiatives and challenges for dynamic spectrum sharing is provided. A subset of these initiatives is briefly summarised below:

TV Band:

The FCC allowed low-power unlicensed devices to utilise unused channels in the TV broadcast bands (TV white spaces) in the USA in September 2010 [9, 51]. The IEEE standards which enable operation in these bands are IEEE 802.22 and IEEE 802.11af. To cater to the technical limitations of sensing and risks of interference, a database-driven approach has been mandated by the FCC when using these bands, where a spectrum-access device can exchange information with the database to obtain spectrum availability information and operational parameters.

AWS-3 Band:

An auction of AWS-3 licences was completed by the FCC in January 2015, where the AWS-3 bands comprise the 1695 - 1710 MHz, 1755 - 1780 MHz, and 2155 - 2180 MHz bands [9]. The incumbent spectrum users of this band are Federal systems and the federal meteorological-satellite systems with whom cellular service providers can share the spectrum by manually coordinating protection zones to protect the incumbents [9, 52].

3.5 GHz Band:

The secondary users are now allowed to utilise the 3.5 GHz (3550 - 3700 MHz) band according to the recent Report and Order and Second Further Notice of Proposed Rule Making (FNPRM) issued by the FCC [9, 53]. The new Citizens Broadband Radio Service (CBRS) will be utilising this band. The primary users (incumbents) and secondary users will share the spectrum using a three-tiered access model comprising the Incumbent Access, Priority Access and General Authorised Access tiers. An automated frequency assignment and control-database mechanism introduced as the Spectrum Access System (SAS) can be employed to ensure the harmonious coexistence of users belonging to these three tiers.

5 GHz Band:

In the Notice of Proposed Rule Making (NPRM) [54] released by the FCC in 2013, the intention for modification of rules governing the operation of Unlicensed National Information Infrastructure (U-NII) devices was announced. It was also announced that an additional 195 MHz of spectrum in the 5 GHz band may be made available. Following that, the First Report and Order [55] released by the FCC in 2014 aims to increase the utility of the 5 GHz band which will require modifications in the relevant U-NII rules and testing procedures. The purpose of these modifications is to make sure that the operation of U-NII devices does not result in causing any harmful interference to the operation of Dedicated Short Range Communications (DSRC) systems which are incumbent users of these bands. A new set of rules is required for utilisation of this band (to be termed the U-NII-4 band), which is in the development stages at the FCC. Further details of activities and progress regarding the U-NII-4 band, focussing on sharing between 802.11 and DSRC, are available in [56].

Millimetre-Wave Bands:

The rules regarding the 57 - 64 GHz band or the 60 GHz band were changed by the FCC in August 2013, to ensure improved utilisation of this unlicensed spectrum. This band offers high-capacity, short-range outdoor backhaul for small cells. The spectrum users of the 60 GHz band are determined by a co-primary allocation between the federal mobile, fixed, inter-satellite and radio-location services, and the non-federal fixed, mobile and radio-location services. There is also a possibility that devices currently operating in the industrial, scientific and medical (ISM) band can also operate in this 60 GHz band in future [9, 57].

2.4 Femtocells

Femtocells, often termed as small cells, are low-power access points, which are used indoors to boost network capacity as their installation provides its users access to the cellular core network [31]. Femtocell base stations (FBSs) ensure that in an indoor arrangement, mobile devices can receive high quality multimedia and voice services. The cellular core network can be accessed by the user equipment through subscribers broadband internet access, cable broadband connection or optical fibre [58, 59]. Moreover, Wi-Fi is often used for accessing the core network. Another mode of accessing the core network is

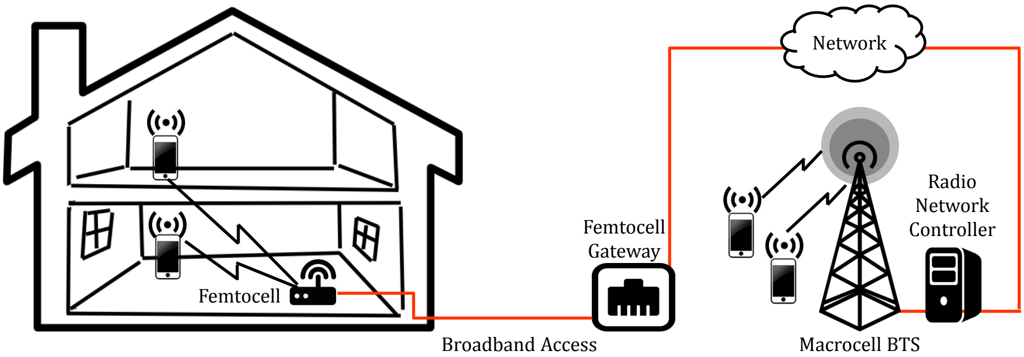

Figure 2.2: A typical illustration of femtocell network in comparison with macrocells.

through a satellite internet connection, which is often the only, yet challenging option in remote areas having poor broadband connectivity [31]. However, this improved coverage using femtocells is only possible after overcoming the challenges of inter-tier and intra-tier interference to avoid performance degradation while using a particular spectrum band.

As highlighted in Chapter 1, the femtocells can access spectrum in two deployment modes: separate-channel deployment and co-channel deployment, and in both cases interference management is essential [31]. With regards to signal transmission and reception, the small cell radius of femtocells ensures minimisation of the distance between receiver and transmitter, which guarantees that there are reduced attenuation effects and the signal strength at the receiver is acceptable. In order to determine whether the received signal strength is acceptable, the term signal-to-interference and noise ratio is often used, which not only is dependent on the transmit power selected by the relevant BS, but also includes transmit powers of interfering signals. Moreover, it also accounts for the effects of path-losses, fading and shadowing. With femtocells, the advantage is that the interfering signal strength is normally weaker especially at higher frequencies, due to penetration losses indoors. Thus, the key feature of femtocells is their low power transmission, and ability to provide improved indoor coverage quality [31].

Femtocells can be freely deployed by end users, who may power them on or off at will, continuously changing both the location and the number of femtocells active within a given coverage area at a given time. Consequently, conventional tools for network design and planning cannot be used to set up and optimise these femtocell networks; instead, the femtocells themselves must have the ability to not only autonomously self-organise into a radio access network, but also to run configuration and optimisation routines as required [31]. This would ensure that the femtocells increase the quality of service to end users without placing additional overhead on the existing network. Furthermore, self-organising femtocell networks reduce operational expenditure of mobile network operators by dispensing with the need for human employees to configure and run the network. Specifically, self-organisation of femtocells falls into three broad sub-categories: self-configuration, self-optimisation, and self-healing [31].

Normally, wireless networks need configuration actions in response to the occurrence of events that modify the network, such as when a new cell site is added, or when any network features need to be added or removed. In addition to these, femtocells need configuration changes when they are rebooted or moved to a different region. Before it starts operation, a femtocell senses the environment to self-configure parameters such as its neighbour list and pilot power [31].

Femtocells self-optimise by applying smart techniques to update and tune acceptable network parameters. For example, physical resources, access modes, and transmit power are various network parameters that need to be tuned to an appropriate level to ensure good performance of a femtocell. Thus, femtocells continuously run self-optimisation routines to achieve optimal performance consistently [31].

Finally, femtocells also have self-healing capabilities, where, to the maximum possible extent, they attempt to locally resolve any problems and failures that occur, after which normal operation is resumed whenever possible [31].

2.5 Game Theory

Game theory is a branch of applied mathematics, and a useful tool to model scenarios where multiple players mutually interact and take decisions to achieve mutual, conflicting or selfish goals. Using the analytical tools offered by game theory, the interactions among players and decision makers, and the resulting consequences, can be analysed. Applications of game theory are frequently found in Economics, where the competition among various market agents can be modelled, and the adopted strategies for maximising profits can be investigated. Moreover, often real-life behaviours and biological processes are modelled using game theory. For example, evolutionary games are mostly used to represent biological processes. Overall, game theory finds its applications in economics, biology, socio-political science, communication engineering etc. The fundamentals of game theory are presented in various textbooks and relevant literature [12, 60–63].

The following sections define some basic terminology which will be referred to in this thesis with regards to game-theoretic spectrum-sharing approaches.

2.5.1 Non-cooperative Games

In a non-cooperative game, a set of players take independent decisions to maximise their own individual benefits, and do not cooperate with each other. Generally, non-cooperative games are analysed using a Nash equilibrium condition, which is an important indicator for convergence analysis of a non-cooperative game.

Nash Equilibrium

In [37], a Nash equilibrium is defined as: "A Nash equilibrium of a strategic game $\langle N, (A_i), (u_i) \rangle$ is a profile $a^* \in A$ of actions such that for every player $i \in N$ we have

$$u_i(a^*, a^*_{-i}) \geq u_i(a_i, a^*_{-i})$$

for all $a_i \in A_i$, where a_i denotes the strategy of player i and a_{-i} denotes the strategies of all players other than player i." A Nash equilibrium is achieved when every player responds with a best possible strategy after considering the possible actions of other players. However, the key questions regarding the Nash equilibrium are its existence and uniqueness. Generally, the existence of a Nash equilibrium is common, whereas the analysis of its uniqueness varies from case to case [37]. A thorough discussion of the Nash equilibrium regarding spectrum sharing is provided in Chapter 3 and Chapter 4 of this thesis.

2.5.2 Cooperative Games

Cooperative games mostly refer to bargaining games and coalitional games (discussed below). In both kinds of games, the players are bound by an agreement to share the resources in a fair and efficient manner.

Bargaining games

In this type of cooperative game, the players are expected to reach an agreement which is mutually beneficial. However, it is assumed that the players can have conflicts of interest, and each player is only bound to follow an agreement it has explicitly approved.

Coalitional game

In this type of cooperative game, the players are allowed to cooperate with each other by forming cooperating groups. These "coalitions" result in an improved payoff for the cooperating players [37].

2.5.3 Evolutionary Games

Traditionally, evolutionary game theory has a static and a dynamic perspective [64]. A static evolutionary game does not involve time-dependent differential equations, and the stability of a static evolutionary game can be established without considering complex scenarios. On the other hand, the dynamic version of an evolutionary game covers the scenario, when an individual strategy of a player among a set of players (or population), can be learnt and replicated by other players [65]. Using a set of differential equations, this learning and strategy duplication process over time can be modelled, and is termed as replicator dynamics. Replicator dynamics mostly finds its application in representing a biological process [64].

2.6 Game Theory based Spectrum Sharing

Game theory has been considered a useful mathematical tool to resolve spectrum-sharing problems. In this regard, a comprehensive survey of game theory based cognitive radio network models was provided in [37], while a general overview of game theory based dynamic spectrum-sharing schemes was provided in [38], where the authors predict the need for flexible spectrum-sharing techniques in future. Although cognitive radio has traditionally been a widely investigated topic for spectrum sharing, some key issues such as sensing inaccuracies and uncertainty about long-term availability of the spectrum remain unresolved.

Considering the usefulness of game theory in spectrum-sharing problems, a promising area of research is to design next-generation, game theory based spectrum-sharing solutions that can address the limitations of the state of the art. For example, as discussed earlier in this chapter, licensed shared access offers a spectrally-efficient sharing mechanism, without compromising on the quality of service of incumbents (primary users) or licensees (secondary users), in contrast to previous spectrum-sharing techniques. By identifying the scope of utilising game-theoretic principles for LSA-based spectrum sharing, the coexistence of incumbents and licensees to achieve spectral efficiency can be ensured. Thus, game-theoretic LSA offers increased spectral efficiency without disturbing the QoS for incumbents, yet ensures additional capacity for supporting the 5G applications of licensees. Similarly, the application of game theory for spectrum sharing in femtocell-based networks is a promising research prospect.

2.7 Game-theoretic Spectrum-Sharing Approaches in the Literature

This section provides a literature review regarding the application of game theory in spectrum sharing.

Spectrum Sharing through Power-Control Games

Power-control games have been a popular approach to model various scenarios of spectrum sharing between primary users and secondary users [66–71].

In [66], a non-cooperative exact-potential game was proposed to jointly allocate power and frequency resources among secondary users. The proposed game converges to a Nash equilibrium point using the best response strategies. During the game formulation, it was assumed that the primary users remain inactive and that each player is aware of opponent player strategies. Moreover, all players had the knowledge of channel gains during the game. These assumptions require coordination between the players throughout the game which increases signalling overhead.

In [67], a non-cooperative power-control game based on a signal-to-interference-ratio dependent pricing scheme was modelled to satisfy user goals such as fairness, aggregate throughput or their trade-off. A unique and Pareto-efficient Nash equilibrium was achieved through appropriate pricing. Throughout the game, the users informed the centralised node about their path gains and their maximum transmit power, and it was assumed that each user knew the number of players and their utility functions. In practice, such a scheme will not only require frequent information exchange inducing real-time delays, but will violate the privacy of individual players by making their utilities public.

An overlay spectrum-sharing scenario for a multi-user multi-channel cognitive radio network was presented in [68]. A power-control game was formulated where the secondary users strive to maximise their throughput. The existence and uniqueness of the Nash equilibrium of the game were investigated. However, the game was based on the assumption that the primary users remain idle while the secondary users use the spectrum.

In [69], the authors formulated a non-cooperative iterated power-control game for spectrum sharing, where the licensees (secondary users) aim to maximise their utility by choosing power levels and fixing their long-term average rates. The private-commons model was employed in the game for secondary sharing of the licensed spectrum. However, the player set included only the secondary network users, and by employing power-control strategies, the secondary network users were able to set their own aggregate rates.

In [70], a spectrum-sharing scheme was presented as an energy-efficient non-cooperative power-control game, where each player selfishly selects its transmit power to maximise its own spatial sum energy-efficiency. The existence, uniqueness and inefficiency of the Nash equilibrium were presented. A pricing scheme was incorporated to address the inefficiency of the Nash equilibrium. During the game, all participating players (heterogeneous systems of transmitters) had the same priority as they aimed to maximise their energy-efficiency.

In [71], a dynamic spectrum-leasing approach was presented where the primary users are rewarded for sharing their spectrum with secondary users. The primary users acted as players along with secondary users in a non-cooperative power-control game, by choosing an interference cap on the total interference they can withstand. The existence and uniqueness of the Nash equilibrium of the proposed game with a linear receiver implementation were investigated. However, it was assumed that the player set includes only one primary network user along with multiple secondary network users.

Spectrum sharing in Femtocell-based Two-Tier Networks

The coexistence of macrocells and small cells (or femtocells) by sharing the given frequency spectrum has been discussed recently from different perspectives in the literature [28, 29, 72].

In [28], an LSA-based spectrum-sharing model was presented to increase the spectral utility of a two-tier network comprising small cells and macrocells in an energy-efficient manner. In the proposed model, the small cells provide offloading services to macrocells for improving the QoS of the macrocells, which served as an incentive for the macrocells to share their spectrum. In reward, the small cells earn licences to operate in the frequency spectrum of the macrocells. The scheme performed optimal categorisation of small cells using a Nash bargaining solution to determine an energy-efficient balance between the offloading and licensing roles of small cells. Moreover, it was assumed that all small cells act as a single entity instead of acting as independent players having individual utilities.

In [29], the authors presented cross-tier interference management by performing optimal power allocation for uplink transmission in a two-tier network comprising femtocells and macrocells. The proposed hierarchical game, using a multiple-leader multiple-follower model, maximised the utilities of macrocell user equipment (MUE) and femtocell user equipment (FUE) devices, while ensuring protection of MUE devices from interference so that the minimum QoS of MUEs is not affected. The convergence of the game to a unique game equilibrium was shown. Moreover, it was assumed that during the hierarchical game the MUEs compete with each other and apply their strategies first, followed by the FUEs who apply their power allocation strategies in response.

In [72], the authors investigated a distributed power-allocation scheme for spectrum sharing in a network comprising a central macrocell and several femtocells, by formulating a Stackelberg game to maximise the utility of both macrocell and femtocells. An effective distributed interference price-bargaining algorithm was proposed to achieve the Stackelberg equilibrium in the game, where the macrocell maintains its QoS by pricing the interference from femtocells. It was assumed that all cells use the same frequency band for operation. During the game, the macrocell acts as the leader to apply its strategy first, by setting the interference price, and based on its strategy the followers (femtocells) apply their strategies by deciding their power.

Chapter 3

An Equal-Priority Power-Control Game for Spectrum Sharing

3.1 Chapter Introduction

In this chapter, a game-theoretic spectrum-sharing framework for next-generation heterogeneous mobile networks is presented. The proposed spectrum-sharing mechanism considers coexistence of a set of femtocells, belonging to multiple networks, in a coverage area where all cells have equal priority of accessing the spectrum. A non-cooperative transmit-power-control game is formulated, in which all the femtocells share the spectrum by adjusting their transmit powers based on measured interference, until the transmit power is stabilised. The existence and uniqueness of the Nash equilibrium of the proposed non-cooperative power-control game is ensured by carefully selecting the game parameters, without interaction among the cells. The presented simulation results prove the convergence of the game to a Nash equilibrium and provide a throughput performance analysis.

3.2 Background and Motivation

The evolution of smart devices and increased worldwide mobile data traffic has compelled the Mobile Network Operators (MNOs) to exploit innovative ways for boosting their network capacity to meet their traffic demands. Femtocells are low-power (user deployed) wireless access points, having a vital role in next-generation mobile networks due to their ability to provide improved coverage for MNOs; MNOs can use them for offloading mobile data traffic from macrocells using the available spectrum resources [28, 29, 73]. It is reported in [1] that in 2015 the mobile traffic that was offloaded exceeded the cellular traffic for the first time, when 51% of the total global mobile data traffic was offloaded onto the fixed network through femtocells or Wi-Fi.

Because of fluctuations in traffic demand, MNOs frequently need to offload data to femtocells during peak demand periods; however, installation of femtocells in close proximity requires the available spectrum to be shared among the femtocells (and often macrocells), which results in a number of challenges. Firstly, current spectrum-sharing approaches are largely opportunistic, with the cells competing for access. Thus, femtocells' connectivity may not be continuous, which makes it challenging to provide any QoS guarantees to the users due to the interference caused by the neighbouring cells. Thus, during spectrum sharing involving femtocell-based networks, the inter-cell interference degrades the network performance [74]. Secondly, as the offloading services provided by femtocells vary with location and traffic requirements, they are often randomly deployed in a given coverage area. Due to this deployment uncertainty, mostly femtocells are not part of the mobile operators' network planning process [75]. Therefore, dedicated cabling is not suitable for connecting femtocells to the core network, and often public data networks are used to enable femtocell signal exchange with the core network [75]. As spectrum sharing traditionally requires complex coordination and planning, it needs to be ensured that the signalling overhead during information exchange for coordination is minimised.

Thus, minimising signalling overhead during information exchange and interference mitigation are significant research challenges for spectrum sharing involving femtocell-based networks [76, 77].

3.3 Related Work

Existing game-theoretic approaches have discussed the challenge of interference mitigation in femtocell-based networks [29, 72, 74, 76, 77], and have discussed power-control in distributed [78, 79] and non-cooperative arrangements [67, 70].

Various game-theoretic approaches have been proposed in the literature to achieve interference mitigation for femtocells [76, 77]. For instance, in [76], the authors discussed interference mitigation for femtocells in a setup where the participating players (femtocells) interacted with each other in an evolutionary game, which converged to an equilibrium. However, it was assumed that the players select their power-allocation strategies based on their instantaneous payoff and the average payoff of all other femtocells. While the objective of interference mitigation was achieved in [76, 77], the schemes required instant information exchange between the systems which has implementation limitations in practice.

A body of work investigates power allocation using game theory in two-tier networks comprising femtocells and macrocells. For instance, a power-allocation scheme using a hierarchical game was presented in [29], and power-allocation schemes using Stackelberg games were presented in [72, 74]. Specifically in [74], spectrum sharing in a two-tier network was considered and a Stackelberg game was formulated to investigate the joint utility maximisation of the macrocell and femtocells. However in all these approaches, it was assumed that the femtocells utilise the same spectrum as the macrocells, i.e. co-channel deployment is considered. In this chapter, separate-channel deployment is considered where femtocells do not share spectrum with macrocells. Thus, the coexistence of a number of femtocells belonging to different networks while using available spectrum resources, which are not being used by macrocells, is considered.

To discuss distributed power control using game theory, in [78] cooperative communication networks were considered and a distributed power-allocation scheme was proposed through a two-level Stackelberg game. During the game, the source node acted as a buyer and the relay nodes acted as sellers. The game considered the benefits of all nodes and it was shown that the game converges to a unique optimal equilibrium. However, instant and frequent exchange of information between the systems about the price and power demand required continuous coordination which is challenging to implement in practice. Moreover, in [79], distributed power control was discussed using a supermodular game. However, the maximum power constraint was not considered during game formulation and it was possible that the game may converge to a non-feasible point.

Traditionally in non-cooperative power-control games, the players are expected to behave selfishly and opt for a strategy that can maximise their payoff. In [70] a spectrum-sharing scheme was presented as an energy-efficient non-cooperative power-control game, where each player selfishly selects its transmit power to maximise its own spatial sum energy-efficiency. The existence, uniqueness and inefficiency of the Nash equilibrium were presented. However, each participating player aimed to maximise energy-efficiency instead of throughput. In [67], a non-cooperative power-control game based on a signal-to-interference-ratio dependent pricing scheme was modelled to satisfy user goals such as fairness, aggregate throughput or their trade-off. A unique and Pareto-efficient Nash equilibrium was achieved; however, the assumption that the users inform the centralised node about their path gains and their maximum transmit power throughout the game can be challenging in practice.

To summarise, a game-theoretic approach for coexistence of femtocells to share available spectrum resources through a power-control game must ensure that

- Instant information exchange and coordination between the cells is minimised [76–78];
- Maximum power constraint is considered so that the game converges to a feasible point [79];
- Appropriate measures are taken to ensure interference mitigation, i.e. the QoS of the users served by the femtocells is not compromised.

In the light of the specifications mentioned above, a game-theoretic approach is presented in this chapter for spectrum sharing between a set of femtocell base stations (BSs) belonging to primary and secondary networks. A non-cooperative power-control game is proposed where the BSs independently adjust their transmit powers until the powers are stabilised, while using the available frequency channels. It is shown that, by choosing appropriate game parameters and maximum power constraint, the existence and uniqueness of the Nash equilibrium of the proposed non-cooperative power-control game can be achieved. The game proposes a novel dual-mode solution that ensures that the coordination among the BSs required to reach an equilibrium point is minimised. A static price coefficient is used to adjust the weight of the price of the transmit power, using which all BSs participating in the game are given equal priority to access the spectrum.

3.4 System Model

In this section, a system model is presented to depict a scenario where multiple femtocell base stations (BSs), having equal priority of accessing the spectrum for their transmission, coexist in a coverage area and utilise the available spectrum resources simultaneously. In the proposed spectrum-sharing model, a power-control game is played in a non-cooperative manner where each player (BS) can take independent decisions based on global information provided to it by a game controller. The game controller coordinates the game by managing the participating BSs and provides them with the common information needed to play the game. In the proposed spectrum-sharing framework, the coordination of the players with this game controller is minimised and the players (BSs) are empowered to take independent decisions regarding their power levels, which enables their users to achieve their performance targets. Thus, it is ensured that the players do not need to exchange information multiple times to avoid real-time delays in practical scenarios.

Consider a set of BSs denoted by $\mathcal{D}_m$, where $|\mathcal{D}_m|$ BSs acting as players are located in a certain coverage area. These BSs can exchange parameter information with the game controller when required during the non-cooperative power-control game, as shown in Figure 3.1. Moreover, during the game the i^{th} base station ($i = 1, \cdots, |\mathcal{D}_m|$) iteratively adjusts its transmit power. It is assumed that the given spectrum band, having bandwidth W, is shared among $|\mathcal{D}_m|$ BSs. In this game, the participating BSs do not share any information with each other directly and can independently select their transmit powers during the course of the game.

During the non-cooperative power-control game, a channel k within W is considered to be used for transmission by the participating BSs. For illustration convenience, it is considered that each BS serves only one user at a time. Hence, BS user equipment $\hat{\imath}$ receives signals from its serving BS i and other BSs j ($j \in \mathcal{D}_m, j \neq i$), where the signals received from other BSs act as interference. For the k^{th} channel, the channel gain from BS j to user $\hat{\imath}$ is given by $G^k_{j,\hat{\imath}} = K_{j,\hat{\imath}} d^{-\alpha}_{j,\hat{\imath}} g^k_{j,\hat{\imath}}$ where $K_{j,\hat{\imath}}$ is the path-loss coefficient from BS j to user $\hat{\imath}$, $d_{j,\hat{\imath}}$ is the distance between BS j and user $\hat{\imath}$, α is the path-loss exponent, and $g^k_{j,\hat{\imath}}$ is the Rayleigh fading component from BS j to user $\hat{\imath}$ when using channel k.

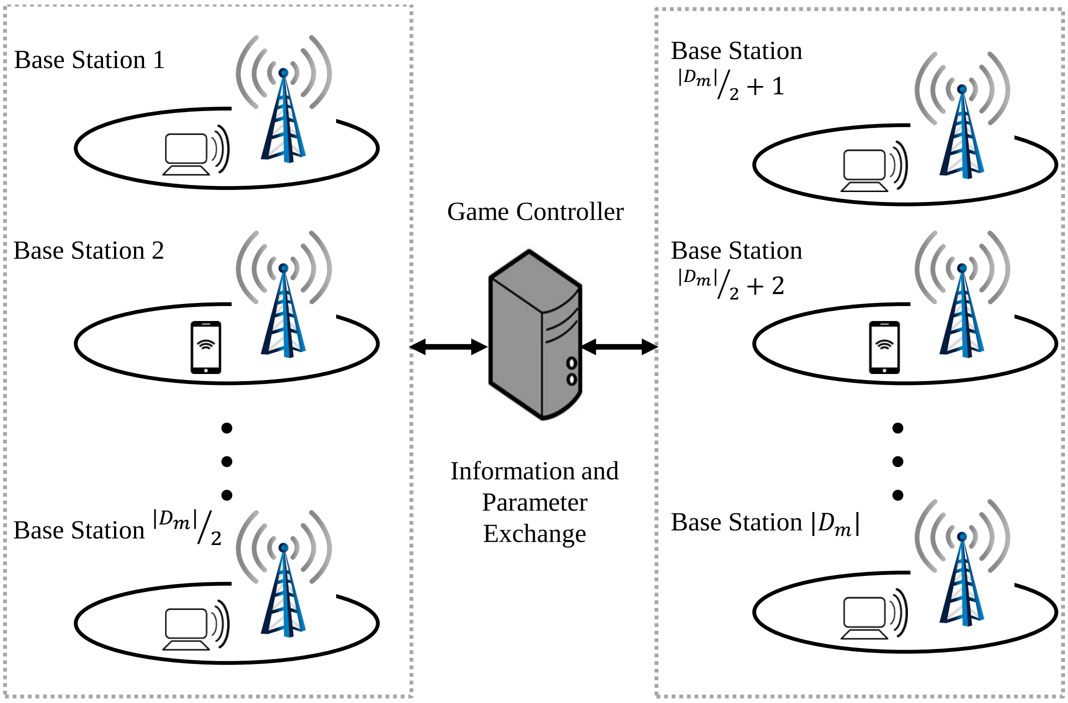

Figure 3.1: Network Configuration.

3.5 Non-Cooperative Power-Control Game

In this section, the proposed non-cooperative power-control game is formulated among the participating BSs. Each BS i ($i = 1, \cdots, |\mathcal{D}_m|$) repetitively adjusts its transmit power $P_i \in [0, P_{\max}]$ until it stabilises. $\boldsymbol{P}_{-i}$ collects the transmit powers of the rest of the BSs and $P_{\max}$ is the upper limit on the transmit power for each BS.

In the following, a surplus function is formulated to represent the achieved throughput and caused interference for each of the femtocells. Since, the interference caused by a cell has a direct relation with the transmit power it chooses, the transmit power of each cell represents the cost of striving for higher throughput by that cell. When a femtocell chooses to transmit using a higher power to increase its throughput, the cost increases at the same time and reduces the overall benefit a cell can get. Thus, each cell does not have an incentive to choose an excessively high power, which reduces the amount of interference it can cause [75]. Based on these arguments, the surplus function, comprising a utility function and a cost function, of this non-cooperative power-control game for femtocells can be formulated for the i^{th} BS ($i = 1, \cdots, |\mathcal{D}_m|$) as

$$\begin{aligned} S_i(\theta_m, P_i, \boldsymbol{P_{-i}}) &= U_i(P_i, \boldsymbol{P_{-i}}) - \theta_m C_i(P_i, \boldsymbol{P_{-i}}) \\ &= \arctan(\alpha_m \gamma_i / \gamma_i^{req}) - \theta_m P_i \end{aligned}$$

where $U_i(P_i, \boldsymbol{P_{-i}}) = \arctan(\alpha_m \gamma_i / \gamma_i^{req})$ is the utility function for BS i. The signal-to-interference ratio (SIR) for user $\hat{i}$ associated with BS $i \in \mathcal{D}_m$ is $\gamma_i = \frac{G^k_{i,\hat{i}} P_i}{\tilde{I}_{i,\hat{i}}}$. The interference measured by user equipment $\hat{i}$ being served by BS $i \in \mathcal{D}_m$ is denoted by $\tilde{I}_{i,\hat{i}} = \sum_{j \in \mathcal{D}_m \setminus \{i\}} P_j G^k_{j,\hat{i}}$. γ_i^{req} represents the minimum target SIR threshold for the user being served by the i^{th} BS ($i = 1, \cdots, |\mathcal{D}_m|$). θ_m and α_m are two adjustable parameters which can adjust the penalty of excessively high transmit power and the convergence speed to the equilibrium state of the game. The use of the $arctan()$ function in the utility function ensures the asymptotic convergence of the utilities of all players to a constant value, i.e. $\pi/2$. Moreover, the use of the $arctan()$ function acts as a limiting factor on excessively high transmit power, as each BS does not have any incentive to aim for an excessively high SIR, which in turn puts a limit on the interference that can be caused. Using $arctan()$ ensures that the power-control game has a concave structure, thus the nodes can independently adjust their transmit powers in a decentralised manner once in the iteration-mode, and attain convergence to an equilibrium [75].

The linear price function $C_i(P_i, \boldsymbol{P_{-i}})$ also restricts BS i from transmitting using a very high power for convergence [75,80]. It is worthwhile to mention that the static price coefficient θ_m and α_m are important game parameters in the proposed design, and their appropriate selection plays a critical role in ensuring the convergence of the game to an equilibrium as explained in Section 3.6.2.

In order to find the optimal transmit power for BS $i \in \mathcal{D}_m$, $S_i(\theta_m, P_i, \boldsymbol{P_{-i}})$ is differentiated with respect to P_i to obtain

$$\frac{\partial S_i}{\partial P_i} = \frac{\alpha_m G^k_{i,\hat{i}} \Big/ \gamma_i^{req} \tilde{I}_{i,\hat{i}}}{1 + \left(\frac{\alpha_m G^k_{i,\hat{i}} P_i}{\gamma_i^{req} \tilde{I}_{i,\hat{i}}} \right)^2} - \theta_m. \tag{3.1}$$

The optimal solution for the i^{th} BS ($i = 1, \cdots, |\mathcal{D}_m|$), denoted by P_i^*, is either the solution for making (3.1) equal to zero or on the boundary of the solution region, as given by

$$P_i^* = \min \left\{ \frac{\gamma_i^{req} \tilde{I}_{i,\hat{i}}}{\alpha_m G^k_{i,\hat{i}}} \sqrt{\frac{G^k_{i,\hat{i}} \alpha_m}{\theta_m \gamma_i^{req} \tilde{I}_{i,\hat{i}}} - 1}, P_{\max} \right\}, \tag{3.2}$$

and the corresponding SIR is given as

$$\gamma_i^* = \frac{\gamma_i^{req}}{\alpha_m} \sqrt{\frac{G^k_{i,\hat{i}} \alpha_m}{\theta_m \gamma_i^{req} \tilde{I}_{i,\hat{i}}} - 1}. \tag{3.3}$$

Each BS can calculate its optimal transmit power adaptively using (3.2) until it stabilises. Taking the second-order partial derivative of $S_i(\theta_m, P_i, \boldsymbol{P_{-i}})$ with respect to P_i, the obtained expression is

$$\frac{\partial^2 S_i}{\partial (P_i)^2} = \frac{-2\alpha_m^3 (G^k_{i,\hat{i}})^3}{(\gamma_i^{req})^3 \tilde{I}^3_{i,\hat{i}}} \frac{P_i}{\left(1 + \left(\frac{\alpha_m G^k_{i,\hat{i}} P_i}{\gamma_i^{req} \tilde{I}_{i,\hat{i}}} \right)^2 \right)^2} \tag{3.4}$$

which is negative, meaning that S_i is continuous and concave w.r.t. P_i ($i = 1, \cdots, |\mathcal{D}_m|$).

3.6 Analysis of the Nash Equilibrium of the Proposed Non-Cooperative Game

In this section, an analysis of the existence and uniqueness of the Nash Equilibrium of the proposed non-cooperative game is provided.

3.6.1 Existence of the Nash Equilibrium

The existence of the Nash equilibrium of the proposed game is proved by using the Debreu-Glicksberg-Fan Theorem [81], as it is noticed that:

1. S_i is continuous and concave w.r.t. P_i, as the second-order partial derivative of S_i w.r.t. P_i is negative as shown in (3.4).

2. S_i is continuous w.r.t. $\boldsymbol{P}_{-i}$.

3. $[P_i, \boldsymbol{P}_{-i}]$ is compact and convex.

3.6.2 Uniqueness of the Nash Equilibrium

In order to prove the uniqueness of the Nash equilibrium of the non-cooperative power-control game, Rosen's criterion [82] is used to equivalently prove that S_i is diagonally strictly concave with respect to P_i and $\boldsymbol{P}_{-i}$ across the region $P_i \in (0, P_{\max}]\,\forall i$.

Note that the constraints specifying the boundary of the solution region, $P_i \leq P_{\max}\,\forall i$, are linear (thus affine), and do not violate the concavity. To this end, only the diagonally strict concavity of S_i with respect to P_i and $\boldsymbol{P}_{-i}$ in the unbounded region $P_i \in (0, +\infty)\,\forall i$ needs to be proved. In this case, (3.2) can be relaxed to

$$P_i^* = \frac{\gamma_i^{req}\tilde{I}_{i,\hat{i}}}{\alpha_m G_{i,\hat{i}}^k}\sqrt{\frac{G_{i,\hat{i}}^k \alpha_m}{\theta_m \gamma_i^{req}\tilde{I}_{i,\hat{i}}} - 1}.$$

As a result, the uniqueness of the Nash equilibrium of the non-cooperative power-control game can be proved if the symmetric matrix $(\mathbf{U}_m + \mathbf{U}_m^T)$ (where T denotes the transpose of the matrix) is shown as negative definite, where $\mathbf{U}_m$, given by (3.5), is evaluated at $P_i^* = \frac{\gamma_i^{req}\tilde{I}_{i,\hat{i}}}{\alpha_m G_{i,\hat{i}}^k}\sqrt{\frac{G_{i,\hat{i}}^k \alpha_m}{\theta_m \gamma_i^{req}\tilde{I}_{i,\hat{i}}} - 1}$ $(i = 1, \cdots, |\mathcal{D}_m|)$, as these are the transmit powers that the BSs would adopt, if unbounded. β_i and ω_i, $i = 1, \cdots, |\mathcal{D}_m|$, are given by

$$\beta_i = 2\theta_m^2 \sqrt{\frac{G^k_{i,\hat{i}}\alpha_m}{\theta_m \gamma_i^{req} \tilde{I}_{i,\hat{i}}} - 1};$$

$$\omega_i = \frac{\theta_m}{\alpha_m \tilde{I}_{i,\hat{i}}} \left(2\theta_m \gamma_i^{req} \tilde{I}_{i,\hat{i}} - G^k_{i,\hat{i}}\alpha_m\right).$$

To prove the negative definiteness of the symmetric matrix $(\mathbf{U}_m + \mathbf{U}_m^T)$, the expression for $\mathbf{y}^T(\mathbf{U}_m + \mathbf{U}_m^T)\mathbf{y}$, $\forall \mathbf{y} \in \mathbb{R}^{|\mathcal{D}_m|\times 1}$, is given by

$$\mathbf{y}^T(\mathbf{U}_m + \mathbf{U}_m^T)\mathbf{y} = -\left[2\sum_{i=1}^{|\mathcal{D}_m|} y_i^2 \beta_i + \sum_{i=1}^{|\mathcal{D}_m|} \sum_{j=1, j\neq i}^{|\mathcal{D}_m|} \left(\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i + \frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j\right) y_i y_j\right]$$

which can be rewritten as given in (3.6).

To ensure the negativity of the left-hand side (LHS) of (3.6), we can set

$$\left(|\mathcal{D}_m| - 1\right) \max_{\forall i,j, i\neq j} \left\{\frac{1}{\sqrt{\beta_i \beta_j}} \left|\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i + \frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j\right|\right\} \leq 2$$

which, by substituting β_i and ω_i ($i = 1, \cdots, |\mathcal{D}_m|$) in, can be rewritten as given in (3.7).

It is noted that that the LHS of (3.7) only depends on $\frac{\alpha_m}{\theta_m}$, rather than explicitly on either α_m or θ_m. Given any reasonable value of $\frac{\alpha_m}{\theta_m}$, i.e.,

$$\frac{\alpha_m}{\theta_m} \in \left(0, \min_{\forall i}\left\{\frac{\gamma_i^{req}\tilde{I}_{i,\hat{i}}}{G^k_{i,\hat{i}}}\right\}\right) \cup \left(\max_{\forall i}\left\{\frac{\gamma_i^{req}\tilde{I}_{i,\hat{i}}}{G^k_{i,\hat{i}}}\right\}, +\infty\right), \quad (3.8)$$

α_m at the right-hand side of (3.7) can be adjusted to preserve the inequality. Given $\frac{\alpha_m}{\theta_m}$ and α_m, θ_m can then be obtained.

Therefore, such selection of α_m and θ_m guarantees $\mathbf{y}^T(\mathbf{U}_m + \mathbf{U}_m^T)\mathbf{y} \leq 0$ for any $\mathbf{y}$, as shown in (3.6). $(\mathbf{U}_m + \mathbf{U}_m^T)$ is negative definite. S_i is diagonally strictly concave over $[P_i, \boldsymbol{P}_{-i}]$ in the unbounded region $P_i \in (0, +\infty)\,\forall i$. By Rosen's criterion, this ensures that there is a unique Nash equilibrium of the non-cooperative game within the entire unbounded region.

$$
\mathbf{U}_m = \begin{bmatrix} \frac{\partial^2 S_1}{\partial P_1^2} & \frac{\partial^2 S_1}{\partial P_1 \partial P_2} & \cdots & \frac{\partial^2 S_1}{\partial P_1 \partial P_{|\mathcal{D}_m|}} \\ \frac{\partial^2 S_2}{\partial P_1 \partial P_2} & \frac{\partial^2 S_2}{\partial P_2^2} & \cdots & \frac{\partial^2 S_2}{\partial P_2 \partial P_{|\mathcal{D}_m|}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 S_{|\mathcal{D}_m|}}{\partial P_1 \partial P_{|\mathcal{D}_m|}} & \frac{\partial^2 S_{|\mathcal{D}_m|}}{\partial P_2 \partial P_{|\mathcal{D}_m|}} & \cdots & \frac{\partial^2 S_{|\mathcal{D}_m|}}{\partial P_{|\mathcal{D}_m|}^2} \end{bmatrix} \tag{3.5}
$$

$$
\mathbf{U}_m = \begin{bmatrix} -\beta_1 & \frac{-G^k_{2,\hat{1}}\omega_1}{G^k_{1,\hat{1}}} & \cdots & \frac{-G^k_{|\mathcal{D}_m|,\hat{1}}\omega_1}{G^k_{1,\hat{1}}} \\ \frac{-G^k_{1,\hat{2}}\omega_2}{G^k_{2,\hat{2}}} & -\beta_2 & \cdots & \frac{-G^k_{|\mathcal{D}_m|,\hat{2}}\omega_2}{G^k_{2,\hat{2}}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{-G^k_{1,\hat{|\mathcal{D}_m|}}\omega_{|\mathcal{D}_m|}}{G^k_{|\mathcal{D}_m|,\hat{|\mathcal{D}_m|}}} & \frac{-G^k_{2,\hat{|\mathcal{D}_m|}}\omega_{|\mathcal{D}_m|}}{G^k_{|\mathcal{D}_m|,\hat{|\mathcal{D}_m|}}} & \cdots & -\beta_{|\mathcal{D}_m|} \end{bmatrix}
$$

$$
\begin{aligned}
\mathbf{y}^T(\mathbf{U}_m+\mathbf{U}_m^T)\mathbf{y} &= -\left[2\sum_{i=1}^{|\mathcal{D}_m|}(y_i\sqrt{\beta_i})^2 + \sum_{i=1}^{|\mathcal{D}_m|}\sum_{j=1,\, j\neq i}^{|\mathcal{D}_m|} \frac{\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i + \frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j}{\sqrt{\beta_i\beta_j}} y_i\sqrt{\beta_i}y_j\sqrt{\beta_j}\right] \\
&\leq -\left[2\sum_{i=1}^{|\mathcal{D}_m|}\left(y_i\sqrt{\beta_i}\right)^2 - \sum_{i=1}^{|\mathcal{D}_m|}\sum_{j=1,\, j\neq i}^{|\mathcal{D}_m|} \frac{\left|\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i + \frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j\right|}{2\sqrt{\beta_i\beta_j}} \left(\left(y_i\sqrt{\beta_i}\right)^2 + \left(y_j\sqrt{\beta_j}\right)^2\right)\right] \\
&= -\sum_{i=1}^{|\mathcal{D}_m|}\left(2 - \sum_{j=1,\, j\neq i}^{|\mathcal{D}_m|} \frac{\left|\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i + \frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j\right|}{\sqrt{\beta_i\beta_j}}\right)\left(y_i\sqrt{\beta_i}\right)^2 \\
&\leq -\left(2 - \left(|\mathcal{D}_m| - 1\right)\max_{\forall i,j,\, i\neq j}\left\{\frac{\left|\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i + \frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j\right|}{\sqrt{\beta_i\beta_j}}\right\}\right)\sum_{i=1}^{|\mathcal{D}_m|}\left(y_i\sqrt{\beta_i}\right)^2
\end{aligned} \tag{3.6}
$$

$$\max_{\forall i,j,\, i\neq j} \left\{ \sqrt[4]{\frac{\gamma_i^{req}\gamma_j^{req}\tilde{I}_{i,\hat{i}}\tilde{I}_{j,\hat{j}}}{\left(G^k_{i,\hat{i}}\frac{\alpha_m}{\theta_m}-\gamma_i^{req}\tilde{I}_{i,\hat{i}}\right)\left(G^k_{j,\hat{j}}\frac{\alpha_m}{\theta_m}-\gamma_j^{req}\tilde{I}_{j,\hat{j}}\right)}}\times \left|\frac{G^k_{j,\hat{i}}}{G^k_{\hat{i},\hat{i}}\tilde{I}_{i,\hat{i}}}\left(2\gamma_i^{req}\tilde{I}_{i,\hat{i}}-G^k_{i,\hat{i}}\frac{\alpha_m}{\theta_m}\right)+\frac{G^k_{i,\hat{j}}}{G^k_{\hat{j},\hat{j}}\tilde{I}_{j,\hat{j}}}\left(2\gamma_j^{req}\tilde{I}_{j,\hat{j}}-G^k_{j,\hat{j}}\frac{\alpha_m}{\theta_m}\right)\right| \right\} \leq \frac{4\alpha_m}{|\mathcal{D}_m|-1} \tag{3.7}$$

As noted earlier, the boundaries of the solution region for $P_i\,\forall i$, specified by the linear constraints $P_i \leq P_{\max}$, do not violate the diagonally strict concavity of S_i. Moreover, the value that $\frac{\alpha_m}{\theta_m}$ can take is still within the range which is specified in (3.8) and ensures the diagonally strict concavity of S_i. This is because the upper-bounded transmit powers can reduce $\tilde{I}_{i,\hat{i}}$ compared to the unbounded transmit powers. For these reasons, S_i is diagonally strictly concave in the bounded solution region $P_i \in (0, P_{\max}]\,\forall i$.

Given the diagonally strict concavity of the bounded solution region $P_i \in (0, P_{\max}]\,\forall i$, there is a unique Nash equilibrium of the non-cooperative game within the region. However, the Nash equilibrium of the bounded region can be on the boundary of the region; see (3.2), if the Nash equilibrium of the entire unbounded region is outside the bounded region. Otherwise, the Nash equilibria of the bounded and unbounded regions coincide. To sum up, the uniqueness of the Nash equilibrium of the non-cooperative power-control game holds and the non-cooperative power-control game is valid.

3.7 Implementation of the Proposed Game

During the proposed non-cooperative power-control game, the participating BSs are empowered to take independent decisions about their transmit powers without excessive coordination with one another or the game controller. However, in order to ensure that the game has a unique Nash equilibrium, all BSs require particular parameter information to calculate their optimal transmit powers. Specifically, each BS $i \in \mathcal{D}_m$ needs the values of the game parameters α_m and θ_m to calculate its optimal transmit power P_i^*.

The game is implemented by designing two modes: an *initialisation-mode* in which the BSs exchange necessary parameter information and an *iteration-mode* in which the BSs repeatedly adjust their optimal transmit power until an equilibrium point is achieved. The tasks executed in each mode are presented in Figure 3.2.

3.7.1 Initialisation-Mode

During this mode, the game controller collects information from all BSs to compute and return necessary parameter values to them so that each BS $i \in \mathcal{D}_m$ can select P_i^* in the iteration-mode. Each participating BS i ($i = 1, \cdots, |\mathcal{D}_m|$) serving user $\hat{i}$

- Transmits using a particular initial transmit power P_i
- Observes the channel gain $G_{i,\hat{i}}^k$
- Collects the interference information $\tilde{I}_{i,\hat{i}}$
- Sets its minimum target SIR (γ_i^{req})
- Calculates the received SIR γ_i

Once each BS $i \in \mathcal{D}_m$ serving user $\hat{i}$ completes the above tasks, it provides γ_i^{req} and the observed values of $\tilde{I}_{i,\hat{i}}$ and $G_{i,\hat{i}}^k$ to the game controller. This enables the game controller to process the up-to-date parameter information for calculating a suitable value of $\frac{\alpha_m}{\theta_m} \forall i \in \mathcal{D}_m$, which is essential to ensure the uniqueness of the Nash equilibrium, as obvious from (3.8). The game controller calculates $\frac{\gamma_i^{req} \tilde{I}_{i,\hat{i}}}{G_{i,\hat{i}}^k} \forall i \in \mathcal{D}_m$, to choose the ratio $\frac{\alpha_m}{\theta_m} \forall i \in \mathcal{D}_m$ within the specified ranges given by (3.8) and determines suitable values of α_m and θ_m which remain constant throughout the iteration-mode. Eventually, these values need to be provided to all BSs, before the start of the iteration-mode. Hence, the

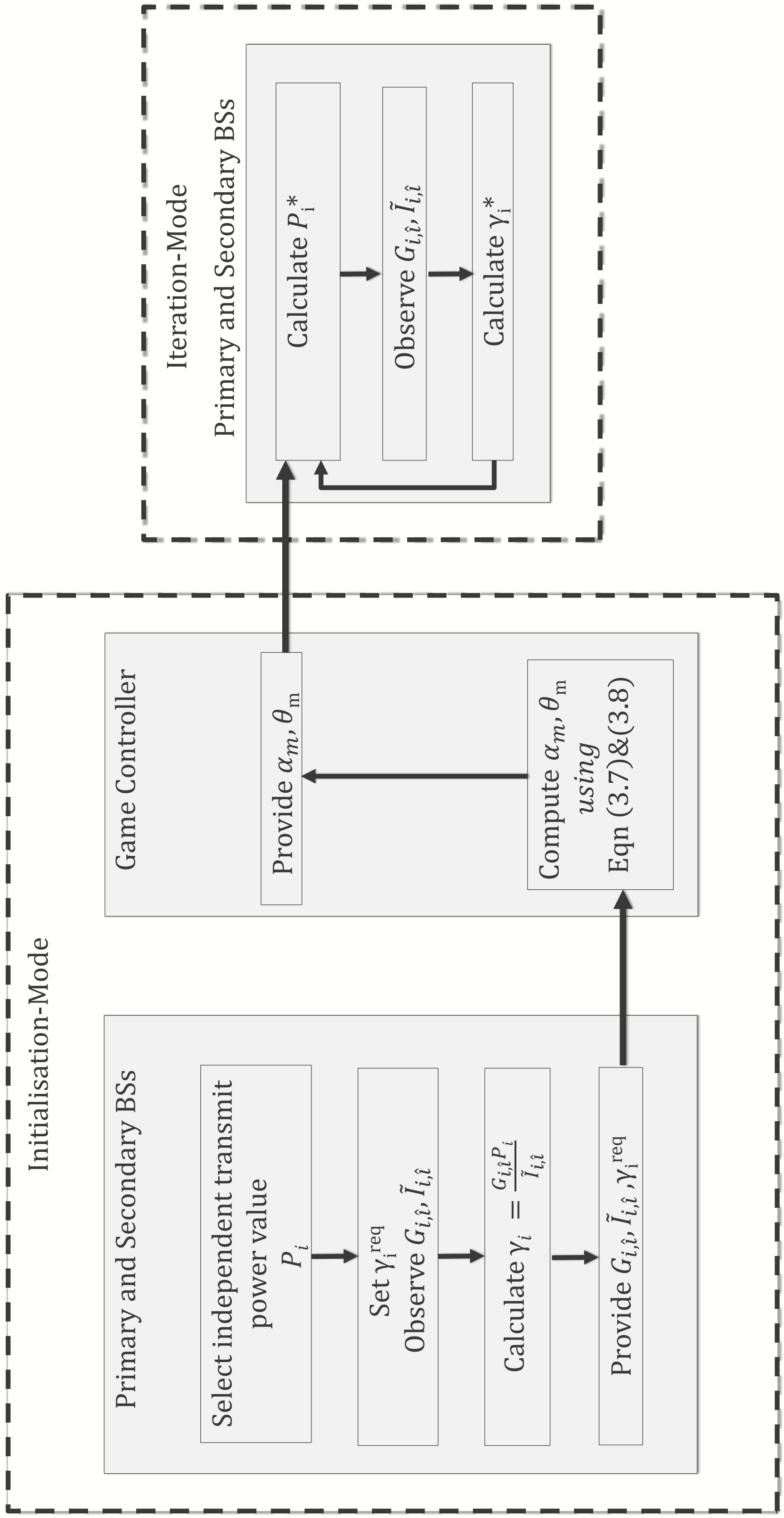

Figure 3.2: Sequence of tasks executed in the initialisation and iteration modes of the game.

initialisation-mode is concluded when α_m and θ_m are returned to relevant BSs so that they can calculate their transmit power in the iteration-mode.

3.7.2 Iteration-Mode

Recall from (3.2) that each BS $i \in \mathcal{D}_m$ serving user $\hat{i}$ can select its optimal transmit power, using the values of $\tilde{I}_{i,\hat{i}}$, $G^k_{i,\hat{i}}$, and γ_i^{req}, all of which are available to it; the additionally needed information, i.e. the values of α_m and θ_m, is provided by the game controller after the initialisation-mode. Using this information, BS $i \in \mathcal{D}_m$ calculates P_i^* for each upcoming iteration, until P_i^* is stabilised. α_m and θ_m remain constant for all iterations. Once each BS $i \in \mathcal{D}_m$ finalises the transmit power, this information is then used to compute an updated γ_i^* and the resulting throughput.

As proved earlier in Section 3.6.2, by satisfying Rosen's criterion for selection of the game parameters, a unique Nash equilibrium of the game can be achieved. To determine an acceptable initial region of the game, in the initialisation-mode the game controller computes values of α_m and θ_m which satisfy (3.7) and (3.8). Using these values in the iteration-mode, all the BSs choose their best-response strategies, i.e. their optimal powers iteratively to suit the traffic conditions, until the individual transmit powers of the BSs stabilise and converge to Nash equilibrium points. Thus, by selecting the game parameters in the initialisation-mode following Rosen's criterion as proposed and using (3.7) and (3.8), the game converges to a unique Nash equilibrium in the iteration-mode.

3.8 Simulation Results

In this section, parameter values are set to carry out MATLAB-based computer simulations and a discussion of the results is provided.

3.8.1 Simulation Setup

During simulations, we consider real scenarios of femtocell deployment. Since our model considers the channel gains from BSs to users, path-loss coefficients from BSs to users, distances between BSs and users and the Rayleigh fading model, these features can be best represented in MATLAB, and can not be accurately represented in NS2 or QualNet. Therefore, we have used MATLAB which is the most suitable tool to represent our system model. We use Monte Carlo simulation technique and run each experiment 50000 times.

The simulations are performed by considering a scenario where $|\mathcal{D}_m|$ BSs are randomly distributed in a coverage area. The BSs transmit over the same frequency, thus sharing the same spectrum resources. The BSs are divided into two subsets: a primary subset η serving the primary network users, and a secondary subset μ serving the secondary network users. Hence, $|\eta|$ is the number of BSs serving the primary network users, and $|\mu|$ is the number of BSs serving the secondary network users ($|\mathcal{D}_m| = |\eta| + |\mu|$). Unlike traditional spectrum-sharing approaches, where the primary network has priority over the secondary network to access the spectrum, in this setup it is assumed that all BSs have equal priority to access the spectrum, irrespective of the subset they belong to. As a practical use case, this scenario can help the service provider in estimating what percentage of additional (secondary) users can be accommodated in the coverage area, without affecting the performance of existing (primary) users.

During simulations, the value of the path-loss exponent α is set as 3.5, appropriate for an urban environment. For all the simulations α_m and θ_m are decided in the initialisation-mode by the game controller and their values are kept constant in the iteration-mode. Considering the channel bandwidth W and SIR γ_i, we define the throughput achieved by user $\hat{i}$, which is being served by BS $i \in \mathcal{D}_m$, as $\Gamma_i = W \log_2 (1 + \gamma_i)$. The maximum transmit power is set as 1000 mW. The minimum target throughput is set as 7 Mb/s unless otherwise stated.

3.8.2 Results and Discussion

In Figure 3.3, Figure 3.4, Figure 3.6 and Figure 3.7 a convergence analysis of the non-cooperative power-control game is provided, and simulations are performed by setting $|\mathcal{D}_m| = 18, |\eta| = 9, |\mu| = 9$. Figure 3.3 shows the convergence of the average surplus of the primary network BSs to an equilibrium point as the game progresses, for three different values of the minimum target throughput. It can be observed for all the cases that, after 10 iterations, the average surplus reaches a stabilised value (equilibrium point), which is below the theoretical maximum of $\pi/2$ as expected.

Figure 3.4 shows the convergence of the individual transmit powers of the primary network BSs to distinct equilibrium points as the game progresses. It can be observed that, after 10 iterations, the individual transmit powers of all the BSs reach stabilised values (equilibrium points). Moreover, Figure 3.5 depicts the convergence of the individual throughput values achieved by the PUs to distinct equilibrium points as the game moves forward. The figure shows that the individual throughput delivered by all the BSs to their respective users reach stabilised values (equilibrium points) after 10 iterations. It must be noted that since each BS receives distinct interference, therefore its optimal transmit power is stabilised at a distinct point, hence the associated SIR and subsequent throughput is stabilised at a distinct point. Thus, the figure shows the convergence of the individual throughput achieved by PUs to a distinct equilibrium point.

Figure 3.6 shows the convergence of the average SIR received by the primary network users (PUs) to an equilibrium point as the game progresses. It can be observed that after 5 iterations the average SIR reaches a stabilised value (equilibrium point). Figure 3.7 shows the convergence of the average throughput achieved by the primary network users to an equilibrium point as the game progresses. It can be observed that after 5 iterations the average throughput reaches a stabilised value (equilibrium point).

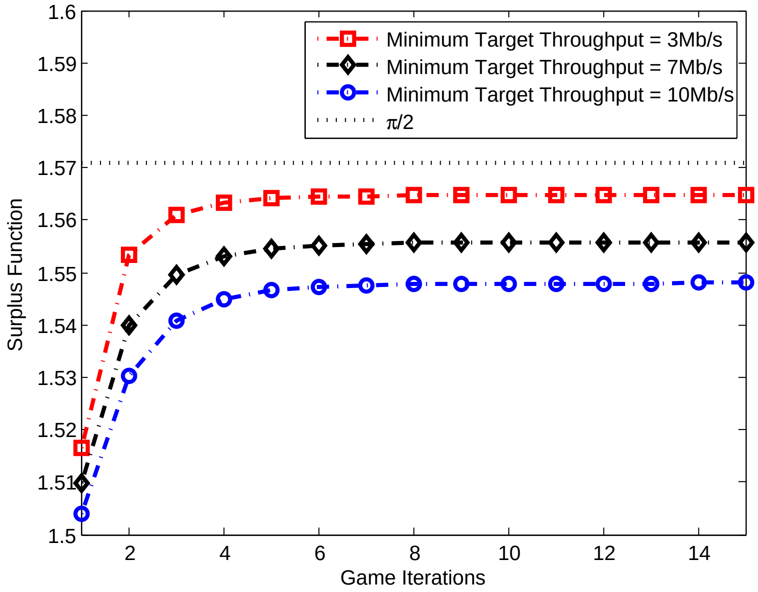

Figure 3.3: Average surplus achieved by the primary network BSs w.r.t. game iterations.

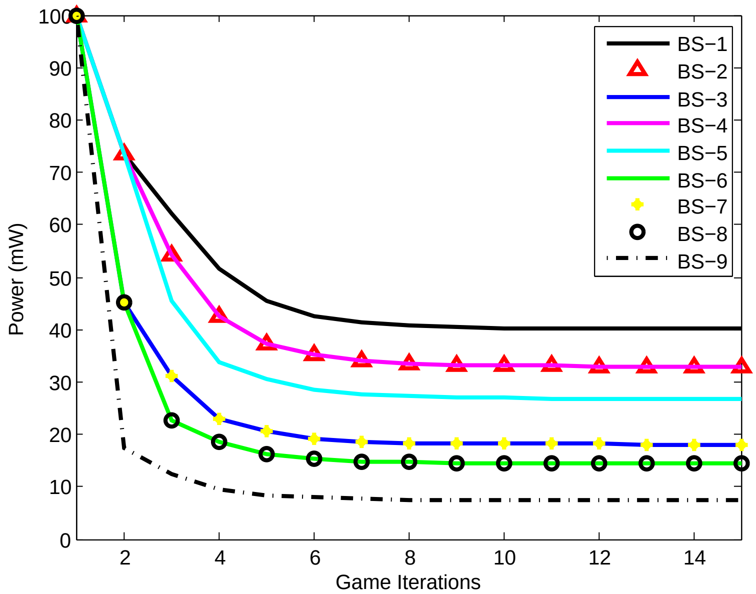

Figure 3.4: Individual transmit powers of the primary network BSs w.r.t. game iterations.

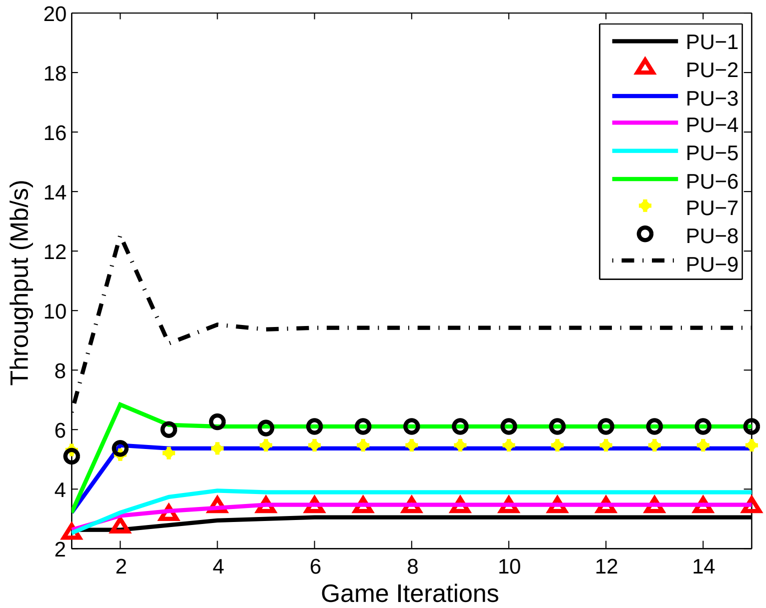

Figure 3.5: Individual throughput achieved by PUs in each iteration of the game.

Summarising Figure 3.6 and Figure 3.7, it can be observed that, for a constant value of the static price coefficient θ_m, varying the minimum target SIR (minimum target throughput) does not affect the received average SIR (achieved average throughput) of the primary network users, as all the BSs in the coverage area have an equal priority for accessing the spectrum.

Figure 3.8 and Figure 3.9 provide a demonstration of the effect of varying the number of secondary network BSs on the received average SIR, and the achieved average throughput of the primary network users at the equilibrium stage, by considering a scenario when $|\eta| = 9$ BSs continuously utilise the spectrum resources.

In Figure 3.8, it is shown that, as $|\mu|$ increases, the average SIR received by the primary network users decreases gradually and approaches their minimum target SIR value. When $|\mu| = 0$, the primary network users receive a high average SIR, as there are no secondary network BSs in the coverage area.

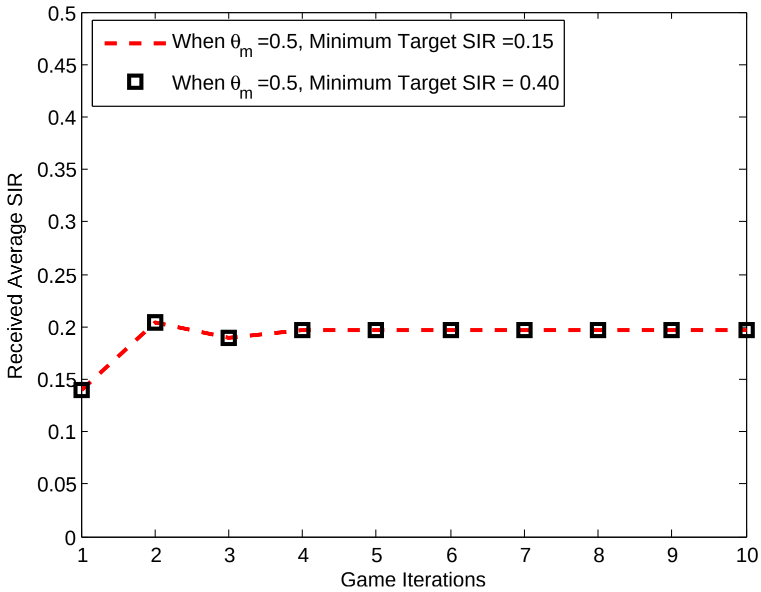

Figure 3.6: Average SIR received by PUs w.r.t. game iterations.

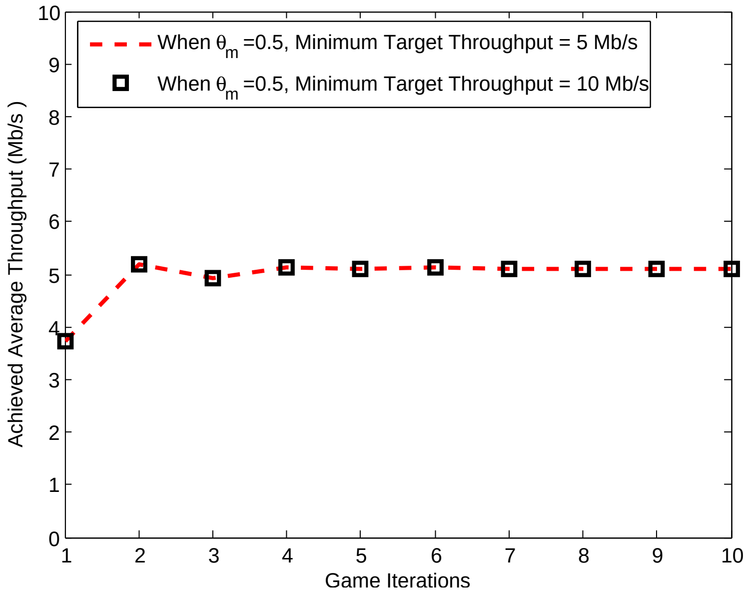

Figure 3.7: Average throughput achieved by PUs w.r.t. game iterations.

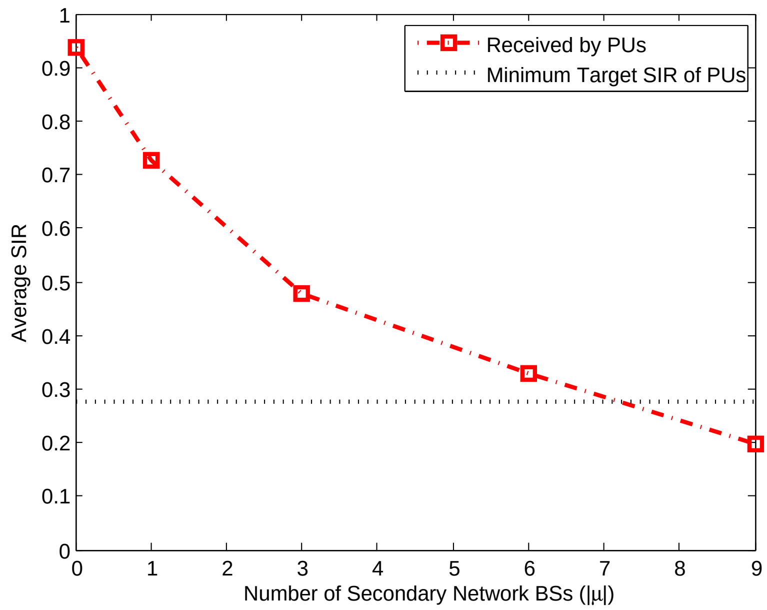

Figure 3.8: The effect on average SIR received by PUs ($|\eta| = 9$), by varying $|\mu|$.

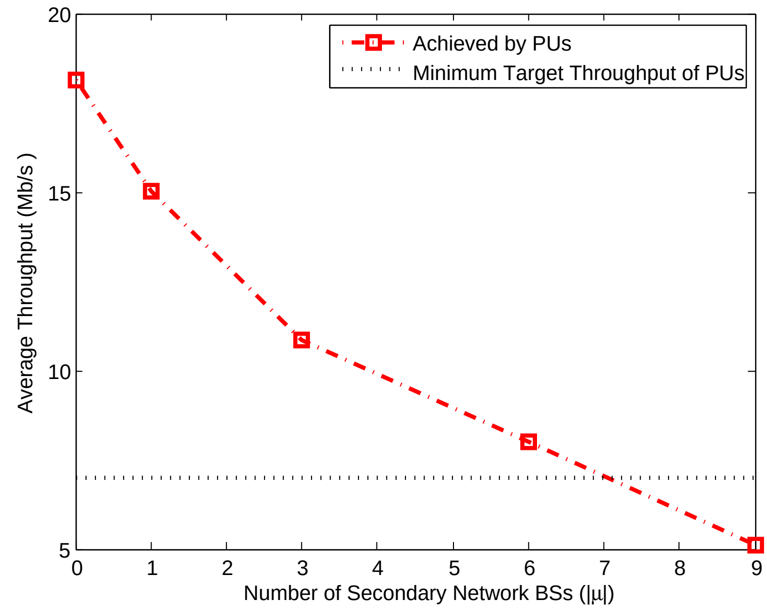

Figure 3.9: The effect on average throughput achieved by PUs ($|\eta| = 9$), by varying $|\mu|$.

As $|\mu|$ increases, the average SIR received by the primary network users decreases due to an increase in the number of secondary network BSs. However, when $|\mu| = 7$ the average SIR received by the primary network users becomes equal to their minimum target SIR, and any further addition of BSs serving the secondary network in the coverage area degrades the QoS of the primary network users.

Similarly, Figure 3.9 shows that, as $|\mu|$ increases, the average throughput achieved by the primary network users decreases gradually and approaches their minimum target throughput. When $|\mu| = 0$, the primary network users achieve a high average throughput, as there are no secondary network BSs in the coverage area. As $|\mu|$ increases, the average throughput achieved by the primary network users decreases due to an increase in the number of secondary network BSs. However, when $|\mu| = 7$ the average throughput achieved by the PUs becomes equal to their minimum target throughput, and any further addition of BSs serving the secondary network in the coverage area degrades the SIR and the resulting throughput of the primary network users.

Overall, when a BS joins (or leaves) the network, the SIR gets degraded (or improved) for existing users being served by the existing BSs, due to increased (or reduced) interference respectively. In both cases, the game controller re-calculates the parameter values, i.e. the game restarts in the initialization-mode and the game controller broadcasts the parameter values so that the network nodes can determine their optimal powers in a decentralized fashion and converge to a new equilibrium point.

Ideally, it is required that sharing their spectrum with the secondary network does not degrade the QoS of the primary network users. The analysis provided in Figure 3.8 and Figure 3.9 shows that, for a given minimum throughput target of 7Mb/s, the primary network users can only achieve their desired QoS (minimum target SIR and minimum target throughput) if the number of secondary network BSs in the coverage area is limited (not more than 7).

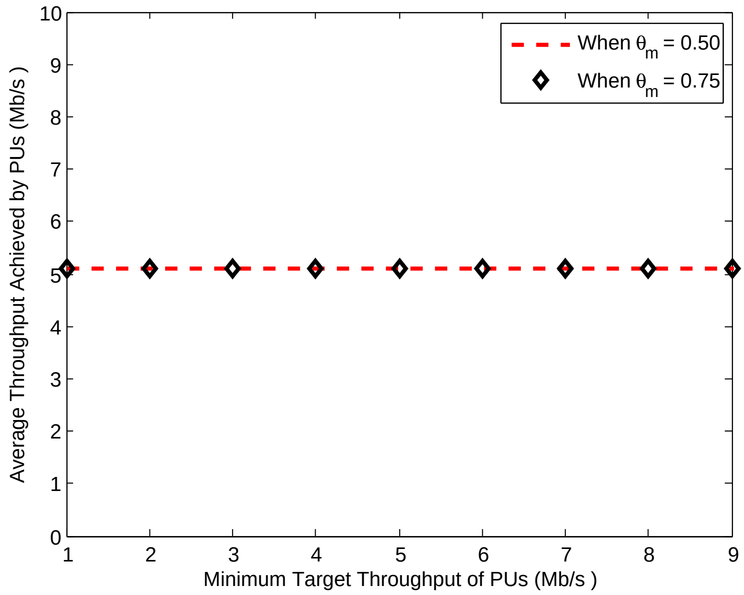

Figure 3.10: Effect of using a static price coefficient θ_m on average throughput achieved by PUs, when $|\mathcal{D}_m| = 18, |\mu| = 9, |\eta| = 9$.

A closer analysis of Figure 3.9 reveals that, when $|\mu| = 9$ the average throughput achieved by the the primary network users is 5 Mb/s. It can be concluded that there is an upper limit on the average throughput that can be achieved by the primary network users under the equal-priority arrangement in a congested scenario.

To investigate further, a congested scenario is considered ($|\mathcal{D}_m| = 18, |\eta| = 9, |\mu| = 9$) to demonstrate the effect of varying the minimum target throughput of the primary network users on their achieved average throughput in Figure 3.10. It is observed that an increase in the minimum target throughput does not affect the average throughput achieved by the primary network users at equilibrium. This is because all the BSs, whether serving the primary network users or the secondary network users in the coverage area, have equal priority for accessing the spectrum in the proposed system model. Thus, in the given simulation setup, the maximum average throughput that the primary network users can achieve is 5 Mb/s regardless of their minimum target throughput or the value of θ_m

as shown in the figure. The equal-priority arrangement identifies a limitation of using the static price coefficient, as it is obvious that, regardless of the target, the primary network users are only able to achieve a constant average throughput in a congested scenario. A solution for this limitation is proposed in Chapter 4, where a dynamic price coefficient is proposed, which plays a critical role in enabling the primary network users to meet a varying minimum target throughput.

Lastly, in order to compare the performance of the proposed dual-mode game implementation scheme with other related methods, we notice that the most relevant works [75, 80] do not provide any mechanism to ensure that knowledge of the game parameters can be provided to the players. Moreover, in a practical network, other optimal centralised algorithms [83–86] are computationally intractable. Thus, we compare the performance of the proposed dual-mode game implementation scheme with an offline centralised counterpart. In the proposed scheme, the parameter values are exchanged only in the initialization-mode of the game, whereas in the offline centralised implementation, the parameters values are exchanged on each iteration of the game.

Figure 3.11 highlights the performance comparison between the proposed dual-mode implementation and the offline centralised implementation. We observe in an offline centralised implementation, the equilibrium point of the average transmit power of the primary network BSs is lower than equilibrium point in case of dual-mode implementation. This is because the nodes can have access to the updated parameter values in each iteration of the game, which allows them to choose lower values of transmit powers. In any case, the game converges to an equilibrium point after 10 iterations.

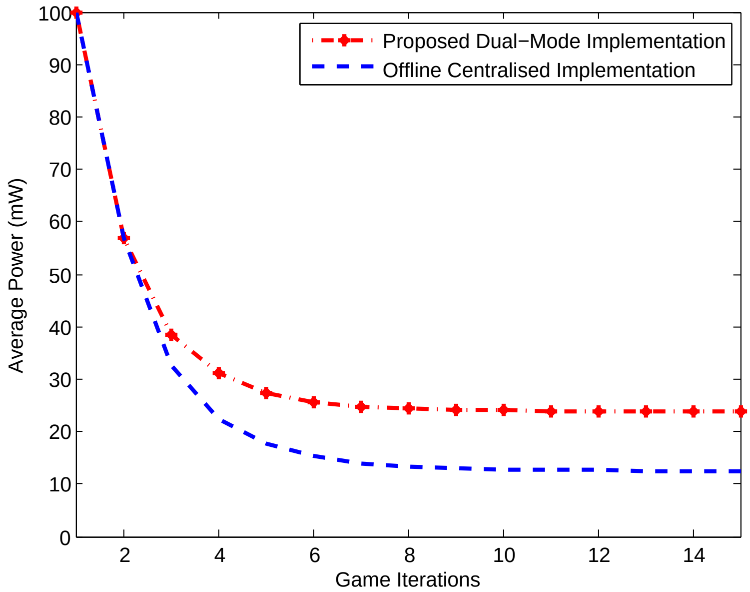

Figure 3.11: Comparison of average transmit power for primary network BSs w.r.t. game iterations.

3.9 Summary

In this chapter, a non-cooperative power-control game for femtocell base stations was proposed, where each base station adaptively adjusted its transmit power by measuring received interference, until it was stablised. A suitable utility function and a surplus function were developed. The existence and uniqueness of the Nash equilibrium of this non-cooperative power-control game were proved. The role of specific game parameters in achieving a unique Nash equilibrium was highlighted, and the convergence was proved theoretically. The presented simulation results showed that all BSs participating in the game could get equal priority to access the spectrum using the static price coefficient. However, this arrangement resulted in a limitation on the achieved performance of the primary network users, as it was observed that, the primary network users were only able to achieve a constant average throughput in a congested scenario regardless of the target. This limitation is addressed in Chapter 4, where a dynamic price coefficient is proposed, which ensures that the primary network users can achieve their minimum target throughput even in a congested scenario.

Supporting Publications

- A. Saadat, W. Ni, R. Vesilo and Q. Cui, " Errata to the paper "An evolutionary game theoretic framework for femtocell radio resource management"," *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 8610-8612, Dec. 2016.

- A. Saadat, W. Ni and R. Vesilo, " An Equal Priority Power-Control Game for Spectrum Sharing in Femtocell based Networks", *in 17th International Symposium on Communications and Information Technologies (ISCIT-2017)*, 25-27 September 2017, Cairns, Australia.

Chapter 4

A Multi-Priority Power-Control Game for Spectrum Sharing

4.1 Chapter Introduction

In this chapter, a multi-priority spectrum-sharing framework for next-generation mobile networks is proposed where the primary network shares the spectrum resources licensed to it with the secondary network in a non-cooperative power-control game. A scenario is considered where multiple femtocell base stations (BSs), coexist in a coverage area and utilise the available spectrum resources at the same time. However, unlike Chapter 3, where the BSs had equal priority of accessing the spectrum for their transmission, in this chapter it is assumed that the primary network BSs have priority over the secondary network BSs when using the spectrum. Thus, the proposed multi-priority scheme ensures that the primary network users can maintain their desired quality of service during the spectrum-sharing process. The proposed power-control game allows the network nodes to adjust their transmit powers based on measured interference, until the transmit power is stabilised. The existence and uniqueness of the Nash equilibrium of this multi-priority non-cooperative game is ensured by carefully selecting the game parameters, such as a *dy-*

namic price coefficient, which is designed to give the primary network BSs priority over the secondary network BSs for accessing the spectrum. The dynamic price coefficient enables the primary network users to reach their minimum target SIR (throughput) adaptively. Extensive simulation results are presented to prove the convergence of the game to a Nash equilibrium, along with a comprehensive throughput performance analysis.

4.2 Background and Motivation

Legacy spectrum-allocation approaches divide the spectrum into pre-allocated, exclusively licensed, bands for primary networks, resulting in inefficient usage of the spectrum when it is not being used by the primary networks. This under-utilisation of the spectrum results in an artificial spectrum scarcity for secondary networks [11]. The spectrum regulatory authorities in the European Union (EU) [24,25] and the USA [26,27] are hence promoting the development of innovative spectrum-sharing schemes that ensure efficient spectrum utilisation while maintaining the quality of service (QoS) of both primary network users and secondary network users.

The coexistence of primary network users and secondary network users while sharing available spectrum resources poses a number of challenges. Firstly, this arrangement must not degrade the QoS of primary network users, i.e. the secondary network operation must not cause harmful interference to the primary network operation [28]. Thus, effective interference management and power-control schemes are needed so that the primary network users can maintain their QoS while allowing the secondary network users to exploit the surplus network capacity [29]. Secondly, contemporary spectrum-sharing schemes require coordination between the network users, to enable information exchange and ensure enforcement of spectrum-sharing rules [9]. However, any information exchange between the systems must avoid excessive signalling overhead. Thirdly, among other spectrum-sharing challenges, enhancements in radio hardware and software are essential to support capabilities such as improved geo-location sensing and interference nulling [9].

4.3 Related Work

To discuss spectrum sharing in two-tier networks comprising macrocells and femtocells (or small cells), in [29] the authors designed an optimal power-allocation scheme for up-link transmission where the utilities of user equipments are maximised in a hierarchical game, assuming that the macrocell user equipments apply their strategies first, followed by the femtocell user equipments, who apply their power-allocation strategies in response. In [72], the authors presented a distributed power-allocation scheme in a network by formulating a Stackelberg game to maximise the utilities of a central macrocell and a number of femtocells. The Stackelberg equilibrium was achieved through an effective distributed interference price-bargaining algorithm in a game where the macrocell acts as the leader to apply its strategy first (by setting an interference price); based on its strategy, the followers (femtocells) apply their strategies (by deciding their power). In [28], a scheme was presented to increase the spectral utility of a network where small cells either provide offloading services to macrocells, or earn licences to operate in the frequency spectrum of macrocells as a reward. A Nash bargaining solution was used to determine an energy-efficient balance between the offloading and licensing roles of small cells. However, it was assumed that all small cells act as a single entity instead of acting as independent players having individual utilities. To sum up, in [28, 29] and [72] it was assumed that femtocells use the same spectrum as macrocells in a two-tier network, i.e. co-channel deployment was considered. However, the proposed spectrum-sharing framework presented in this chapter considers a separate-channel deployment scenario where femtocells (small cells) do not share the spectrum with macrocells. Instead, in the proposed framework the coexistence of a number of femtocells serving either the primary network users or the secondary network users while using available spectrum resources is considered, and all the players in this framework choose their strategies at the same time.

A body of work discusses spectrum sharing between primary network users and secondary network users using power-control games [66, 68, 69, 71]. In [68] the authors presented an overlay spectrum-sharing scenario for a multi-user multi-channel cognitive radio network, where the secondary network users maximise their throughput in a power-control game, and the existence and uniqueness of the Nash equilibrium are investigated. However, it was assumed that the secondary network users utilise the spectrum when the primary network users remain idle. In [66], a non-cooperative exact-potential game, which converges to a Nash equilibrium point using the best response strategies, was proposed to jointly allocate power and frequency resources among secondary network users. However, during the game formulation, the assumptions that the primary network users remain inactive, that each player is aware of opponent player strategies and that knowledge of channel gains is available to all players, can be challenging in practice. In [69], the authors addressed the spectrum-sharing problem by formulating a non-cooperative iterated power-control game, where the licensees (SUs) aim to maximise their utilities by choosing power levels and fixing their long-term average rates. The game used the private-commons model for secondary sharing of licensed spectrum, and the role of access coordination by the primary licence holder was eliminated. However in this spectrum-sharing game, only secondary network users were considered as players, who employed power-control strategies to set their own aggregate rates. In [71], a dynamic spectrum-leasing approach was presented using a non-cooperative power-control game, where the primary network users select an interference cap on the total interference they can withstand. The existence and uniqueness of the Nash equilibrium of the proposed game with linear receiver implementation were investigated, and it was assumed that the player set includes only one primary network user along with multiple secondary network users.

In [75] and [80], a non-cooperative power-control game was presented where the femtocells independently adjust their transmit power until it stabilises while using available frequency channels; however a static price coefficient was used to adjust the weight of the price of the transmit power, which remained constant for all base stations (BSs) in a coverage area. Moreover, all BSs participating in the game were given equal priority for accessing the spectrum.

Based on the discussion above and in Chapter 3, to design a multi-priority game-theoretic approach for coexistence of femtocells to share available spectrum resources, the following features need to be considered:

- Instant information exchange and coordination between the cells needs to be minimised;
- The primary users should get higher priority of accessing the spectrum, i.e. they should have first right to improve or maintain their QoS;
- All players must choose their strategies at the same time and use the spectrum simultaneously, i.e. neither network should be idle;
- Maximum power constraint needs to be considered so that the game converges to a feasible point;
- Appropriate measures need to be taken to ensure interference mitigation, i.e. it must be ensured that the QoS of the users served by the femtocells is not compromised.

In the light of the specifications mentioned above, a game-theoretic approach is presented for spectrum sharing between a set of femtocell base stations (BSs) belonging to primary and secondary networks while ensuring that the QoS of the primary network users is maintained. A multi-priority non-cooperative game is formulated where the BSs independently adjust their transmit powers until the powers are stabilised, while using the available frequency channels. As a key idea, a game parameter, *dynamic price coefficient*, is designed which gives the primary network BSs priority over the secondary network BSs for accessing the spectrum in this multi-priority non-cooperative game. It is shown that, by choosing appropriate game parameters and maximum power constraint, the existence and uniqueness of the Nash equilibrium of the proposed non-cooperative power-control game can be achieved. Moreover, the game does not require excessive coordination, so the real-time signalling overhead between the networks can be reduced, by proposing a novel dual-mode solution that ensures that the coordination among the BSs required to reach an equilibrium point is minimised. The proposed spectrum-sharing scheme involves an active role of the primary network BSs during the non-cooperative game, and ensures that the primary network is rewarded for sharing its licensed spectrum with the secondary network, in a game where all players choose their strategies at the same time.

4.4 System Model

In this section, a system model is presented which considers a scenario where multiple femtocell base stations (BSs), coexist in a coverage area and utilise the available spectrum resources at the same time. However, unlike Chapter 3, where the BSs had equal priority of accessing the spectrum for their transmission, in this chapter it is assumed that the primary network BSs have priority over the secondary network BSs when using the spectrum. In practice, the primary network can receive financial compensation for sharing the spectrum resources licensed to it with the secondary network. However, in this sharing framework the focus is on the QoS aspect of spectrum sharing, i.e. the ability of the primary network users to reach their throughput targets, assuming that the financial-compensation aspect of spectrum sharing is already negotiated between the

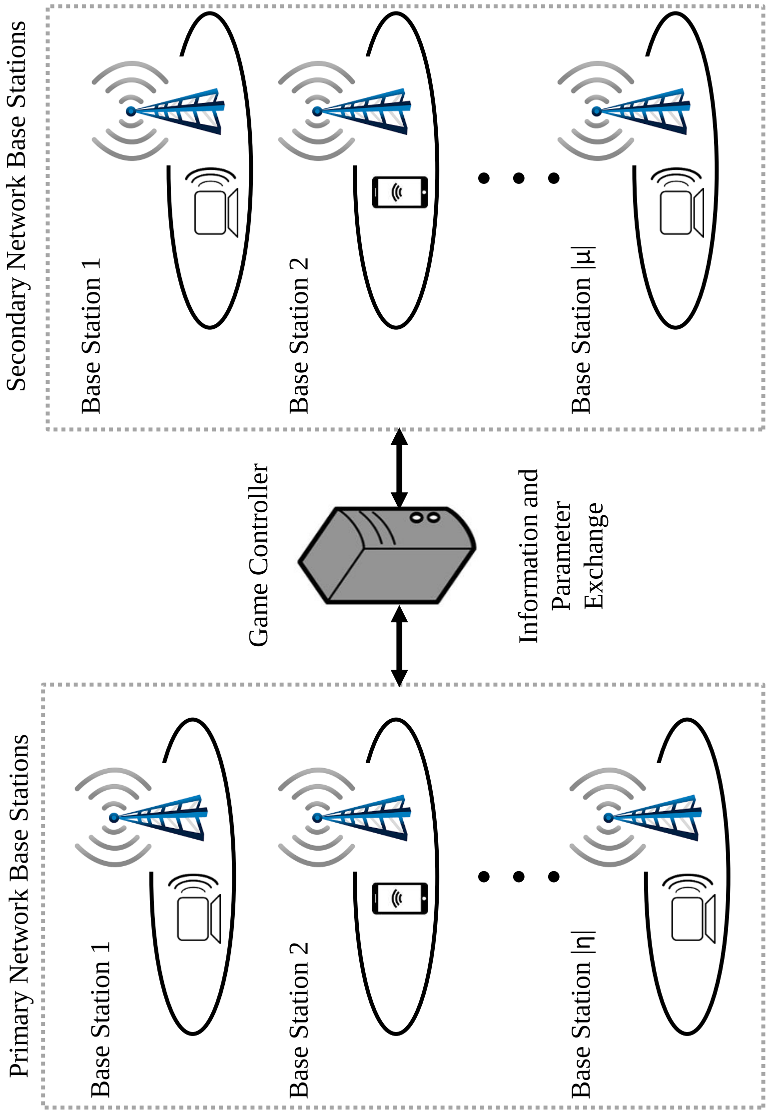

Figure 4.1: Network configuration.

networks. The primary network is given priority to access the spectrum so that the primary network users can obtain better QoS than the secondary network users. In the proposed spectrum-sharing model, the game is played in a non-cooperative manner where each player (BS) can take independent decisions based on global information provided to it by a game controller. The game controller coordinates the game by managing the participating BSs and provides them with the common information needed to play the game. The role of this game controller is minimised and the players are empowered to take decisions independently for reducing real-time signalling overhead, while ensuring that the primary network users can maintain their QoS by achieving their throughput targets.

Consider a coverage area having $|\mathcal{D}_m|$ base stations (players) as shown in Figure 4.1. $\mathcal{D}_m$ is the set of BSs participating in the non-cooperative power-control game where the i^{th} base station ($i = 1, \cdots, |\mathcal{D}_m|$) iteratively adjusts its transmit power. It is assumed that the given spectrum band, having bandwidth W, is shared among BSs serving the secondary network users and BSs serving the primary network users. It is considered that the BSs are divided into two subsets: a primary subset η serving the primary network users, and a secondary subset μ serving the secondary network users. Hence, $|\eta|$ is the number of BSs serving the primary network users, and $|\mu|$ is the number of BSs serving the secondary network users ($|\mathcal{D}_m| = |\mu| + |\eta|$). The participating BSs do not share any information with each other directly and can independently select their transmit powers.

During the proposed non-cooperative power-control game, it is considered that a channel k within W is being used for transmission by the participating BSs. For illustration convenience, it is considered that each BS serves only one user at a time. Hence, a BS user equipment $\hat{i}$ receives signals from its serving BS i and other BSs j ($j \in \mathcal{D}_m, j \neq i$), where the signals received from other BSs act as interference. For the k^{th} channel, the channel gain from BS j to user $\hat{i}$ is given by $G^k_{j,\hat{i}} = K_{j,\hat{i}} d^{-\alpha}_{j,\hat{i}} g^k_{j,\hat{i}}$ where $K_{j,\hat{i}}$ is the path-loss coefficient from BS j to user $\hat{\imath}$, $d_{j,\hat{\imath}}$ is the distance between BS j and user $\hat{\imath}$, α is the path-loss exponent, and $g^k_{j,\hat{\imath}}$ is the Rayleigh fading component from BS j to user $\hat{\imath}$ when using channel k.

4.5 Non-Cooperative Power-Control Game

In this section, a new non-cooperative power-control game is formulated for spectrum sharing among the BSs serving either the primary network users or the secondary network users. Each BS i $(i = 1, \cdots, |\mathcal{D}_m|)$ repetitively adjusts its transmit power $P^x_i \in [0, P_{\max}]$ until it stabilises, where x identifies which network the BS is serving, and is replaced by c to represent the primary network and l to represent the secondary network. $\boldsymbol{P}_{-i}$ collects the transmit powers of the rest of the BSs and $P_{\max}$ is the upper limit on the transmit power for each BS.

Based on the motivation provided in Chapter 3, the surplus function, formulated based on the utility function and the cost function, of this multi-priority non-cooperative power-control game for femtocells, can be written for the i^{th} BS $(i = 1, \cdots, |\mathcal{D}_m|)$ as

$$\begin{aligned} S^x_i(\theta^x_i, P^x_i, \boldsymbol{P_{-i}}) &= U^x_i(P^x_i, \boldsymbol{P_{-i}}) - \theta^x_i C^x_i(P^x_i, \boldsymbol{P_{-i}}) \\ &= \arctan(\alpha_m \gamma^x_i / R^x_i) - \theta^x_i P^x_i \end{aligned}$$

where $U^x_i(P^x_i, \boldsymbol{P_{-i}}) = \arctan(\alpha_m \gamma^x_i / R^x_i)$ is the utility function for BS i [75, 80]. The signal-to-interference ratio (SIR) for user $\hat{\imath}$ associated with BS $i \in \mathcal{D}_m$ is $\gamma^x_i = \frac{G^k_{i,\hat{\imath}} P^x_i}{\tilde{I}_{i,\hat{\imath}}}$. The interference measured by user equipment $\hat{\imath}$ being served by BS $i \in \mathcal{D}_m$ is denoted by $\tilde{I}_{i,\hat{\imath}} = \sum_{j \in \mathcal{D}_m \setminus \{i\}} P^x_j G^k_{j,\hat{\imath}}$. R^x_i represents the minimum target SIR threshold for the user being served by the i^{th} BS $(i = 1, \cdots, |\mathcal{D}_m|)$. An adjustable parameter α_m is used to modify the convergence speed to reach the equilibrium state of the game.

A dynamic price coefficient θ_i^x represents the individual penalty of excessively high transmit power for the i^{th} BS ($i = 1, \cdots, |\mathcal{D}_m|$), and is defined as

$$\theta_i^x = \begin{cases} \theta^c \times \Delta r_i^c \times d_f & \text{when } x = c \\ \theta^l & \text{when } x = l \end{cases} \tag{4.1}$$

where $\Delta r_i^c = R_i^c - \gamma_i^c$ is the difference between the minimum target SIR and the received SIR for the i^{th} BS ($i = 1, \cdots, |\eta|$) serving the primary network users. The discount coefficient d_f, θ^c and θ^l are constants determined by the game controller.

Unlike the game parameters proposed in Chapter 3, where a static price coefficient was used to adjust the weight of the price of the transmit power, a dynamic price coefficient has been introduced in this chapter, which ensures that the priority users (primary network users) are rewarded for sharing their spectrum. The dynamic price coefficient enables the primary network users to reach their minimum target SIR (throughput) adaptively, while the non-priority users (secondary network users) receive a static discount coefficient as given in (4.1). As emphasised in Chapter 3, the use of the $arctan()$ function in the utility function ensures the asymptotic convergence of the utilities of all players to a constant value, and acts as a limiting factor on excessively high transmit power. The linear price function $C_i^x(P_i^x, \boldsymbol{P_{-i}})$ also restricts BS $i \in \mathcal{D}_m$ from transmitting using a very high power for convergence [75, 80].

The QoS requirements of the low-priority BSs, i.e. the SBSs are variable, as it is not guaranteed that they can achieve their minimum target throughput in all the cases, unlike the high-priority BSs, i.e. PBSs. All the BSs use the same generic utility function, however, the difference is that the high-priority BSs use a dynamic price coefficient whereas the low-priority BSs use a static price coefficient. The motivation of using a dynamic parameter, i.e. dynamic price coefficient for the high-priority BSs, is that if the number of low-priority BSs in the coverage area increases, the interference in the coverage area increases and there is a need for a suitable mechanism using which the high-priority BSs can achieve their minimum target throughput. Thus, in the proposed scheme, the use of dynamic price coefficient enables the high-priority BSs to adaptively reach an equilibrium point, where the high-priority BSs can always deliver the minimum target throughput for their users. This is due to the multi-priority game arrangement, where only the high-priority BSs are enabled to adjust these parameters to meet their throughput targets. Thus, the low-priority BSs may or may not achieve their minimum target throughput depending on the number of high-priority BSs in the coverage area at any given time.

The empowerment of the BSs to learn and adapt to the traffic conditions, by fine-tuning the dynamic price coefficient, is a critical aspect of the proposed design. In traditional dynamic spectrum-access systems, multiple parameters need to be updated and adjusted simultaneously (e.g. transmit power, coding scheme, sensing algorithm, etc.), which requires complex interactions among these factors and their impact on the radio-frequency (RF) environment. In the proposed design, the spectrum-access systems, i.e. the BSs are empowered to dynamically adjust their transmit powers. Moreover, these BSs need to interact with the game controller only once (as will be shown in section 4.7), to exchange information for calculation of α_m, d_f, θ^c and θ^l as they are empowered to adjust $\theta_i^x \forall i \in \mathcal{D}_m$ themselves adaptively. This way, the complicated challenge of learning in a network of spectrum-access systems is simplified, as traditionally each system not only has to update its parameters according to the RF environment but also needs to estimate the actions of other systems. In the proposed model, each player does not need to estimate the parameters selected by other players, rather it can adjust its transmission parameters independently based on its own traffic conditions and interference measurements.

In order to find the optimal transmit power for BS $i \in \mathcal{D}_m$, $S_i^x(\theta_i^x, P_i^x, \boldsymbol{P_{-i}})$ is differentiated with respect to P_i^x to obtain

$$\frac{\partial S_i^x}{\partial P_i^x} = \frac{\alpha_m G_{i,\hat{i}}^k \Big/ R_i^x \tilde{I}_{i,\hat{i}}}{1 + \left(\frac{\alpha_m G_{i,\hat{i}}^k P_i^x}{R_i^x \tilde{I}_{i,\hat{i}}}\right)^2} - \theta_i^x. \tag{4.2}$$

The optimal solution for the i^{th} BS ($i = 1, \cdots, |\mathcal{D}_m|$), denoted by P_i^{x*}, is either the solution making (4.2) equal to zero or on the boundary of the solution region, as given by

$$P_i^{x*} = \min\left\{ \frac{R_i^x \tilde{I}_{i,\hat{i}}}{\alpha_m G_{i,\hat{i}}^k} \sqrt{\frac{G_{i,\hat{i}}^k \alpha_m}{\theta_i^x R_i^x \tilde{I}_{i,\hat{i}}} - 1}, P_{\max} \right\}, \tag{4.3}$$

and the corresponding SIR is given by

$$\gamma_i^{x*} = \frac{R_i^x}{\alpha_m} \sqrt{\frac{G_{i,\hat{i}}^k \alpha_m}{\theta_i^x R_i^x \tilde{I}_{i,\hat{i}}} - 1}. \tag{4.4}$$

Each BS can calculate its optimal transmit power adaptively using (4.3) until it stabilises and reaches an equilibrium point. The existence and uniqueness of the Nash equilibrium can be achieved by carefully selecting the initial region of the game as discussed in the next section.

The second-order partial derivative of $S_i^x(\theta_i^x, P_i^x, \boldsymbol{P_{-i}})$ with respect to P_i^x, is given by

$$\frac{\partial^2 S_i^x}{\partial (P_i^x)^2} = \frac{-2\alpha_m^3 (G_{i,\hat{i}}^k)^3}{(R_i^x)^3 \tilde{I}_{i,\hat{i}}^3} \frac{P_i^x}{\left(1 + \left(\frac{\alpha_m G_{i,\hat{i}}^k P_i^x}{R_i^x \tilde{I}_{i,\hat{i}}}\right)^2\right)^2} \tag{4.5}$$

which is negative, meaning that S_i^x is continuous and concave w.r.t. P_i^x ($i = 1, \cdots, |\mathcal{D}_m|$).

4.6 Analysis of the Nash Equilibrium of the Proposed Non-Cooperative Game

In this section, an analysis of the existence and uniqueness of the Nash equilibrium of the proposed non-cooperative game is provided.

4.6.1 Existence of the Nash Equilibrium

The existence of the Nash equilibrium of the proposed non-cooperative game is proved using the Debreu-Glicksberg-Fan Theorem [81], by noticing that:

1. S_i^x is continuous and concave w.r.t. P_i^x, as the second-order partial derivative of S_i^x w.r.t. P_i^x is negative as shown in (4.5)

2. S_i^x is continuous w.r.t. $\boldsymbol{P}_{-i}$.

3. $[P_i^x, \boldsymbol{P}_{-i}]$ is compact and convex.

4.6.2 Uniqueness of the Nash Equilibrium

In order to prove the uniqueness of the Nash equilibrium of the non-cooperative power-control game, Rosen's criterion [82] is used to equivalently prove that S_i^x is diagonally strictly concave with respect to P_i^x and $\boldsymbol{P}_{-i}$ across the region $P_i^x \in (0, P_{\max}]\,\forall i$. This can be proved if the symmetric matrix $(\mathbf{U}_m + \mathbf{U}_m^T)$ (where T denotes the transpose of the matrix) can be shown as negative definite, where $\mathbf{U}_m$ defined by (4.6) is evaluated at the optimal transmit powers P_i^{x*} $(i = 1, \cdots, |\mathcal{D}_m|)$, and β_i and ω_i are given by

$$\begin{aligned}\beta_i =& 2(\theta_i^x)^2 \sqrt{\frac{G_{i,\hat{i}}^k \alpha_m}{\theta_i^x R_i^x \tilde{I}_{i,\hat{i}}}} - 1;\\ \omega_i =& \frac{\theta_i^x}{\alpha_m \tilde{I}_{i,\hat{i}}} \left(2\theta_i^x R_i^x \tilde{I}_{i,\hat{i}} - G_{i,\hat{i}}^k \alpha_m\right)\end{aligned}$$

where $x = c$ or $x = l$ represents how $|\eta|$ BSs serving the primary network users and $|\mu|$ BSs serving the secondary network users are arranged for $i = 1, \cdots, |\mathcal{D}_m|$.

$$\mathbf{U}_m = \begin{bmatrix} \frac{\partial^2 S_1^x}{\partial (P_1^x)^2} & \frac{\partial^2 S_1^x}{\partial P_1^x \partial P_2^x} & \cdots & \frac{\partial^2 S_1^x}{\partial P_1^x \partial P_{|\mathcal{D}_m|}^x} \\ \frac{\partial^2 S_2^x}{\partial P_1^x \partial P_2^x} & \frac{\partial^2 S_2^x}{\partial (P_2^x)^2} & \cdots & \frac{\partial^2 S_2^x}{\partial P_2^x \partial P_{|\mathcal{D}_m|}^x} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 S_{|\mathcal{D}_m|}^x}{\partial P_1^x \partial P_{|\mathcal{D}_m|}^x} & \frac{\partial^2 S_{|\mathcal{D}_m|}^x}{\partial P_2^x \partial P_{|\mathcal{D}_m|}^x} & \cdots & \frac{\partial^2 S_{|\mathcal{D}_m|}^x}{\partial (P_{|\mathcal{D}_m|}^x)^2} \end{bmatrix} \tag{4.6}$$

$$\mathbf{U}_m = \begin{bmatrix} -\beta_1 & \frac{-G_{2,\hat{1}}^k \omega_1}{G_{1,\hat{1}}^k} & \cdots & \frac{-G_{|\mathcal{D}_m|,\hat{1}}^k \omega_1}{G_{1,\hat{1}}^k} \\ \frac{-G_{1,\hat{2}}^k \omega_2}{G_{2,\hat{2}}^k} & -\beta_2 & \cdots & \frac{-G_{|\mathcal{D}_m|,\hat{2}}^k \omega_2}{G_{2,\hat{2}}^k} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{-G_{1,\hat{|\mathcal{D}_m|}}^k \omega_{|\mathcal{D}_m|}}{G_{|\mathcal{D}_m|,\hat{|\mathcal{D}_m|}}^k} & \frac{-G_{2,\hat{|\mathcal{D}_m|}}^k \omega_{|\mathcal{D}_m|}}{G_{|\mathcal{D}_m|,\hat{|\mathcal{D}_m|}}^k} & \cdots & -\beta_{|\mathcal{D}_m|} \end{bmatrix}$$

To prove the negative definiteness of the symmetric matrix $(\mathbf{U}_m + \mathbf{U}_m^T)$, the expression for $\mathbf{y}^T(\mathbf{U}_m + \mathbf{U}_m^T)\mathbf{y}$, $\forall \mathbf{y} \in \mathbb{R}^{|\mathcal{D}_m| \times 1}$, is given as

$$\mathbf{y}^T(\mathbf{U}_m + \mathbf{U}_m^T)\mathbf{y} = -\Bigg[2\sum_{i=1}^{|\mathcal{D}_m|} y_i^2 \beta_i + \sum_{i=1}^{|\mathcal{D}_m|} \sum_{j=1,\, j\neq i}^{|\mathcal{D}_m|} \left(\frac{G_{j,\hat{i}}^k}{G_{i,\hat{i}}^k}\omega_i + \frac{G_{i,\hat{j}}^k}{G_{j,\hat{j}}^k}\omega_j \right) y_i y_j \Bigg]$$

which can be rewritten as given in (4.7). To ensure the negativity of the left-hand side (LHS) of (4.7), it must be ensured that

$$\Big(|\mathcal{D}_m| - 1\Big) \max_{\forall i,j,\, i\neq j} \left\{ \frac{1}{\sqrt{\beta_i \beta_j}} \left| \frac{G_{j,\hat{i}}^k}{G_{i,\hat{i}}^k}\omega_i + \frac{G_{i,\hat{j}}^k}{G_{j,\hat{j}}^k}\omega_j \right| \right\} \leq 2$$

which, by substituting β_i and ω_i ($i = 1, \cdots, |\mathcal{D}_m|$) in, can be rewritten as given in (4.8).

$$
\begin{aligned}
\mathbf{y}^T(\mathbf{U}_m+\mathbf{U}_m^T)\mathbf{y} &= -\left[2\sum_{i=1}^{|\mathcal{D}_m|}(y_i\sqrt{\beta_i})^2+\sum_{i=1}^{|\mathcal{D}_m|}\sum_{j=1,\,j\neq i}^{|\mathcal{D}_m|}\frac{\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i+\frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j}{\sqrt{\beta_i\beta_j}}y_i\sqrt{\beta_i}y_j\sqrt{\beta_j}\right]\\
&\leq -\left[2\sum_{i=1}^{|\mathcal{D}_m|}\left(y_i\sqrt{\beta_i}\right)^2-\sum_{i=1}^{|\mathcal{D}_m|}\sum_{j=1,\,j\neq i}^{|\mathcal{D}_m|}\frac{\left|\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i+\frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j\right|}{2\sqrt{\beta_i\beta_j}}\left(\left(y_i\sqrt{\beta_i}\right)^2+\left(y_j\sqrt{\beta_j}\right)^2\right)\right]\\
&= -\sum_{i=1}^{|\mathcal{D}_m|}\left(2-\sum_{j=1,\,j\neq i}^{|\mathcal{D}_m|}\frac{\left|\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i+\frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j\right|}{\sqrt{\beta_i\beta_j}}\right)\left(y_i\sqrt{\beta_i}\right)^2\\
&\leq -\left(2-\left(|\mathcal{D}_m|-1\right)\max_{\forall i,j,\,i\neq j}\left\{\frac{\left|\frac{G^k_{j,\hat{i}}}{G^k_{i,\hat{i}}}\omega_i+\frac{G^k_{i,\hat{j}}}{G^k_{j,\hat{j}}}\omega_j\right|}{\sqrt{\beta_i\beta_j}}\right\}\right)\sum_{i=1}^{|\mathcal{D}_m|}\left(y_i\sqrt{\beta_i}\right)^2
\end{aligned}
\tag{4.7}
$$

$$
\begin{aligned}
&\max_{\forall i,j,\,i\neq j}\left\{\frac{1}{\theta_i^x\theta_j^x}\sqrt[4]{\frac{R_i^xR_j^x\tilde{I}_{i,\hat{i}}\tilde{I}_{j,\hat{j}}}{\left(G^k_{i,\hat{i}}\frac{\alpha_m}{\theta_i^x}-R_i^x\tilde{I}_{i,\hat{i}}\right)\left(G^k_{j,\hat{j}}\frac{\alpha_m}{\theta_j^x}-R_j^x\tilde{I}_{j,\hat{j}}\right)}}\times\right.\\
&\qquad\left.\left|\frac{G^k_{j,\hat{i}}(\theta_i^x)^2}{G^k_{i,\hat{i}}\tilde{I}_{i,\hat{i}}}\left(2R_i^x\tilde{I}_{i,\hat{i}}-G^k_{i,\hat{i}}\frac{\alpha_m}{\theta_i^x}\right)+\frac{G^k_{i,\hat{j}}(\theta_j^x)^2}{G^k_{j,\hat{j}}\tilde{I}_{j,\hat{j}}}\left(2R_j^x\tilde{I}_{j,\hat{j}}-G^k_{j,\hat{j}}\frac{\alpha_m}{\theta_j^x}\right)\right|\right\}\leq\frac{4\alpha_m}{|\mathcal{D}_m|-1}
\end{aligned}
\tag{4.8}
$$

It must be ensured that the selection of α_m and θ_i^x $(i = 1, \cdots, |\mathcal{D}_m|)$ is appropriate so that $\mathbf{y}^T(\mathbf{U}_m + \mathbf{U}_m^T)\mathbf{y} \leq 0$ for any $\mathbf{y}$, as shown in (4.7). It can be noted that the LHS of (4.8) depends on $\frac{\alpha_m}{\theta_i^x}$ and $\theta_i^x \forall i \in \mathcal{D}_m$, rather than explicitly on α_m. Assuming $|\theta_i^x| < 1$, $\forall i \in \mathcal{D}_m$, given any reasonable value of $\frac{\alpha_m}{\theta_i^x}$, i.e.,

$$\frac{\alpha_m}{\theta_i^x} \in \left(0, \min_{\forall i}\left\{\frac{R_i^x \tilde{I}_{i,\hat{i}}}{G_{i,\hat{i}}^k}\right\}\right) \cup \left(\max_{\forall i}\left\{\frac{R_i^x \tilde{I}_{i,\hat{i}}}{G_{i,\hat{i}}^k}\right\}, +\infty\right) \tag{4.9}$$

α_m can be adjusted at the right-hand side of (4.8) to preserve the inequality. By obtaining appropriate values of α_m and θ_i^x $(i = 1, \cdots, |\mathcal{D}_m|)$ which satisfy (4.8) - (4.9), it can be ensured that $\mathbf{y}^T(\mathbf{U}_m + \mathbf{U}_m^T)\mathbf{y} \leq 0$ for any $\mathbf{y}$, as shown in (4.7). This guarantees that $(\mathbf{U}_m + \mathbf{U}_m^T)$ is negative definite, which in turn implies that S_i^x is diagonally strictly concave over $[P_i^x, \boldsymbol{P}_{-i}]$ in the unbounded region $P_i^x \in (0, +\infty)\,\forall i$. By Rosen's criterion, this ensures that there is a unique Nash equilibrium of the non-cooperative game [82].

4.7 Implementation of the Proposed Game

During the proposed non-cooperative power-control game, the participating BSs are empowered to take independent decisions about their transmit power without excessive coordination with one another or the game controller. However, in order to ensure that the game has a unique Nash equilibrium, all BSs require particular parameter information to calculate their optimal transmit powers. Specifically, each BS $i \in \mathcal{D}_m$ needs information about α_m and either θ^l or θ^c along with d_f to calculate its optimal transmit power P_i^*.

The game is implemented by designing two modes: an *initialisation-mode* in which the BSs exchange necessary parameter information and an *iteration-mode* in which the BSs repeatedly adjust their optimal transmit power until an equilibrium point is achieved. The tasks executed in each mode are presented in Figure 4.2.

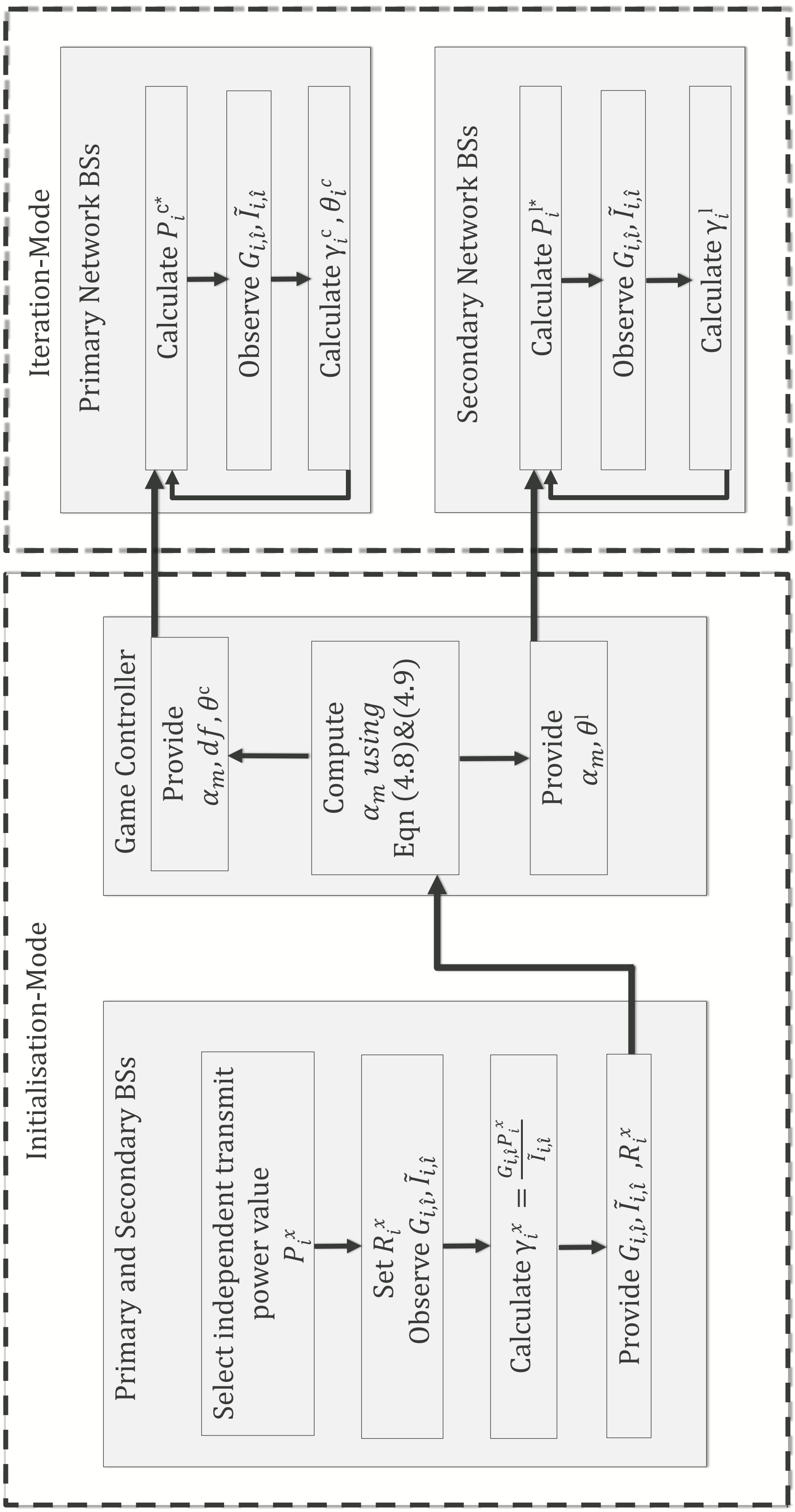

Figure 4.2: Sequence of tasks executed in the initialisation and iteration modes of the game.

4.7.1 Initialisation-Mode

During this mode, the game controller collects information from all BSs to compute and return necessary parameter values to them so that each BS $i \in \mathcal{D}_m$ can select θ_i^x in the iteration-mode. Each participating BS i $(i = 1, \cdots, |\mathcal{D}_m|)$ serving user $\hat{i}$

- Transmits using a particular initial transmit power P_i^x
- Observes the channel gain $G_{i,\hat{i}}^k$
- Collects the interference information $\tilde{I}_{i,\hat{i}}$
- Sets its minimum target SIR R_i^x
- Calculates the received SIR γ_i^x

Once each BS $i \in \mathcal{D}_m$ serving user $\hat{i}$ completes the above tasks, it provides R_i^x and the observed values of $\tilde{I}_{i,\hat{i}}$ and $G_{i,\hat{i}}^k$ to the game controller. This enables the game controller to process the up-to-date parameter information for calculating a suitable value of $\frac{\alpha_m}{\theta_i^x} \forall i \in \mathcal{D}_m$, which is essential to ensure the uniqueness of the Nash equilibrium, as obvious from (4.9). The game controller calculates $\frac{R_i^x \tilde{I}_{i,\hat{i}}}{G_{i,\hat{i}}^k} \forall i \in \mathcal{D}_m$, to choose the ratio $\frac{\alpha_m}{\theta_i^x} \forall i \in \mathcal{D}_m$ within the specified ranges given by (4.9) and determines suitable values of α_m, d_f, θ^l and θ^c which remain constant throughout the iteration-mode. Eventually, these values need to be provided to all BSs, before the start of the iteration-mode. Hence, the initialisation-mode is concluded when α_m, d_f, θ^l and θ^c are returned to relevant BSs so that they can calculate their transmit power in the iteration-mode.

4.7.2 Iteration-Mode

Recall from (4.3) that each BS $i \in \mathcal{D}_m$ serving user $\hat{i}$ can select its optimal transmit power, using the values of $\tilde{I}_{i,\hat{i}}$, $G_{i,\hat{i}}^k$, and R_i^x, all of which are available to it; the additionally needed information, i.e. the values of α_m and either θ^l or θ^c along with d_f, is provided by the game controller after the initialisation-mode. Using this information, BS $i \in \mathcal{D}_m$ calculates P_i^{x*} for each upcoming iteration until P_i^{x*} is stabilised. α_m and $\theta_j^x(j \in \mu)$ remain constant for all iterations. However, each BS $i \in \eta$ serving the primary network users updates θ_i^x based on Δr_i^c and d_f, for each iteration. Once each BS $i \in \mathcal{D}_m$ finalises the transmit power, this information is then used to compute an updated γ_i^x and the resulting throughput.

4.8 Simulation Results

In this section, parameter values are set to carry out MATLAB-based computer simulations, and a discussion of the results is provided.

4.8.1 Simulation Setup

During simulations, we consider real scenarios of femtocell deployment. Since our model considers the channel gains from BSs to users, path-loss coefficients from BSs to users, distances between BSs and users and the Rayleigh fading model, these features can be best represented in MATLAB, and can not be accurately represented in NS2 or QualNet. Therefore, we have used MATLAB which is the most suitable tool to represent our system model. We use Monte Carlo simulation technique and run each experiment 50000 times.

The simulation setup presented in this chapter closely resembles the setup provided in Chapter 3. However, unlike Chapter 3 where all the BSs were awarded equal priority for accessing the spectrum, in this chapter it is assumed that using the dynamic price coefficient, the primary network BSs can get priority over the secondary network BSs. For all the simulations, the values of α_m, θ^c, d_f and θ^l are decided in the initialisation-mode by the game controller and their value are kept constant in the iteration-mode. For the i^{th} BS $\forall i \in \eta$ serving the primary network users, θ_i^x is updated for each iteration in the iteration-mode, using the values of Δr_i^c and d_f. For simulations, $\theta^c = 0.5$, $\theta^l = 0.75$ and

$d_f = 0.5$ unless stated otherwise. The maximum transmit power is set as 1000 mW. The throughput achieved by user $\hat{i}$ associated with BS $i \in \mathcal{D}_m$ is $\Gamma_i^x = W \log_2 (1 + \gamma_i^x)$ where W is the bandwidth of the channel and γ_i^x is the SIR. The minimum target throughput, which is computed using the minimum target SIR, for the primary network users is set as 7 Mb/s unless otherwise stated. The value of the path-loss exponent α is set as 3.5, appropriate for an urban environment.

4.8.2 Results and Discussion

In Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6, a convergence analysis of the non-cooperative power-control game is provided, and simulations are performed by setting $|\mathcal{D}_m| = 18, |\mu| = 9, |\eta| = 9$. Figure 4.3 shows the convergence of the average surplus of the primary network BSs and the secondary network BSs to their respective equilibrium points as the game progresses. It can be observed that the primary network achieves a higher surplus than the secondary network, as the primary network BSs get priority using the dynamic price coefficient. Moreover in both cases, after 10 iterations the average surplus reaches a stabilised value (equilibrium point), which is below the theoretical maximum of $\pi/2$ as expected. Figure 4.4 shows the convergence of the average transmit powers of the primary network BSs and the secondary network BSs to their respective equilibrium points as the game progresses. It can be observed that, on average the primary network BSs are able to choose higher transmit powers as compared to the secondary network BSs, using the dynamic price coefficient. In both cases, after 10 iterations the average transmit power reaches a stabilised value (equilibrium point). Figure 4.5 and Figure 4.6 show the convergence of the individual transmit powers of the primary network BSs and the secondary network BSs to distinct equilibrium points respectively, as the game progresses. It can be observed that after 10 iterations, the individual transmit powers of all the BSs reach stabilised values (equilibrium points).

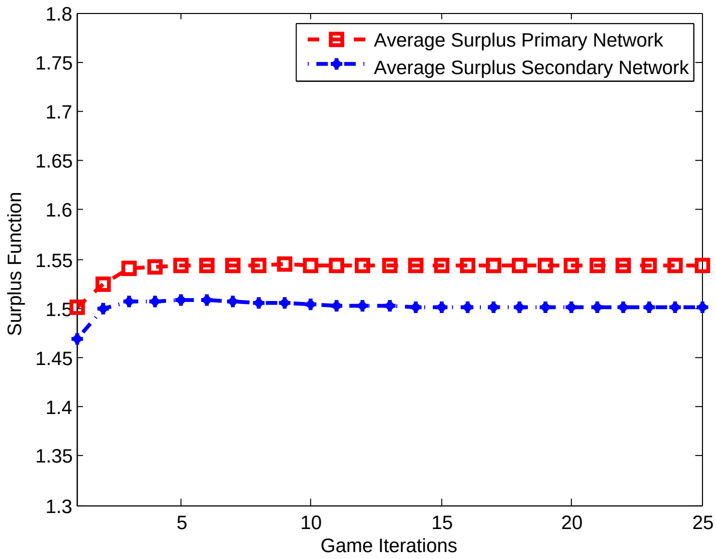

Figure 4.3: Average surplus achieved by the primary network BSs and the secondary network BSs w.r.t. game iterations.

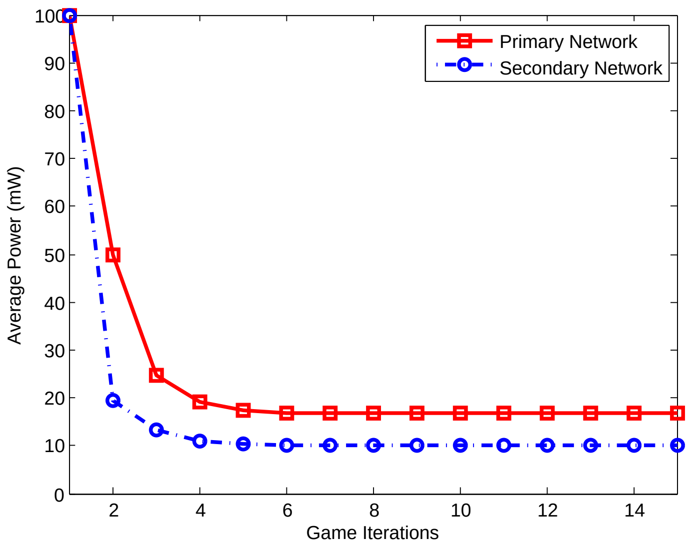

Figure 4.4: Average transmit powers of the primary network BSs and the secondary network BSs w.r.t. game iterations.

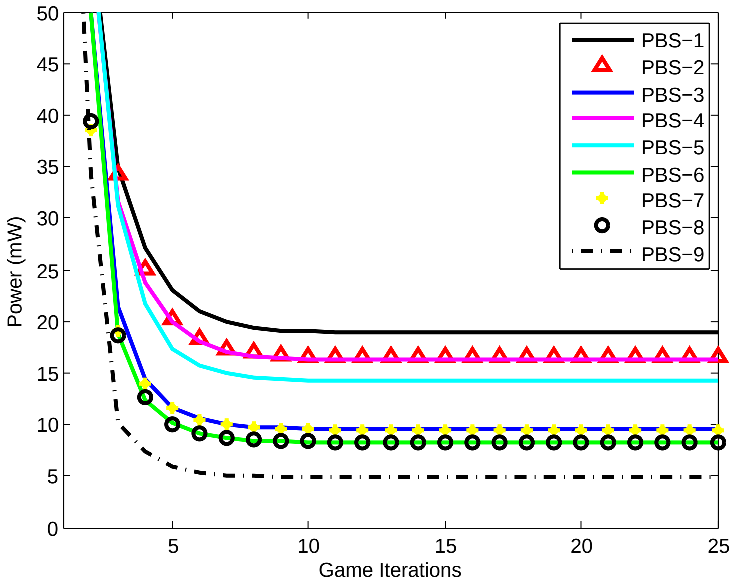

Figure 4.5: Individual transmit powers of the primary network BSs (PBSs) w.r.t. game iterations.

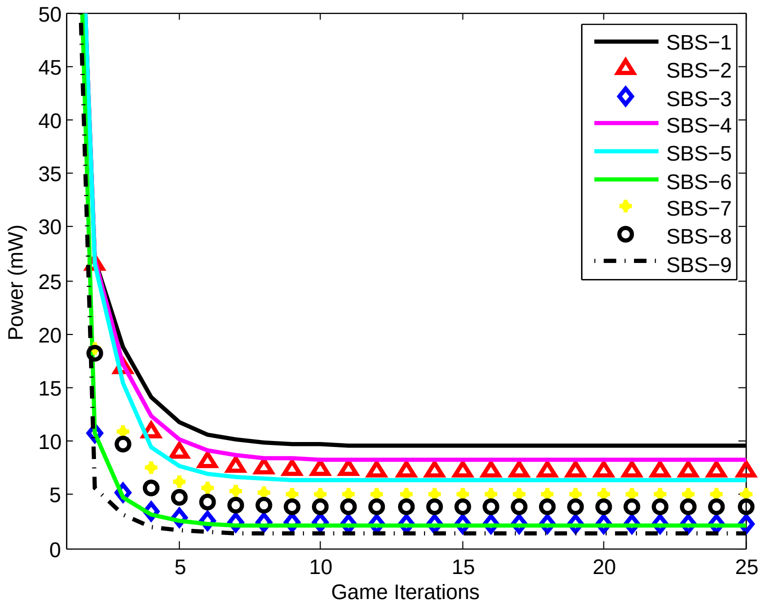

Figure 4.6: Individual transmit powers of the secondary network BSs (SBSs) w.r.t. game iterations.

Note that the individual transmit power of each BS can converge to a distinct equilibrium point, as its power gets stabilised at a point depending on the interference it receives. Nevertheless, all the users being served by the primary network BSs are still able to meet their minimum target throughput, i.e. 4 Mb/s; see Figure 4.7.

Figure 4.9 shows that the dynamic price coefficient enables the primary network BSs to adaptively minimise the received interference and ensure that the interference power constraint is always satisfied throughout the iteration-mode, as the measured interference values of the primary network BSs converge to distinct equilibrium points.

Figure 4.10 and Figure 4.11 provide a demonstration of the effect of varying $|\eta|$, the number of primary network BSs in the coverage area, on received average SIR and achieved average throughput of users of both networks respectively at the equilibrium stage, by considering a scenario when $|\mu| = 9$ secondary network BSs continuously utilise the spectrum resources.

In Figure 4.10, it is shown that, as $|\eta|$ increases, the average SIR received by the secondary network users decreases gradually. When $|\eta| = 0$, the secondary network users receive a high average SIR, as there are no priority BSs (primary network BSs) in the coverage area. As $|\eta|$ increases, the average SIR received by the secondary network users decreases due to an increase in the number of priority BSs. Moreover, it is also observed that, when the number of primary network BSs increases, the average SIR received by the primary network users also decreases due to the competition among them. However, the primary network users are still able to receive their minimum target SIR by adjusting the dynamic price coefficient, unlike the secondary network users whose average SIR decreases beyond a certain level of congestion in the coverage area.

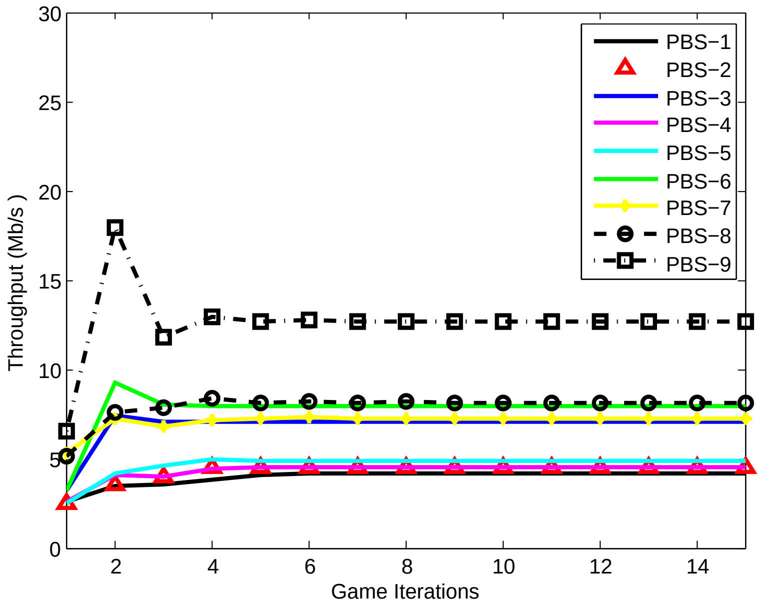

Figure 4.7: Individual throughput provided by each primary network BS to its respective users.

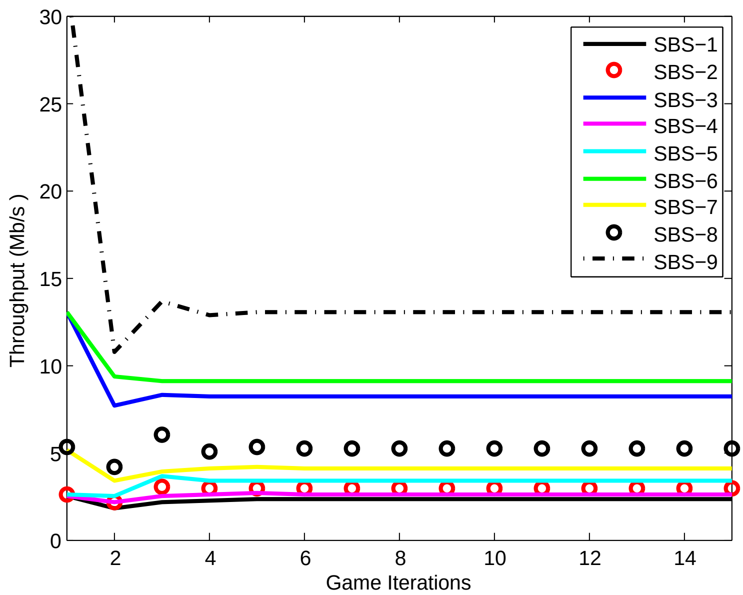

Figure 4.8: Individual throughput provided by each secondary network BS to its respective users.

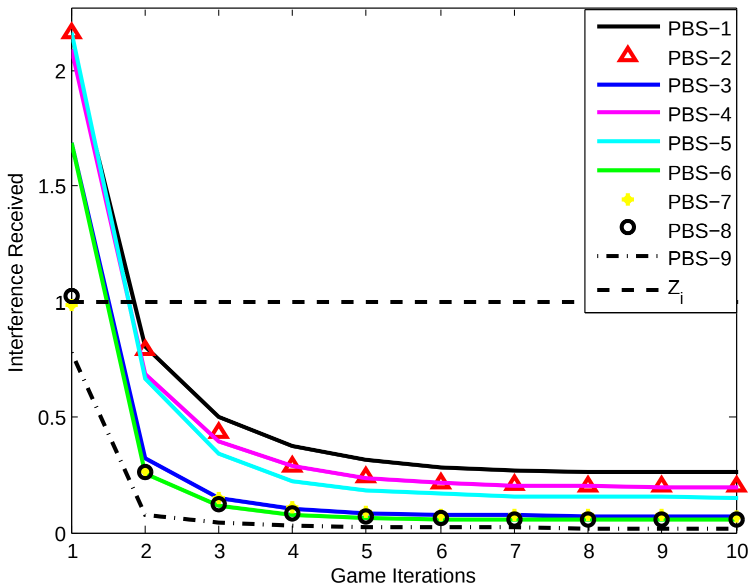

Figure 4.9: Effect of using a dynamic price coefficient on received interference for primary network BSs.

Similarly, Figure 4.11 shows that as $|\eta|$ increases the average throughput achieved by the secondary network users decreases gradually. When $|\eta| = 0$, the secondary network users achieve a high average throughput (18 Mb/s) as there are no priority BSs (primary network BSs) in the coverage area. As $|\eta|$ increases, the average throughput achieved by the secondary network users decreases due to an increase in the number of priority BSs. Moreover, it is also observed that, when the number of primary network BSs increases, the average throughput achieved by the primary network users also decreases due to the competition among them. However, the primary network users are still able to achieve their minimum target throughput by adjusting the dynamic price coefficient, unlike the secondary network users, whose average throughput decreases after a certain level of congestion in the coverage area.

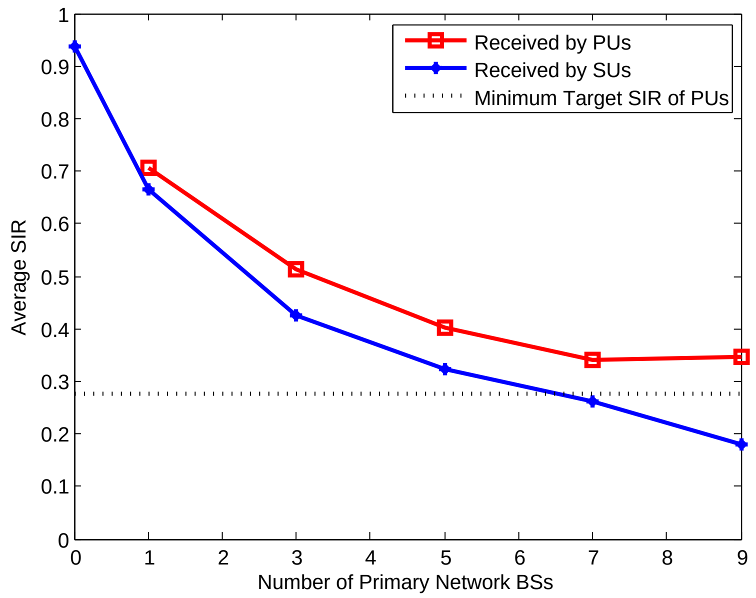

Figure 4.10: The effect on average SIR received by users of both networks, by varying the number of primary network BSs, when $|\mu| = 9$.

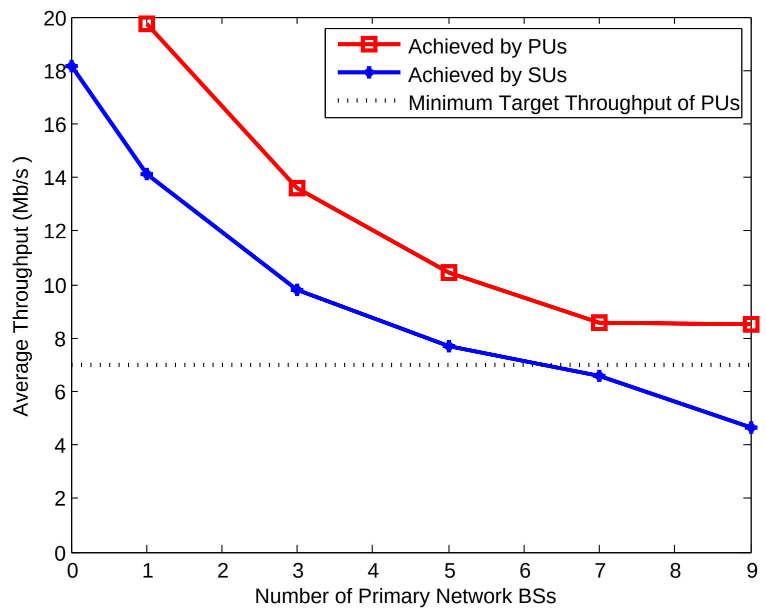

Figure 4.11: The effect on average throughput achieved by users of both networks, by varying the number of primary network BSs, when $|\mu| = 9$.

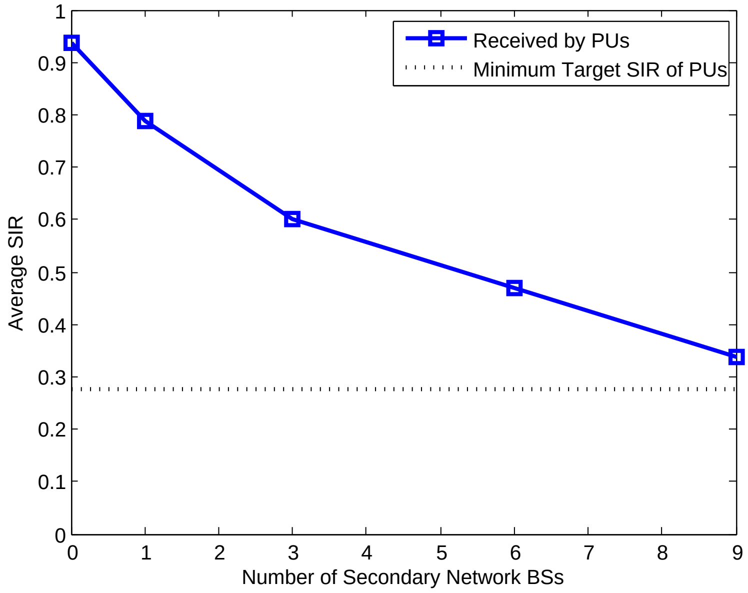

Figure 4.12: The effect on average SIR received by the primary network users (PUs), by varying the number of secondary network BSs, when $|\eta| = 9$.

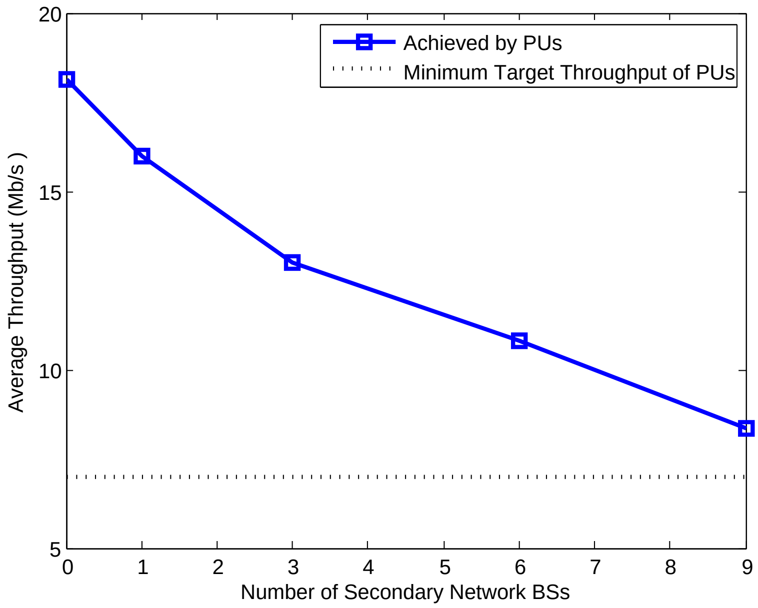

Figure 4.13: The effect on average throughput achieved by the primary network users (PUs), by varying the number of secondary network BSs, when $|\eta| = 9$.

Figure 4.12 and Figure 4.13 provide a demonstration of the effect of varying $|\mu|$, the number of BSs serving the secondary network in a coverage area, on received average SIR and achieved average throughput of the primary network users respectively at the equilibrium stage, by considering a scenario when $|\eta| = 9$ primary network BSs continuously utilise the spectrum resources.

Figure 4.12 shows that, as $|\mu|$ increases the received average SIR of the primary network users is degraded, in turn degrading the average throughput achieved by the primary network users, which begins to approach their minimum target throughput, i.e. 7 Mb/s, as shown in Figure 4.13.

In Figure 4.14 and Figure 4.15, a throughput analysis is presented by considering a congested scenario, where the number of primary network BSs is equal to the number of secondary network BSs, i.e. $|\mathcal{D}_m| = 18, |\mu| = 9, |\eta| = 9$. Figure 4.14 depicts a variation in the received average SIR of users from both networks as the game progresses through the initialisation-mode to the iteration-mode. It is observed that the average SIR received by the primary network users increases as the game progresses, resulting in a decrease in the average SIR received by the secondary network users. Similarly, Figure 4.15 provides an overview of the variation in the achieved average throughput of users from both networks as the game progresses and it is observed that, the average throughput achieved by the primary network users increases as the game progresses, resulting in a decrease in the average throughput achieved by the secondary network users.

In Chapter 3, a static price coefficient was used to award all the BSs participating in the game an equal priority to access the spectrum. However, this arrangement resulted in a limitation on the achieved performance of the primary network users, as it was observed that, the primary network users were only able to achieve a constant average throughput in a congested scenario regardless of the target.

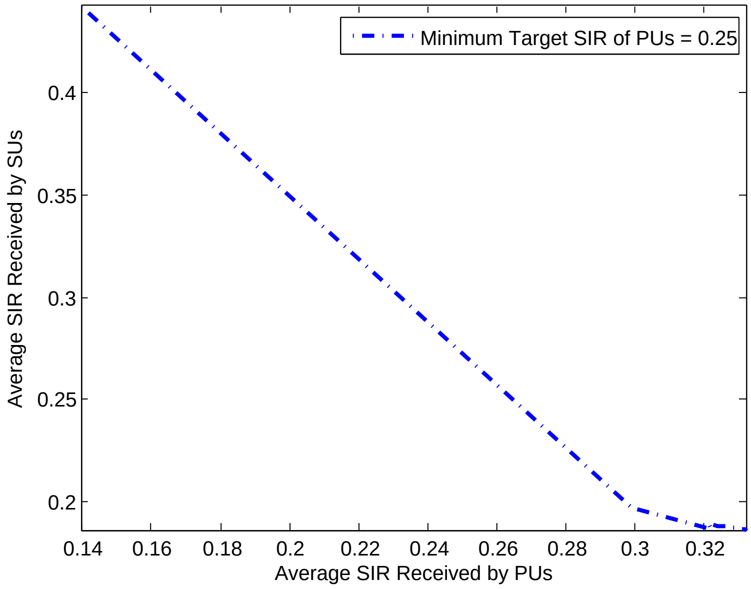

Figure 4.14: Received SIR comparison between users of both networks, when $|\mathcal{D}_m| = 18, |\mu| = 9, |\eta| = 9$.

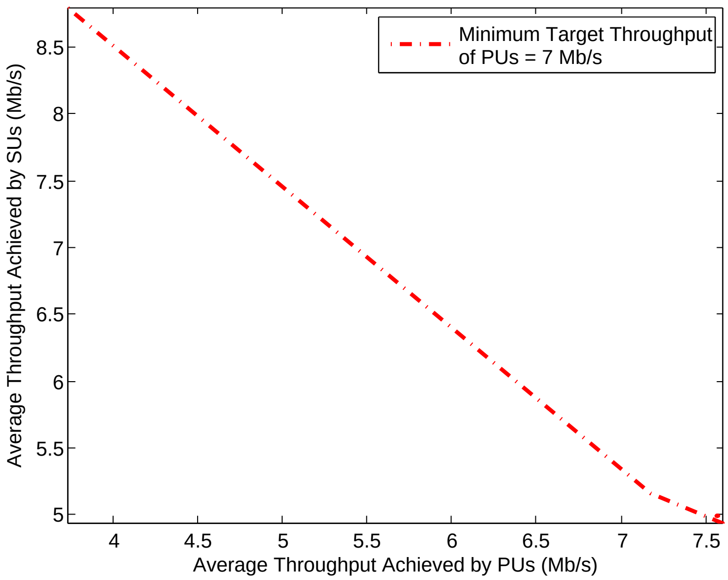

Figure 4.15: Achieved throughput comparison between users of both networks, when $|\mathcal{D}_m| = 18, |\mu| = 9, |\eta| = 9$.

Building on that discussion, the benefit of using the dynamic price coefficient is highlighted in Figure 4.16 by considering a congested scenario where the number of primary network BSs is equal to the number of secondary network BSs, i.e. $|\mathcal{D}_m| = 18, |\mu| = 9, |\eta| = 9$. The figure demonstrates the effect of varying the minimum target throughput of the primary network users on the achieved average throughput of users of both networks at the equilibrium stage.

It is observed that an increase in the minimum target throughput of primary network users results in a decrease in the average throughput achieved by the secondary network users, whereas the average throughput achieved by the primary network users increases, as desired. To elaborate the advantage provided by the dynamic price coefficient, the solid line in the figure shows the average throughput achieved by the primary network users if they use a static price coefficient (instead of the dynamic price coefficient proposed in this chapter). Thus, when the static price coefficient is used, the primary network users are only able to achieve a constant average throughput regardless of the target. On the other hand, it can be noted that, as the minimum target throughput of the primary network users increases, the dynamic price coefficient enables them to achieve their throughput targets. In comparison, it is observed that the average throughput achieved by the secondary network users starts degrading once the minimum target throughput of the primary network users reaches 5 Mb/s. The dynamic price coefficient is therefore critical in enabling primary network users to meet a varying minimum target throughput.

As explained in Chapter 3, we compare the performance of the proposed dual-mode game implementation scheme with an offline centralised counterpart. In the proposed scheme, the parameter values are exchanged only in the initialization-mode of the game, whereas in the offline centralised implementation, the parameters values are exchanged on each iteration of the game.

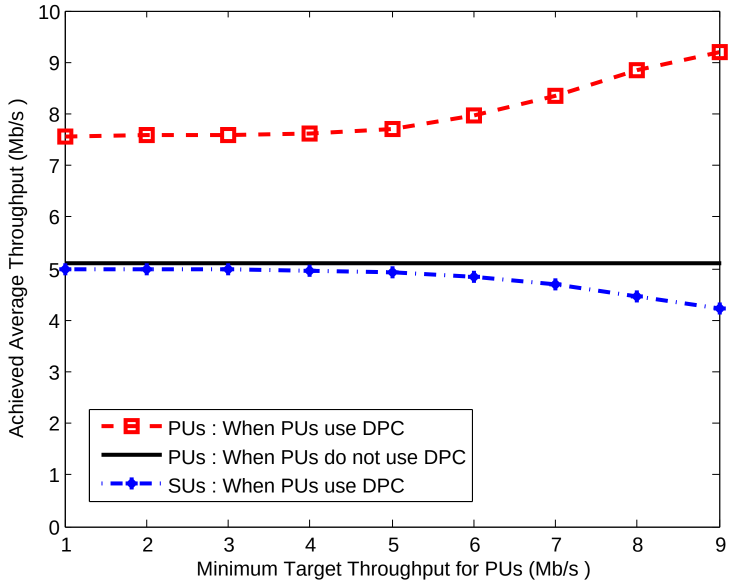

Figure 4.16: Effect of using a dynamic price coefficient on achieved average throughput for users when $|\mathcal{D}_m| = 18, |\mu| = 9, |\eta| = 9$.

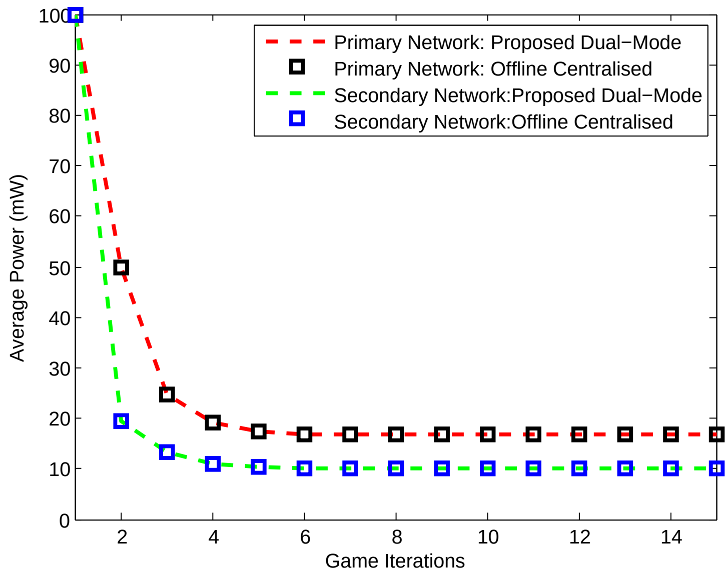

Figure 4.17: Comparison of average transmit power for the BSs w.r.t. game iterations.

Figure 4.17 highlights the performance comparison between the proposed dual-mode implementation and the offline centralised implementation. However, we note that in this case the performance of the dual-mode implementation is identical to the performance of the offline centralised implementation. That is, in both cases the equilibrium points of the average transmit power of the BSs are identical. This is because in this scheme, the nodes are allowed to update their dynamic price coefficient adaptively in each iteration. Therefore, this automates the parameter selection process and eliminates the need of parameter exchange at each iteration for better performance.

4.9 Summary

In this chapter, a game-theoretic spectrum-sharing framework for next-generation heterogeneous mobile networks was proposed, where the primary network and the secondary network share spectrum resources through a non-cooperative power-control game. The participating base stations serving either primary network users or secondary network users, dynamically adjusted their transmit powers by measuring received interference. A game parameter dynamic price coefficient was introduced, which can be adjusted to allow the game to converge to a unique Nash equilibrium. The convergence of the game to a unique Nash equilibrium was proved theoretically. The presented simulation results showed that the dynamic price coefficient can be adjusted by the primary network such that the primary network users can achieve their minimum target throughput.

Supporting Publications

- A. Saadat, W. Ni, R. Vesilo, “ Collaborative Spectrum Sharing through non-collaborative gaming for next-generation small cells”, *IEEE Access*, vol. 5, pp. 10182-10192, December 2017.

Chapter 5

A Two-Layer Evolutionary Game for LSA-based Spectrum Sharing

5.1 Chapter Introduction

In this chapter, a two-layer evolutionary game for dynamic spectrum sharing using Licensed Shared Access (LSA) is proposed to serve the additional capacity needs of Mobile Network Operators (MNOs). The proposed game algorithm ensures demand-driven allocation of spectrum resources to LSA licensees, guaranteeing spectrum availability for licensees, unlike previous spectrum-sharing techniques. The proposed evolutionary game is further extended by modelling the dynamic price-adjustment strategies adopted by incumbents achieving an improved total gain for the incumbents. The stability of the proposed evolutionary algorithm is proved using Lyapunov stability criteria. The presented simulation results show that the game can achieve stability through the evolutionary algorithm, and highlight the effects of dynamic parameters offered by incumbents, such as price, on overall average licensee payoff.

5.2 Background and Motivation

As detailed throughout this thesis, the evolution of smart devices and increased worldwide mobile broadband usage has raised the need for a next-generation of mobile communication technologies, which has to be spectrally-efficient. In this regard, the concept of LSA has emerged as a popular solution to enable dynamic spectrum sharing, so that the unused spectrum of incumbents (primary spectrum users or licensed spectrum users) can be shared with licensees (secondary spectrum users or unlicensed spectrum users) to enable the licensees to exploit extra capacity and provide mobile services [32]. Unlike previous spectrum-sharing techniques such as cognitive radio, LSA does not require the devices to be equipped with the capability of sensing spectral availability. The available spectrum that can be leased is advertised through out-of-band signalling. Successful implementation of LSA-based technologies involves challenges of ensuring reliable quality of service (QoS) for participating incumbents and licensees through sharing agreements and suitable communication protocols, ensuring coexistence and thus increasing spectral efficiency [24, 25]. For these reasons, major mobile industry manufacturers such as Intel, Qualcomm, etc. are leading research on LSA implementation for MNOs [19, 20].

As emphasised throughout this thesis, game theory is considered a useful mathematical tool to resolve the spectrum-sharing problems [87–89]. Thus, applying game-theoretic principles to LSA-based spectrum sharing problem is a promising research prospect. However, since LSA is a recent approach for spectrum sharing, game-theoretic approaches for LSA have received very limited attention so far. Nevertheless, details of recent LSA-based spectrum sharing approaches can be found in [90–95], while an account of auction-theory based LSA approaches can be found in [96–98].

To emphasise the importance of LSA as compared to previous spectrum-sharing schemes, it must be mentioned that traditional spectrum-sharing techniques such as cognitive radio provide various methods to utilise the spectrum white spaces. However, some key issues such as uncertainty about long-term availability of the spectrum for the secondary users remain unresolved. For example, in [99], an evolutionary game for joint spectrum sensing and access in cognitive radio networks was formulated to ensure robustness to handle selfish strategies adopted by secondary users. However, the issues of uncertainty about long-term spectrum availability for secondary users were not addressed. Moreover, a body of research work deals with limiting interference between users sharing the same spectrum in a game [100, 101]. Specifically, in [100], a scheme for spectrum sharing between primary users and secondary users for cognitive radio was presented using an optimality analysis [100]. Similarly, in [101], a scheme for spectrum sharing between primary users and secondary users for cognitive radio was presented using a game-theoretic model [101]. However in both schemes [100, 101], the spectrum of primary users was accessible to secondary users only by ensuring limited interference to primary users with no guarantee for maintaining the QoS for secondary users.

With regards to spectrum-sharing games, a multiple-seller multiple-buyer cognitive radio spectrum-sharing scenario was modelled as the evolution of behaviour of secondary users using an evolutionary game approach in [65]. However, the assumptions of primary users broadcasting the spectrum bands on offer, and average group payoff knowledge availability for each secondary user, may not be practical considering the limitations of cognitive radios. Moreover, the possibility of primary users re-acquiring the spectrum, hence long-term availability of spectrum for secondary users, was not addressed. Furthermore, Etkin et al. [102] presented a self-enforcing spectrum-sharing scheme for unlicensed bands using a repeated game model. However, the assumption that systems coexist without a sharing agreement for a sufficiently long period to allow repeated game formulation has limited applicability for contemporary dynamic spectrum sharing demands.

To address these limitations, a game-theoretic model is presented in this chapter, which can provide theoretical QoS and long-term spectrum availability bounds under an

LSA-based spectrum-sharing scheme specifically. A two-layer evolutionary game for dynamic spectrum sharing using LSA, serving the additional capacity needs of MNOs, is presented. As the key contribution, an evolutionary algorithm for demand-driven allocation of spectrum resources to the LSA licensees is proposed. The evolutionary game is extended by incorporating an incumbent's perspective which enables the incumbents to adaptively adjust spectrum price, and proves that the dynamic strategies adopted by the incumbents during the incumbent-layer evolutionary game improve the total gain of the incumbents. The stability of the algorithm is rigorously proved through Lyapunov stability criteria, and convergence of the algorithm to an equilibrium state is proved through simulation results.

5.3 System Model

5.3.1 Conventional Licensed Shared Access Architecture

As briefed in Chapter 2, a typical LSA system comprises an LSA controller, LSA repository and LSA regulator [103, 104]. The LSA controller controls the process of spectrum access by the licensees, according to predefined sharing rules (negotiated between the incumbents and the licensees) and the incumbents' spectrum usage details [50]. The LSA repository maintains a database containing a list of available frequency resource blocks, and is capable of exchanging information with the incumbents (available frequencies, usage details etc.) and the LSA controller [103]. The LSA regulator is responsible for finalising a set of spectrum-sharing rules with the incumbents and the licensees to formulate a spectrum-sharing agreement. These rules remain valid throughout the duration of an LSA sharing agreement, which includes information such as duration of the agreement, required evacuation time for the licensees etc. [103]. For wider and effective adoption of the LSA sharing framework, the sharing framework has to be negotiated between participating systems, i.e., the regulator, the incumbents and the licensees. Moreover, it is emphasised that the advantage of an LSA-based spectrum-sharing framework is that both the incumbents and the licensees can agree on a set of rules and conditions for coexistence and sharing the same spectrum, and both can maintain their QoS requirements [103].

5.3.2 Proposed Architecture for Licensed Shared Access

In order to support the proposed game algorithm, a few modifications are required in the typical LSA architecture. Therefore, a modified LSA model for demand-driven spectrum resource allocation is proposed in this chapter as shown in Figure 5.1. The sharing agreement, including the conditions and policies of spectrum sharing, is negotiated between the incumbents and the licensees under supervision of the regulator. The LSA regulator ensures that the incumbents and the licensees comply with agreed sharing conditions during the sharing process. An incumbent interface of the LSA controller is designed, which enables the incumbents to share the information about available spectrum resources with the LSA repository through the LSA controller. This empowers the LSA controller in such a way that it always has up-to-date information about the available spectrum bands. The LSA repository maintains a database of usage parameters concerning each of the available spectrum bands, such as price and location. Moreover, a licensee interface of the LSA controller is designed which enables the licensees to exchange information with the LSA controller. The exchanged information includes payoff information and details of the request, allocation and configuration of the frequency bands. Overall, the LSA controller controls the spectrum allocation based on the licensee spectrum requests and spectrum availability.

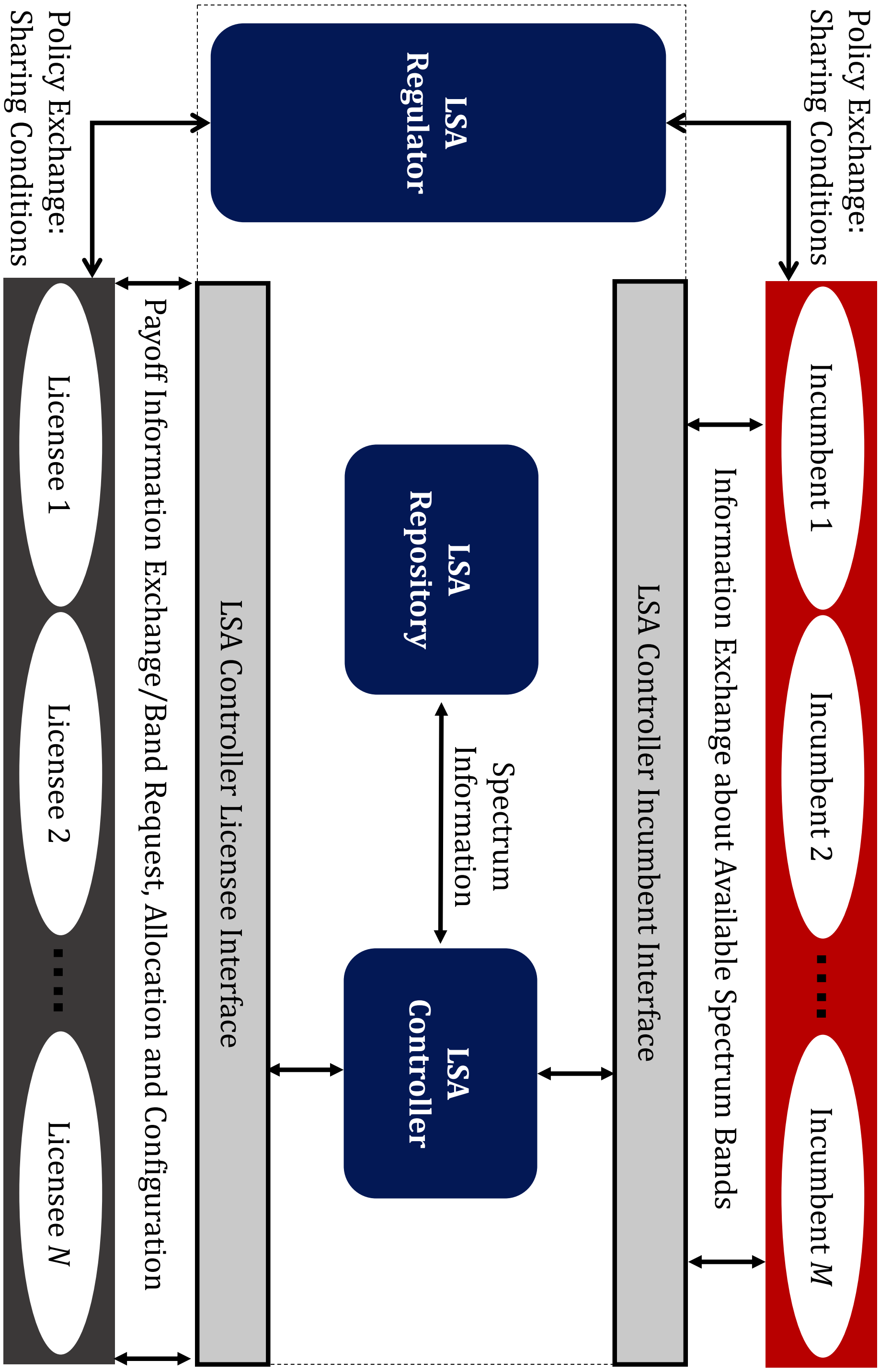

Figure 5.1: LSA architecture and game model.

5.3.3 Evolutionary Game Model

The proposed two-layer evolutionary game for dynamic spectrum sharing is modelled by considering a scenario where multiple incumbents offer spectrum resources as the sellers and multiple licensees act as the spectrum buyers. The LSA controller performs the evolutionary algorithm for the incumbents and the licensees, and at each iteration interested licensees can be granted spectrum resources offered by any of the incumbents. As a possible practical scenario, it is assumed that there are N^a licensees in each group $a \in A$, where A is a set which contains a number of independent licensee groups, hence $|A|$ is the number of independent licensee groups. Each group has a particular LSA agreement with every incumbent. The content of an LSA agreement includes a particular discount percentage for the group given by $d^{(a)}$. The LSA controller decides about the allocation to each licensee selecting spectrum from the LSA repository offered by the i^{th} incumbent, where $i = 1, ..., M$ and M is the total number of incumbents. The LSA controller informs each licensee and each incumbent about the number of licensees belonging to the a^{th} licensee group utilising the spectrum offered by the i^{th}incumbent, given by $n_i^{(a)}$.

5.4 Proposed Algorithm for the Evolutionary Game

The proposed LSA algorithm is a two-layer evolutionary game, where the incumbents offer their spectrum to the licensees, i.e. MNOs through the LSA controller and dynamically adjust the price they charge for their offered spectrum. Based on the spectrum requests received from the licensees, the LSA controller scans the LSA repository for bands on offer and performs an evolutionary game algorithm for allocation of spectrum resources to the licensees. The role of the LSA controller is significant, and it communicates with the incumbents and the licensees through respective interfaces to ensure provision of gains for both incumbents and licensees.

5.4.1 Licensee-Layer Model of the Evolutionary Game

The licensee-layer evolutionary game is modelled from the licensee's perspective assuming that the LSA repository has available spectrum resources offered by the incumbents. In order for the game to be fair, it is ensured that the payoff of each licensee approaches the overall average licensee payoff as the game evolves.

Each licensee calculates its payoff based on the possible spectrum allocation information returned to it by the LSA controller, and decides whether to accept the allocation offer. The net payoff function for a licensee belonging to the a^{th} licensee group being allocated spectrum by the i^{th} incumbent is defined as

$$\pi_i^a = \sigma_a \log(\lambda_a \frac{b_i g_l t_i}{n_i^a}) - \beta_a d^{(a)} p_{i,e} \tag{5.1}$$

where b_i is the bandwidth offered by the i^{th} incumbent. $p_{i,e}$ is the price set by the incumbent where the subscript e indicates the round of the game in which the incumbent adjusts its price. t_i is the time availability coefficient decided by the i^{th} incumbent, enabling the incumbents to re-acquire the licensed spectrum by following the procedure mutually negotiated with the licensees at the time of agreement. g_l is the grant factor calculated by the licensee at the l^{th} iteration, where the subscript l indicates the round of the game in which the licensee calculates its payoff until its individual payoff becomes equal to the overall average licensee payoff. The grant factor is a measure of licensee satisfaction and is defined as the ratio of the offered bands to requested bands, i.e. if the k^{th} licensee requests R_k bands of spectrum and is offered F_k bands, then $g_l = F_k/R_k$. Thus, a higher grant factor means better user satisfaction. The constants σ_a, β_a and λ_a are empirically determined by the licensee.

In the first round of events of the licensee-layer evolutionary game, each licensee estimates the bandwidth it needs at a particular location. It provides the information about the amount of bandwidth needed at a particular location to the LSA controller. The LSA controller takes the decision about bandwidth allocation according to licensee requests and spectrum availability and offers the spectrum at a given price to licensees. Each licensee, in return, calculates its individual payoff based on its grant factor, the bandwidth and price offered. The payoff information is provided to the LSA controller for comparison with the overall average licensee payoff for next-round decisions. The LSA controller randomly picks one licensee having payoff less than the overall average licensee payoff and advises it to switch to a different incumbent to increase the licensee's individual payoff.

Under the proposed LSA-based spectrum-sharing scheme, the process when the licensees switch to a different incumbent can be best represented using the replicator dynamics concept [65]. More specifically, in the proposed model, the LSA controller allocates the available spectrum resources to the participating licensees. The spectrum resources are originally provided by the incumbents, at a given price. The licensees utilising spectrum offered by an incumbent, selling at a cheaper price, can receive a higher payoff and licensees buying from another incumbent, selling at a higher price, obtain lower payoff. The LSA controller ensures that the licensees belonging to the low-payoff category must be able to switch to the other incumbent category to increase their individual payoff. An increase in the number of licensees buying from an incumbent at a cheaper price congests the spectrum and reduces the total bandwidth offered to each licensee buying from that incumbent, eventually decreasing their average payoff. Both categories evolve with time and, after a few iterations, the average payoff for each category converges to the same overall average licensee payoff. Eventually, a stage is reached when all the licensees have their individual payoff equal to the overall average licensee payoff hence the switching process ends and the game converges to the evolutionary equilibrium point.

Thus, the evolution of the licensee-layer game towards equilibrium is represented using replicator dynamics [65, 99], where the individual licensee payoff is compared to the overall average licensee payoff. Thus, we proceed to analyse the change over time in the proportion of licensees using a particular incumbent's spectrum as they switch between incumbents. At a particular time, this proportion is given by $x_i^{(a)}(t) = n_i^{(a)}/N^{(a)}$. Thus, replicator dynamics is defined as

$$\frac{d}{dt}\left(x_i^{(a)}(t)\right) = \omega x_i^{(a)}(t)\left(\pi_i^{(a)} - \overline{\pi}^{(a)}\right) \tag{5.2}$$

where $\overline{\pi}^{(a)} = \sum_{i=1}^{M} x_i^{(a)} \pi_i^{(a)}$ is the average group payoff of the licensees belonging to the a^{th} group and parameter ω determines the speed of change in spectrum selection for each licensee. As the game progresses, a stage is reached when all the licensees have their individual payoff equal to the overall average licensee payoff, hence the switching process ends and the game converges to the evolutionary equilibrium point. Mathematically, the licensee-layer evolutionary equilibrium point can be determined by solving $\dot{x}_i^{(a)} = 0 \forall a, i$ [65].

5.4.2 Incumbent-Layer Model of the Evolutionary Game

To start with, each incumbent sets an initial price for offered spectrum bands, i.e. the i^{th} incumbent sets the price $p_{i,e}$ where the subscript e indicates the round of the incumbent-layer evolutionary game in which the incumbent adjusts its price. Each incumbent also sets parameters such as time availability coefficient etc., which are assumed to remain constant for all rounds of the licensee-layer evolutionary game. After one licensee evolutionary game comprising a finite number of iterations is completed, the LSA controller exchanges information with the incumbents about the number of licensees utilising their spectrum. The incumbents can update spectrum parameters such as price, bandwidth etc. to improve their individual payoff in the following round of the incumbent-layer evolutionary game. Therefore, in order to maximise their payoff, the incumbents independently update their spectrum price as compared to the price set in the previous round. Each incumbent does not have knowledge of the price offered by other incumbents, and it can only analyse the market behaviour by assessing the number of licensees utilising its bands. The payoff function Uc_i for the i^{th} incumbent can be represented as

$$Uc_i = \sigma_c \log(\lambda_c b_i t_i) + \beta_c p_{i,e} d^{(a)} n_i^{(a)} \tag{5.3}$$

where b_i is the bandwidth offered by the i^{th} incumbent and t_i is the time availability coefficient decided by the i^{th} incumbent. The constants σ_c, β_c and λ_c are empirical parameters determined by the incumbent. As the incumbent-layer evolutionary game progresses, an equilibrium stage is reached where all the incumbents receive a similar individual payoff.

The two-layer evolutionary game comprising the licensee-layer and the incumbent-layer is graphically represented in Figure 5.2.

5.5 Stability Analysis of the Equilibrium

Lyapunov functions are commonly used for carrying out the stability analysis of the equilibrium of an ordinary differential equation. To perform the stability analysis of the licensee-layer evolutionary game model, a pool of licensees belonging to a single group, buying spectrum from two incumbents ($M = 2$) through LSA are considered. Furthermore, the stability analysis for the licensee pool denoted by group one ($a = 1$) is carried out by choosing an appropriate Lyapunov function such as $(\pi_1^{(1)} - \overline{\pi}^{(1)})^2$. The proposed Lyapunov function can be re-written as

$$\left(\pi_1^{(1)} - \overline{\pi}^{(1)}\right)^2 = \left(x_2^{(1)}(\pi_1^{(1)} - \pi_2^{(1)})\right)^2. \tag{5.4}$$

It is obvious that (5.4) is positive definite in the neighbourhood of the equilibrium

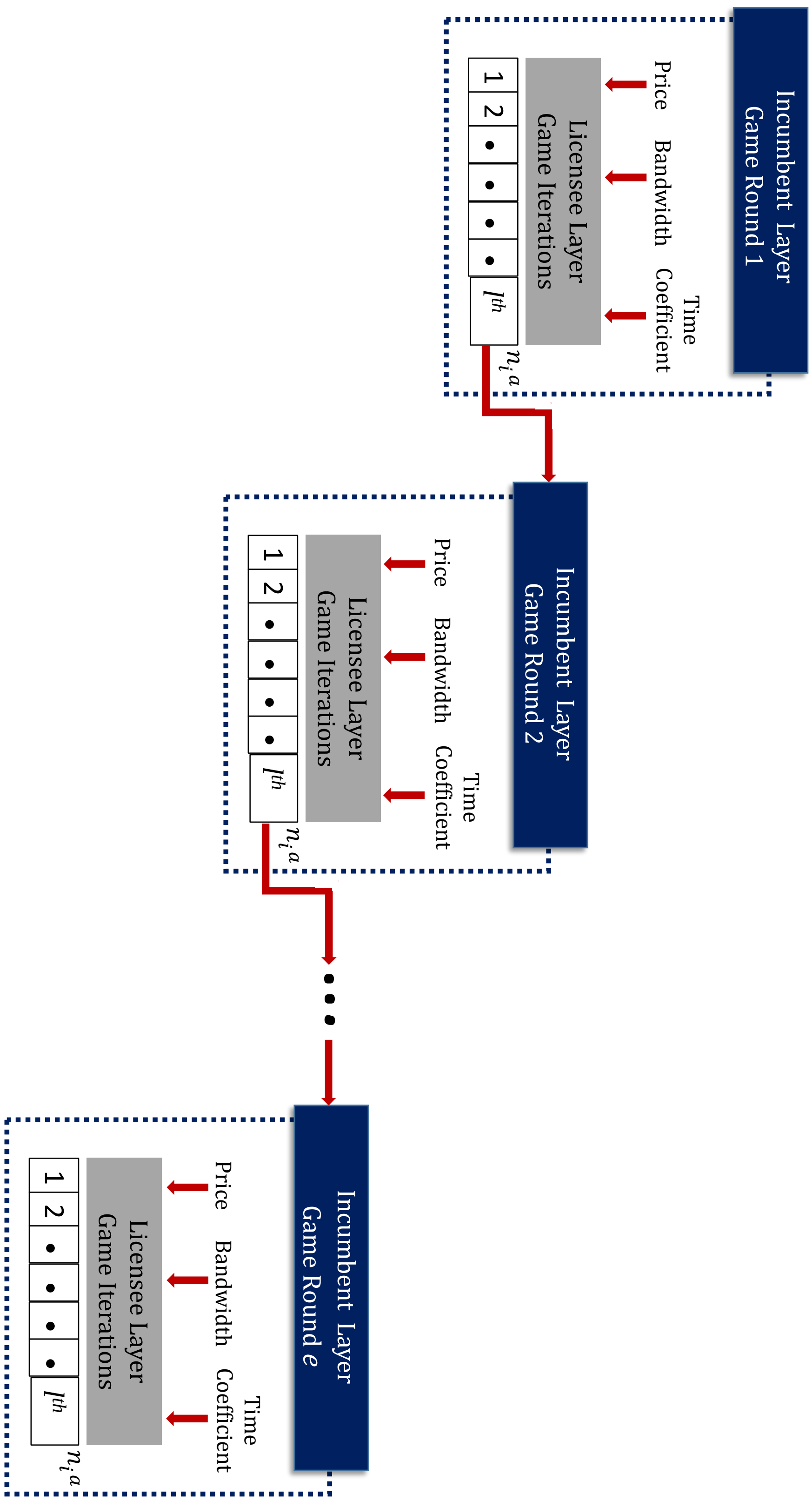

Figure 5.2: Two-layer evolutionary game.

point. Furthermore, to prove the stability of the evolutionary game, the proposed Lyapunov function has to be negative semi-definite in the neighbourhood of the equilibrium region, i.e. the following inequality must be true.

$$\frac{d}{dt}\left(\pi_1^{(1)} - \overline{\pi}^{(1)}\right)^2 = 2 \times \left(x_2^{(1)}(\pi_1^{(1)} - \pi_2^{(1)})\right) \left(\{\frac{d}{dt}x_2^{(1)}\}(\pi_1^{(1)} - \pi_2^{(1)}) + x_2^{(1)}(\frac{d}{dt}\pi_1^{(1)} - \frac{d}{dt}\pi_2^{(1)})\right) \leq 0$$

By closely observing the terms, it can be noticed that the term $2 \times \left(x_2^{(1)}\right)$ is a constant so it becomes irrelevant in the inequality. The term $\{\frac{d}{dt}x_2^{(1)}\}(\pi_1^{(1)} - \pi_2^{(1)})$ is also equal to zero due to the derivative of proportion term, which is zero as the term is constant near the equilibrium time. Thus, the following simplified inequality needs to hold:

$$\left(\pi_1^{(1)} - \pi_2^{(1)}\right)\left(\frac{d}{dt}\pi_1^{(1)} - \frac{d}{dt}\pi_2^{(1)}\right) \leq 0$$

Again, careful analysis of the inequality reveals that there are three possible cases near the equilibrium. At the point of equilibrium, $\pi_1^{(1)} = \pi_2^{(1)}$ so the first term makes the inequality true. In the neighborhood of the equilibrium point, if it is assumed that $\pi_1^{(1)} > \pi_2^{(1)}$ then to approach the equilibrium $\frac{d}{d}\pi_1^{(1)} < \frac{d}{dt}\pi_2^{(1)}$. Similarly, when $\pi_1^{(1)} < \pi_2^{(1)}$ then the equilibrium can only be reached if $\frac{d}{dt}\pi_1^{(1)} > \frac{d}{dt}\pi_2^{(1)}$. Since the terms have opposite signs in both cases, so the inequality holds, and the function is negative semi-definite. Therefore, using Lyapunov stability criteria, it is concluded that the licensee-layer evolutionary equilibrium is stable.

5.6 Simulation Results

In this section, simulation results are presented for an LSA-based dynamic spectrum-sharing model using MATLAB-based computer simulations.

5.6.1 Simulation Setup

As parameter values, the number of incumbents is set as $M = 2$ and the number of licensee groups is set as $|A| = 1$. The number of licensees in this single group is $N^1 = 100$. Initially the percentage of category 1 licensees (licensees utilising spectrum opportunities from incumbent 1) is set equal to the percentage of category 2 licensees (licensees utilising spectrum opportunities from incumbent 2). Unless mentioned otherwise, the initial price per unit spectrum band offered by incumbent 1 is set as less than the initial price offered by incumbent 2, i.e. $p_1 < p_2$. The discount percentage for the single group is given by $d^{(1)} = 2$. The time availability coefficients decided by both incumbents are equal, i.e. $t_1 = t_2 = 1$. The values of the constants are chosen as $\sigma_a = 1$, $\beta_a = 1$, $\lambda_a = 100$, $\sigma_c = 1$, $\beta_c = 1$, $\lambda_c = 100$ and $\omega = 1$.

5.6.2 Performance Evaluation

The price offered by each incumbent is a significant factor in determining each licensee's payoff and hence the average payoff of the incumbent category it belongs to.

Figure 5.3 provides a demonstration of the effect of the price value set by each incumbent on the licensee payoff. Keeping the number of licensees in each category equal initially, it is assumed that incumbent 2 charges a higher price than incumbent 1, i.e. $p_1 < p_2$. The licensees offered spectrum by incumbent 1 receive a higher payoff due to the cheaper price and licensees buying from incumbent 2 at a higher price obtain lower payoff. The LSA controller ensures that the licensees belonging to the low-payoff category must be able to switch to the other incumbent category to increase their individual payoff. An increase in the number of licensees buying from incumbent 1 at a cheaper price congests the spectrum and reduces the total bandwidth offered to each category 1 licensee, eventually decreasing the category 1 average payoff.

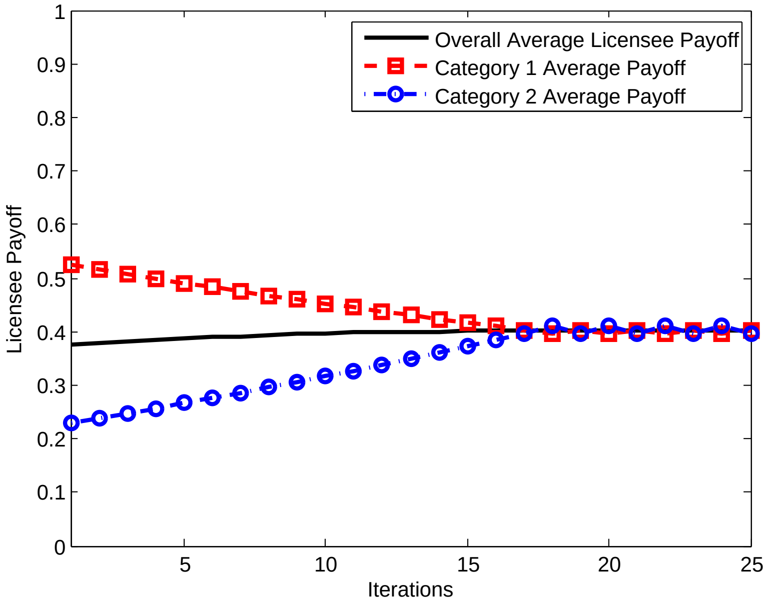

Figure 5.3: Convergence of average payoff of each licensee category to the overall average licensee payoff as the algorithm evolves towards equilibrium ($p_1 < p_2$).

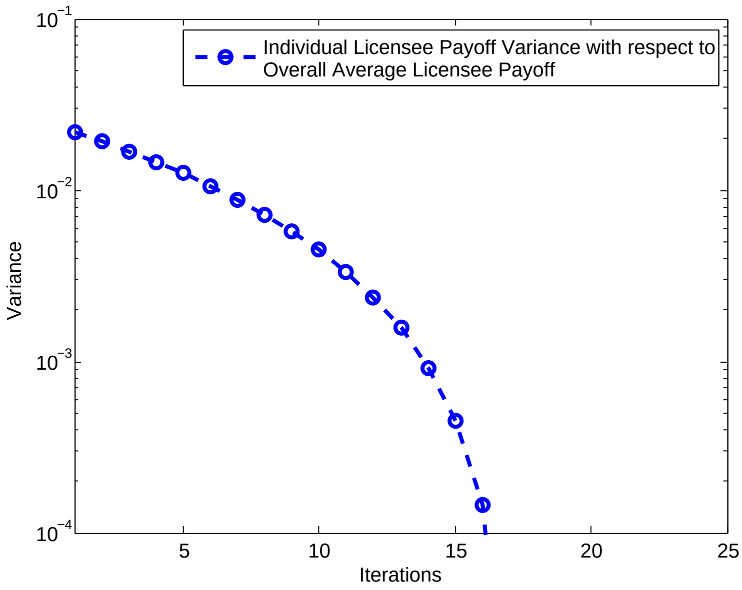

Figure 5.4: Variance of each individual licensee payoff as the algorithm evolves towards equilibrium ($p_1 < p_2$).

Both categories evolve with time and, after a few iterations, the average payoff for each category converges to the overall average licensee payoff and equilibrium is achieved. This behaviour is further demonstrated by showing the variance of individual licensee payoff, for each licensee as the licensee-layer evolutionary game evolves towards equilibrium, in Figure 5.4.

Furthermore, the effect of variation in the total number of licensees utilising the spectrum resources is analysed in Figure 5.5, which shows that an increase in the total number of licensees increases the competition for using the spectrum given a fixed number of available spectrum opportunities. Therefore, the total licensee payoff decreases as a result of this congestion.

Figure 5.6 shows how licensees switch between the incumbents based on the offered price, to increase their individual licensee payoff. Initially, $p_1 << p_2$ so the LSA controller provides the opportunity to some of the licensees buying from incumbent 2 to switch to incumbent 1, as incumbent 1 offers a lower spectrum price. Therefore, at the time of licensee equilibrium, most of the licensees prefer to buy from incumbent 1. As the price offered by incumbent 2 is gradually reduced for succeeding licensee-layer evolutionary games, a gradual increase is observed in the number of licensees preferring to buy from incumbent 2. When the price offered by both incumbents is identical, i.e. when $p_1 = p_2$, the number of licensees buying from each incumbent becomes equal at the time of licensee equilibrium. Further price reduction by incumbent 2 attracts more licensees, and hence the overall percentage of the licensees utilising spectrum resources offered by incumbent 2 increases significantly when $p_1 >> p_2$.

Figure 5.7 demonstrates how the game converges to a different equilibrium point, when the time availability coefficient is varied. More specifically, the figure shows the effect on licensee payoff due to variation in the availability of the spectrum resources. It can be observed that a lower time availability decreases the overall licensee payoff as expected.

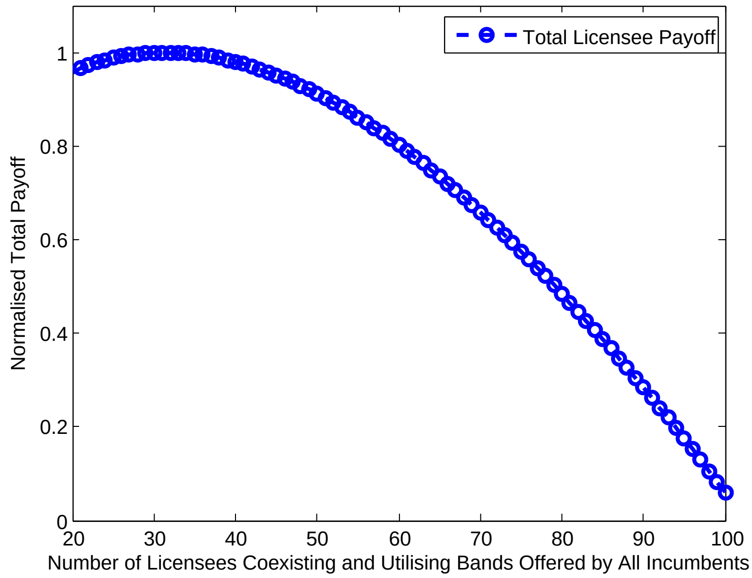

Figure 5.5: Effect on total licensee payoff due to variation in the total number of licensees utilising available spectrum opportunities.

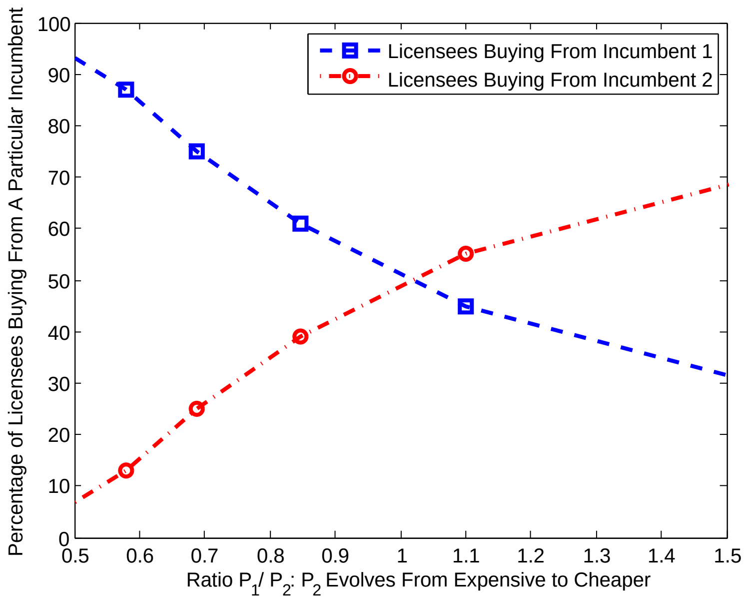

Figure 5.6: Effect of price offered by the incumbents, as the licensees switch between incumbents to achieve licensee evolutionary equilibrium.

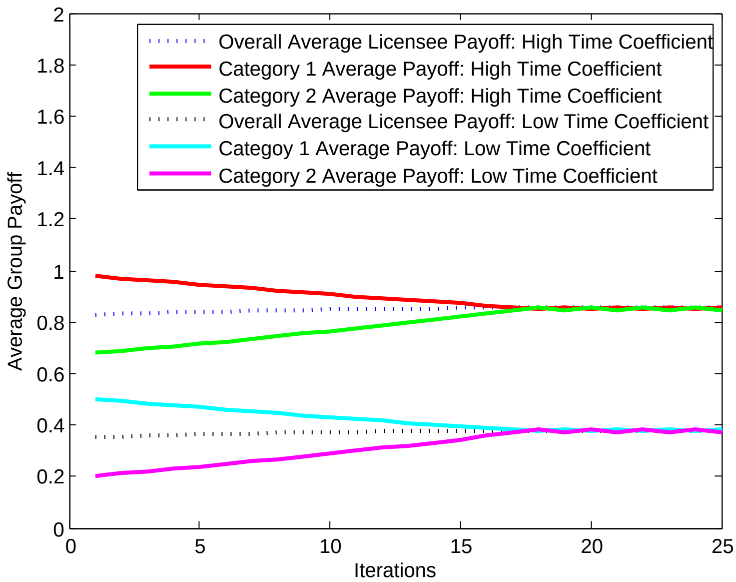

Figure 5.7: Effect on licensee payoff due to variation in the time availability coefficient.

Finally, Figure 5.8 highlights the increased total gain achieved by the incumbents as a result of the incumbent-layer evolutionary game . After one licensee evolutionary game is completed, the incumbents receive information from the LSA controller about the number of licensees using their spectrum, enabling them to calculate their individual payoff. The incumbent charging a higher spectrum price than the other eventually receives lower payoff due to a reduced number of customers. For the next round of the incumbent-layer evolutionary game, each incumbent updates its price to increase its individual payoff. The licensees tend to switch to the incumbent offering lower price, which increases the proportion of licensees buying spectrum from that incumbent, thus increasing the incumbent's payoff. From a perspective of all the incumbents, the total payoff grows with iterations of the incumbent-layer evolutionary game, as shown in Figure 5.8. Moreover, Figure 5.9 demonstrates the convergence of the individual incumbent payoff as the incumbent-layer evolutionary game progresses.

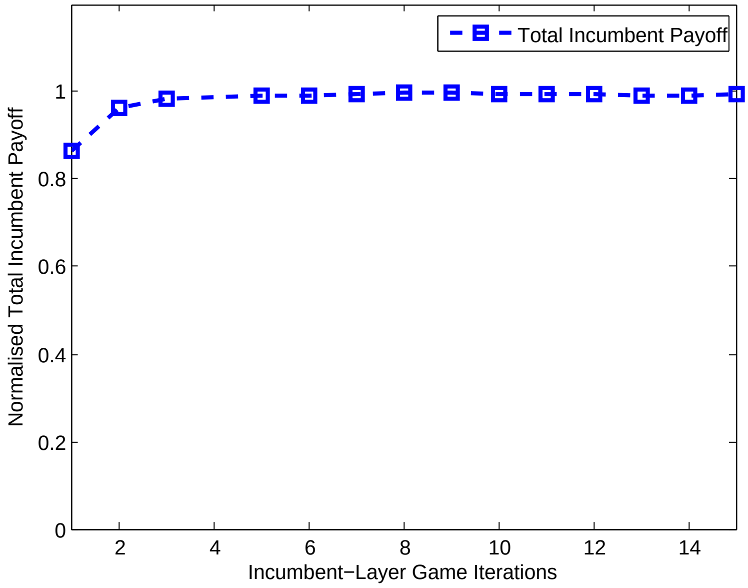

Figure 5.8: Effect on total incumbent payoff as the incumbent-layer evolutionary game progresses.

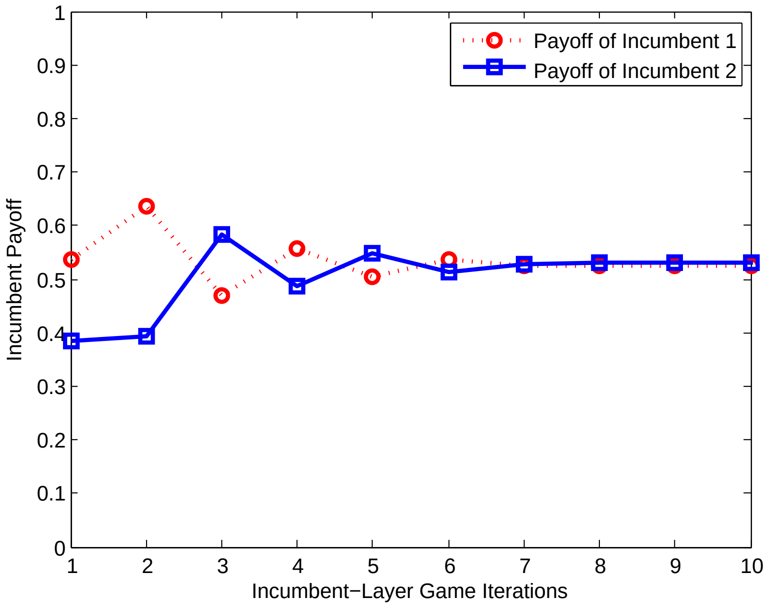

Figure 5.9: Individual incumbent payoff as the incumbent-layer evolutionary game progresses.

5.7 Summary

In this chapter, a two-layer evolutionary game based on LSA for dynamic allocation of spectrum resources, enabling coexistence of incumbents and LSA licensees, was presented. Suitable payoff functions were developed enabling the LSA controller to make fair decisions for spectrum allocation using the proposed evolutionary algorithm. Using Lyapunov stability analysis, the stability of the evolutionary algorithm was proved. Simulation results show that the proposed algorithm is convergent and increases the overall gain for both incumbents and licensees in the LSA-based spectrum-sharing scheme. Moreover, the effects of dynamic parameters offered by the incumbents, such as price, on the overall average licensee payoff were highlighted. The proposed solution ensures that the key challenges of maintaining QoS for both incumbents and LSA licensees and adequately long-term availability of spectrum for the licensees are addressed.

Supporting Publications

- A. Saadat, G. Fang, and W. Ni, "A two-tier evolutionary game theoretic approach to dynamic spectrum sharing through licensed shared access ", *in 15th IEEE International Conference on Computer and Information Technology (CIT-2015)*, pp. 6-11, 26-28 October 2015, Liverpool, UK.

Chapter 6

Cross Border Licensed Shared Access

6.1 Chapter Introduction

In this chapter, a practical scenario for spectrum sharing using Licensed Shared Access (LSA) is considered. Specifically, using game-theoretic principles, a non-coordinated LSA model is presented which enables Mobile Network Operators (MNOs) acting as domestic licensees to provide enhanced Quality of Service (QoS) in border areas. The proposed spectrum-sharing model allows the domestic licensees to rely on their backup strategies while utilising available spectrum resources to avoid severe interference and maintain their QoS, whenever foreign incumbents initiate their operation in a similar frequency spectrum across the border. An LSA-based game-theoretic algorithm is proposed, and the convergence of this game-theoretic algorithm to an equilibrium point after a finite number of iterations is proved, analytically and through simulations.

6.2 Background and Motivation

Throughout this thesis, the importance and usefulness of Licensed Shared Access (LSA) has been highlighted as an efficient means of dynamic spectrum-sharing [24] which, in contrast to cognitive radio, addresses key spectrum-sharing issues such as sensing inaccuracies and uncertainty about long-term spectrum availability. It has been emphasised that an LSA system empowers both incumbents and licensees to maintain a reliable QoS, through spectrum-sharing agreements and suitable communication protocols, thus increasing spectral efficiency [24, 25]. It has been established that an LSA system specifically helps licensees to improve their QoS by providing them with spectrum resources with an agreed availability guarantee.

Among other interesting unresolved LSA problems, a key challenge is to investigate how an LSA system can cope with cross-border interference issues to avoid user experience degradation in border areas. As cross-border interference violates the QoS guarantee for licensees operating in border areas, the challenge of maintaining QoS domestically for the licensees is an interesting research problem.

With regards to the feasibility of LSA in border areas, the work in [105] recommended two basic models to support cross-border LSA: (a) individual LSA systems implemented at each side of the border, and (b) a common LSA system where the spectrum usage information at each side of the border can be maintained and accessed through a common LSA repository. Due to the sensitivity of spectrum utilisation information, the latter possibility may not be a popular choice among regulatory authorities. Therefore, it is more practical to investigate the former model, where the LSA system in each country is independent and does not coordinate with foreign LSA systems while maintaining QoS for its users. The licensees and incumbents under agreement with this independent LSA system are termed as domestic licensees and domestic incumbents respectively. Using the LSA architecture proposed in Chapter 5, an LSA-based QoS guarantee solution is proposed in this chapter which uses *backup strategies* negotiated with domestic licensees in varying interference conditions in border areas. To the best of our knowledge, no current research provides a game-theoretic model to ensure a QoS guarantee for MNOs under LSA in border areas.

In this chapter, a practical scenario for an LSA-based spectrum-sharing problem is considered. A non-coordinated LSA model is presented, which proposes a *backup strategy* based game-theoretic solution for maintaining the QoS of domestic licensees in border areas. Under the backup strategy based approach, domestic licensees agree to compromise on either price or QoS, allowing the LSA system to reallocate available spectrum resources to cope with interference caused by foreign incumbent operations. In other words, backup strategies of the domestic licensees are used to cope with varying interference conditions in border areas, instead of actively trying to prevent interference through traditional interference mitigation schemes. Furthermore, analytical modelling proves the convergence of the game-theoretic algorithm to an equilibrium point. Thus, the proposed solution ensures that domestic licensees are equipped to provide enhanced QoS in border areas by reacting efficiently to the interference caused by foreign incumbent operations.

6.3 System Model

Typically, an LSA system ensures a QoS guarantee for domestic licensees by providing them with spectrum resource blocks (SRBs), with an agreed availability guarantee, for their operations. These SRBs are originally offered by domestic incumbents [103]. However when foreign incumbents across the border begin their operations using the same SRBs, they may cause harmful interference to domestic licensee operations [106], as both parties use the same SRBs simultaneously. Therefore, in this situation, an LSA system needs to ensure that foreign incumbent operations must not severely degrade the

QoS targeted by the domestic licensees in their coverage areas. To address this issue, a Cross-Border Licensed Shared Access (CBLSA) system is proposed which implements a game-theoretic algorithm to ensure a QoS guarantee for domestic licensees through a backup strategy based LSA agreements. These agreements enable domestic licensees to cope with varying interference conditions in border areas. In this regard, a multi-player, tri-strategy game is modelled, where domestic licensees act as players when utilising the SRBs offered by domestic incumbents under supervision of the domestic LSA regulator.

6.3.1 Proposed Architecture for the CBLSA System

In order to develop the proposed CBLSA system, some modifications are required in the existing LSA system architecture. As mentioned earlier, a typical LSA system comprises an LSA controller, an LSA repository and an LSA regulator [103,104]. However, in Chapter 5, an LSA architecture was presented as a game-theoretic model [35]; it is extended in this chapter by including the capability to handle cross-border interference [107].

The proposed CBLSA architecture is shown in Figure 6.1. In this model, it is assumed that the domestic CBLSA system uses spectrum cartography [108], to measure the signal to interference plus noise ratio (SINR) experienced at each of the available SRBs, by positioning suitable sensing nodes within a specified geographical area along the border. Typically, the LSA repository maintains the spectrum availability information, provided by domestic incumbents. The CBLSA controller retrieves the spectrum availability information from the repository and performs spectrum cartography to measure the SINR for each SRB, and stores the SINR information back in the repository. Therefore, the CBLSA repository also contains the SINR information for each SRB. The SRBs are then divided into multiple categories based on sensed SINR information. The domestic licensees come into agreement with the CBLSA system and share their preferred SINR choices along with their backup strategies. Backup strategies are their second-tier

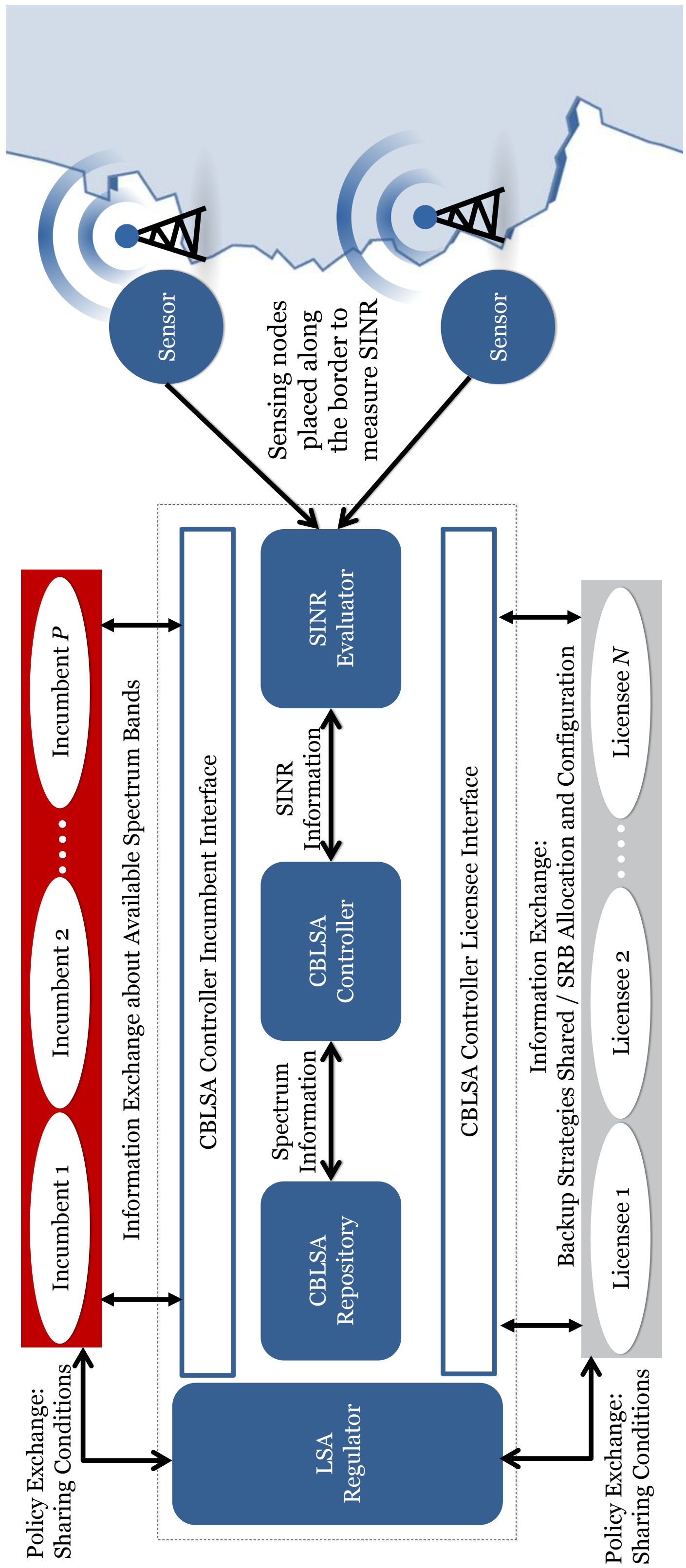

Figure 6.1: Cross-border licensed shared access (CBLSA) system architecture.

preferences which determine whether they want to compromise on price or SINR category when foreign incumbent operations cause notable interference to their operations. The spectrum-sharing agreements are negotiated between domestic incumbents and domestic licensees under supervision of the regulator to ensure that the incumbents and licensees comply with agreed sharing conditions during the sharing process [35, 109].

6.3.2 Proposed Game Model

A scenario is considered where N licensees provide coverage using W^t SRBs, offered by P domestic incumbents, at time t, in a certain geographical area A along a border. It is assumed that the sensing nodes placed within A can measure interference caused by foreign incumbent operations in these W^t SRBs. When foreign incumbents begin operating in the k^{th} SRB ($k = 1, ..., W^t$), an updated SINR value γ_k^t is calculated by the sensing nodes at time t. Although the k^{th} SRB remains available for the domestic licensees, through domestic incumbents, the interference caused by foreign incumbent operations degrades γ_k^t. Hence, the targeted QoS for domestic licensees using the k^{th} SRB is affected. At this stage, an updated SRB categorisation is needed to compensate the licensees who were using the affected SRBs. An SRB reallocation process is thus initiated which either provides the unaffected SRBs at an increased price or provides the affected SRBs at a reduced price to licensees. This spectrum reallocation process is repeated based on the backup strategies already negotiated at the time of the LSA agreements between domestic licensees and incumbents. This way, the CBLSA system has the necessary knowledge about the backup preferences of each domestic licensee, so it can optimally perform spectrum reallocation based on updated SINR information. Thus, the backup strategies provide the CBLSA system with the freedom to perform spectrum allocation on behalf of domestic licensees in varying interference situations. The novelty of the proposed game model is the centralised role of the CBLSA controller and its capability to take optimised spectrum allocation decisions on behalf of domestic licensees.

6.4 Proposed Algorithm for the Spectrum-Sharing Game

In a traditional non-cooperative spectrum-sharing game, each player cares only for its own benefit and tries to maximise its payoff by selecting appropriate strategies [37]. In the proposed spectrum-sharing game model, players share their backup strategies in advance with the CBLSA controller at the time of agreement. The CBLSA controller has the responsibility to calculate their payoff and take a decision on their behalf, based on the provided backup strategies. Thus, the CBLSA controller as a central body accommodates player strategies based on licensee preferences and available interference information.

The proposed non-cooperative game algorithm as a multi-player, tri-strategy game assumes that at time $t < 0$, i.e. before foreign incumbent operations begin, N domestic licensees are using W^t SRBs. This spectrum-sharing is coordinated through the domestic CBLSA controller. The domestic CBLSA repository contains the SINR information for all the available SRBs obtained through sensing nodes, and makes this information readily available for the domestic CBLSA controller.

It is assumed that, for the complete duration of a single game, foreign incumbents continue to operate using certain SRBs and cause uniform interference. Each player's payoff depends on the SINR category it belongs to and the offered price and bandwidth. Therefore, all the SRBs available for domestic licensee operations at this point are termed high-quality SRBs, ensuring a reasonable starting payoff for the licensees. For time $t < 0$, $h^t = W^t$ where h^t is the total number of high-quality SRBs. If γ_k^t for the k^{th} SRB ($k = 1, ..., W^t$) satisfies the inequality $0.75\gamma_{max} < \gamma_k^t \leq \gamma_{max}$; then the k^{th} SRB is categorised as a high-quality SRB. Any SRB not satisfying the given inequality is termed a low-quality

SRB; l^t is the total number of low-quality SRBs at time t. γ_{max} is the targeted (maximum) SINR for all the SRBs and $W^t = h^t + l^t$ holds $\forall t$. At time $t = 0$, foreign incumbents begin operating in θ^t SRBs ($\theta^t \subset W^t$) which decreases h^t and increases l^t. As a result, the payoff for domestic licensees using the same SRBs is severely degraded as will be discussed shortly.

The game starts at time $t > 0$, as the CBLSA controller retrieves the updated SINR information measured for all SRBs and categorises them again into high and low quality categories based on the sensed SINR. As possible actions each player is provided with SRBs from a higher or lower SINR category at an updated price based on its backup strategy, which determines its payoff. In all cases, foreign incumbent operations across the border result in a reduction in h^t SRBs to be offered by the domestic CBLSA, i.e. $h^t < W^t$ for $t \geq 0$.

At this stage, the CBLSA controller notifies all the licensees that one of the strategies maintain (M), reduce (R) or switch (S) needs to be chosen on their behalf. For example, if the backup strategies suggest that strategy M should be selected on behalf of all the players, then this request cannot be granted due to spectrum unavailability, as $h^t < W^t$ holds $\forall t > 0$, hence this represents a deadlock. The overall payoff for all the players is degraded in this case, as the CBLSA controller has no option but to distribute the available SRBs among all players according to the previous sharing ratio, and to increase the cost to discourage this selection. It must be considered that, due to limited availability of high-quality SRBs, a player may not always get its requested SRBs even if its backup strategies suggest strategy M. Table 6.1 shows the possible outcomes for each combination of player strategies in a two-player game. The solution of the game is considered when all players allow the domestic CBLSA to perform optimised spectrum allocation on their behalf based on the updated spectrum availability and associated SINR information as explained in Tables 6.1 and 6.2.

Table 6.1: Non-cooperative Strategy Selection by Licensees and Possible Outcomes

Player 2 / Player 1	**Maintain (M)** Licensee requests to retain the SRBs irrespective of price	**Reduce (R)** Licensee agrees to withdraw a fixed number of SRBs, expecting lower cost	**Switch (S)** Licensee authorises CBLSA controller to take an allocation decision to maximise its payoff in a given situation by adjusting price, bandwidth and SINR category
Maintain (M)	Neither player compromises and reduces SRB request - deadlock. CBLSA reduces SRBs allocated to both players according to previous sharing ratio, and increases spectrum cost to discourage this choice.	P1 maintains its SRBs provided CBLSA has enough SRB availability. P2 agrees to reduce, and suffers a degraded outcome as its payoff is reduced due to SRB reduction.	P1 maintains its SRBs provided CBLSA has enough SRB availability. P2 authorises CBLSA to maximise its payoff as fairly as possible by adjusting price/QoS.
Reduce (R)	P2 maintains its SRBs provided CBLSA has enough SRB availability. P1 agrees to reduce, and suffers a degraded outcome as its payoff is reduced due to SRB reduction.	Both players agree to reduce their SRB request. This combination results in a degraded outcome for both players, as their payoff is reduced due to SRB reduction.	P1 agrees to reduce its SRB request, and suffers a degraded outcome as its payoff is reduced due to SRB reduction. P2 authorises CBLSA to maximise its payoff as fairly as possible by adjusting price/QoS.
Switch (S)	P2 maintains its SRBs provided CBLSA has enough SRB availability. P1 authorises CBLSA to maximise its payoff as fairly as possible by adjusting price/QoS.	P2 agrees to reduce its SRB request, and suffers a degraded outcome as its payoff is reduced due to SRB reduction. P1 authorises CBLSA to maximise its payoff as fairly as possible by adjusting price/QoS.	P1 and P2 authorise CBLSA to reallocate the SRBs based on updated SINR information and maximise their payoff by adjusting price/QoS.

Table 6.2: Best Responses and Convergence to Nash Equilibrium

Player 1 \ Player 2	**Maintain (M)**	**Reduce (R)**	**Switch (S)**
Maintain (M)	M,M	M,R	M,S*
Reduce (R)	R,M	R,R	R,S*
Switch (S)	S*,M	S*,R	S*,S*

6.5 Convergence Analysis of the Proposed Algorithm

Nash equilibrium is an important indicator for the convergence analysis of a non-cooperative game [37]. Nash equilibrium is achieved when every player responds with a best-possible strategy after considering the possible actions of other players. In the context of an LSA-based spectrum-sharing model, a traditional non-cooperative game may not be directly applicable due to the involvement of a central body (LSA system) in the spectrum allocation process. However in the proposed CBLSA system, the domestic licensees provide their backup strategies to the CBLSA system beforehand, which ensures that the game is played within the CBLSA domain by utilising the information about available SRBs, SINR and licensee preferences. The domestic licensees do not cooperate with each other and would always act selfishly, hence the proposed game algorithm can still be analysed as a non-cooperative game and it can be ensured that it converges to an equilibrium point, i.e. the Nash equilibrium. However, the proposed game algorithm converges to a Nash equilibrium if the game can reach a stage when none of the players would expect the CBLSA controller to change the player's strategy unilaterally on its behalf, given that other players have adopted a Nash equilibrium strategy already. The change of strategy for an individual player, at this point, does not improve its payoff further. For the proposed game model, it can be analytically proved and concluded that the action $< S^*, S^* >$, is the best response for all players, as explained in Table 6.2. Generally, the real challenge in dynamic spectrum-sharing games is how to reach an equilibrium if the players do not have access to the strategies adopted by other players [37]. In the presented algorithm, the players can analyse the global information provided to them by the CBLSA controller during each game, to update their backup strategies in future games. Therefore, the players choose arbitrary strategies initially, and then they evaluate their own payoff to eventually learn their best responses, and converge to the Nash equilibrium as the game progresses.

In general, considering a particular outcome as the only possible equilibrium for the game, the equilibrium strategies of all players can be worked out [37]. This is possible by optimisation of the design parameters of the game, i.e. appropriate design of payoff functions for the players, so that a rational strategic plan by players can result in efficient spectrum-sharing as the game evolves towards the equilibrium. However, it must be noted that the uniqueness of an equilibrium is valid only for particular special cases.

6.6 Performance Evaluation

In order to investigate the performance of the proposed model, initially we assume that all incumbents charge equal price for their respective SRBs. This assumption simplifies the game as a competition between N licensees to utilize available SRBs. However, the SINR value associated with each SRB can vary with time. Before the foreign incumbent activity, for $t < 0$, the SINR value associated with the SRBs is higher so the licensees are expected to obtain better payoffs. Once the foreign incumbent activity is initiated, at $t = 0$, a severe degradation is experienced in the SINR values, resulting in degradation of licensee payoff. At this point, the licensees need to select a strategy, which can result in increasing their payoff for $t > 0$.

Figure 6.2 provides a demonstration of this behavior, by highlighting results for a 4x4 licensee game, where 4 licensees pick up one of the three strategies for time $t > 0$. For time $t < 0$, the licensees have a better payoff as the SINR value associated with SRBs is maximum, owing to the absence of foreign incumbent activity. At $t = 0$, the licensee payoff gets severely degraded, as the SINR associated with the SRBs being used by licensees gets affected by the foreign incumbent activity. At $t = 1$, the licensees respond by selecting a strategy. If the licensees choose strategy 1 or strategy 2, it is highly likely that their request (allocation of desired SRBs) will be turned down as the number of high quality SRBs is reduced. If the licensees select strategy 3, there is a higher possibility that the CBLSA controller can compensate the licensees for any loss in high quality bandwidth by adjusting and offering appropriate price for low quality bandwidth. The curves shown are for two cases: firstly when the licensees randomly select one of the three strategies at $t = 1$, and secondly when the licensees pick either strategy 1 or strategy 2 with an equal probability. At this point, the licensee calculate their payoff at $t = 1$ based on their first selection of strategy, and compare with the payoff calculated at $t = 0$. For all game iterations, licensees compare their payoff with the payoff received in the previous iteration and take a decision whether to change their strategy if needed to improve their payoff. Within a few game iterations, all players realize that it is in their best interest to allow CBLSA controller to perform spectrum allocation on their behalf according to their preferences. The licensee payoff increases gradually as soon as they start selecting strategy 3, and by comparing their payoff with the previously earned payoff at each iteration they finally converge to the all-switch solution termed as the Nash equilibrium. At this point, none of the licensees prefers to change its current strategy, as any unilateral deviation in strategy selection now will only reduce its payoff. Figure 6.3 shows similar behavior for a 2x2 game.

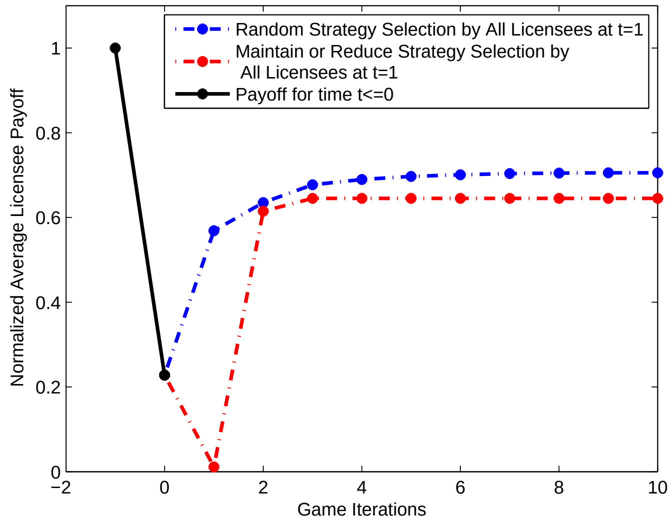

Figure 6.2: Improvement due to random selection of strategy at t=1, when all licensees have the option of selecting one of the three strategies ($N = 4$).

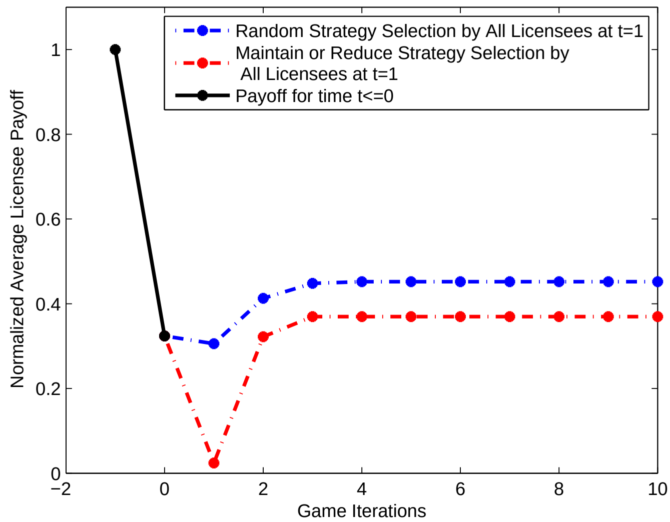

Figure 6.3: Improvement due to random selection of strategy at t=1, when all licensees have the option of selecting one of the three strategies ($N = 2$).

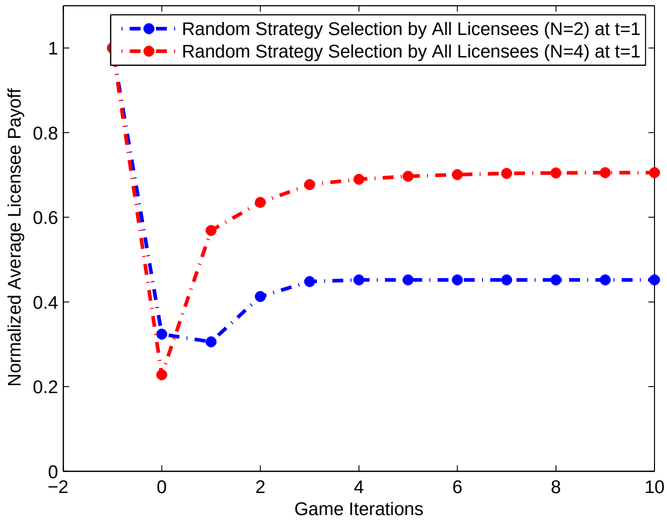

Figure 6.4: Effect of increasing number of licensees competing for spectrum resources by random selection of strategy at t=1.

Moreover, the effect of user congestion on the convergence rate and overall average payoff is investigated. Fig. 6.4 highlights the variation in licensee payoff by comparing 2x2 and 4x4 game. An increase in number of licensees also increases the average licensee payoff. While the 4x4 case experiences a severe dip in payoff at $t = 0$, it undergoes a sharp improvement curve due to higher number of licensees selecting random strategies at $t = 1$. The greater the number of licensees, the lesser the average payoff will be affected by an individual selection going wrong, keeping the available spectrum opportunities constant.

6.7 Summary

Using a non-coordinated CBLSA model, a novel spectrum-sharing mechanism was proposed to enable domestic licensees to provide enhanced QoS in border areas. In the proposed model, the domestic licensees rely on backup strategies, provided to the CBLSA controller, to maintain their QoS by avoiding cross-border interference. This is ensured through the proposed game-theoretic algorithm which converges to a Nash equilibrium state. Future work includes the extension of this non-coordinated CBLSA model, by introducing cross-border coordination between neighboring countries through the respective LSA systems, for maximising overall spectral efficiency and ensuring improved gains for incumbents and licensees across the border. Overall, the proposed solution ensured that the domestic licensees are equipped to provide enhanced QoS in border areas by reacting efficiently to the interference caused by foreign incumbent operations.

Supporting Publications

- A. Saadat, G. Fang, E. Dutkiewicz, M. Mueck and S. Srikanteswara, "Enhanced QoS for domestic licensees in border areas through game theory based licensed shared access", *in 16th International Symposium on Communications and Information Technologies (ISCIT-2016)*, pp. 44-47, 26-28 September 2016, Qingdao, China.

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Chapter 7

Thesis Conclusion and Future Work

In this chapter, a summary of the research findings of this thesis are presented, along with a discussion on future research directions.

7.1 Thesis Conclusion

In this thesis, a comprehensive analysis of a number of dynamic spectrum-sharing scenarios using game-theoretic principles has been presented. As legacy spectrum-allocation approaches often result in under-utilisation of the radio spectrum and cause artificial spectrum scarcity, dynamic spectrum sharing promises to be an effective solution to minimise spectrum scarcity in next-generation mobile networks. In this regard, the main contributions of this thesis are summarised below:

- A non-cooperative power-control game for femtocell base stations was formulated in Chapter 3 where all the nodes, having an equal priority for accessing the spectrum resources, adapted their transmit powers according to the measured interference and traffic conditions. A utility function and a surplus function were developed to represent the achieved throughput and caused interference for each of the femtocells. The existence and uniqueness of the Nash equilibrium of this non-cooperative power-control game were proved. A static price coefficient was designed to adjust the weight of the price of the transmit power, and its role in achieving a unique Nash equilibrium was highlighted. The convergence of the game to a unique Nash equilibrium was proved theoretically and through simulations. A novel dual-mode solution was proposed to ensure that the coordination among the BSs, required to reach an equilibrium point, is minimised. The presented simulation results showed that all BSs participating in the game could get equal priority to access the spectrum using the static price coefficient. However, this arrangement resulted in a limitation on the achieved performance of the primary network users, as it was observed that the primary network users were only able to achieve a constant average throughput (5 Mb/s) in a congested scenario regardless of the target.

- The non-cooperative power-control game formulated in Chapter 3 was extended in Chapter 4, as a game-theoretic spectrum-sharing framework for next-generation mobile networks, where the primary network and the secondary network share spectrum resources under a multi-priority arrangement. The participating base stations, serving either primary network users or secondary network users, dynamically adjusted their transmit powers by measuring the received interference. A dynamic price coefficient was designed to adjust the weight of the price of the transmit power, which ensured that the primary network nodes can get priority over the secondary network nodes. The convergence of the game to a unique Nash equilibrium was verified theoretically and through simulations. An active role of the primary network was highlighted during the non-cooperative game, and it was ensured that the primary network is rewarded for sharing its licensed spectrum with the secondary network, as the scheme enables the primary network users to maintain their desired QoS.

Moreover, a modified dual-mode solution was proposed to ensure that the coordination among the femtocells, required to reach an equilibrium point, is minimised.

- A two-layer evolutionary game based on LSA for dynamic allocation of spectrum resources was presented in Chapter 5, to enable coexistence of incumbents and LSA licensees while sharing the available spectrum. The developed payoff functions enabled the LSA controller to make decisions for spectrum allocation using the proposed evolutionary algorithm. Using Lyapunov stability analysis, the stability of the evolutionary algorithm was proved. Simulation results highlighted that the proposed algorithm is convergent and increases the overall gain for both incumbents and licensees in the LSA-based spectrum-sharing scheme. Moreover, the effects of the dynamic parameters decided by the incumbents, such as price, on the overall average licensee payoff were highlighted. The proposed solution ensured that the key challenges of maintaining the QoS for both incumbents and LSA licensees, and adequately long-term availability of spectrum for the licensees, were addressed.

- In Chapter 6, a non-coordinated LSA model was presented as a novel spectrum-sharing mechanism to empower domestic licensees such that they are enabled to provide an enhanced QoS in border areas. The domestic licensees rely on backup strategies, provided to the CBLSA controller, to maintain their QoS by avoiding cross-border interference. This was ensured through the proposed game-theoretic algorithm which was shown to converge to a Nash equilibrium state. Overall, the proposed solution ensured that the domestic licensees were equipped to provide an enhanced QoS in border areas by reacting efficiently to the interference caused by foreign incumbent operations.

7.2 Future Research Directions

The game-theoretic approaches proposed in this thesis provide a road-map for developing game-theoretic approaches for other spectrum-sharing frameworks, for example Spectrum Access Systems (SAS). The non-cooperative power-control games presented in this thesis can be modified to suit other spectrum-sharing schemes where instead of femtocell-based networks, multi-tier networks can be considered. In a multi-tier network, multiple spectrum access systems such as femtocells, Wi-Fi, LTE devices can coexist and share the available spectrum.

With regards to LSA, the non-coordinated CBLSA model can be extended, by introducing cross border coordination between neighbouring countries through the respective LSA systems, for maximising overall spectral efficiency and ensuring improved gains for incumbents and licensees across the border.

Throughout this thesis, it has been emphasised that dynamic spectrum sharing is the way forward to meet the spectrum demands of next-generation mobile networks. However, practical implementation of dynamic spectrum access for 5G networks is a broad problem that poses challenges at a number of levels. These challenges are beyond the scope of the research presented in this thesis, but nonetheless represent necessary avenues of future research. Broadly, future research on 5G networks must address three main challenges.

- The first of these challenges is the development of modern radio software and hardware, capable of supporting practical implementation of next-generation dynamic spectrum-sharing schemes. For example, development of energy-efficient mobile and wireless devices, hardware with interference-nulling capabilities and design of reconfigurable antennas, filters etc. are all necessary for successful 5G implementation. Moreover, to carry out extensive experimentation and rigorous testing of developed 5G technologies, appropriate simulation tools and test-beds need to be designed.

- The second major challenge is the standardisation of the spectrum-sharing process in terms of defining both quantifiable performance indicators and standardised sharing protocols. The former involves, for example, quantifying receiver performance or setting minimum bounds on harmful interference, while the latter involves developing protocols that will ensure coexistence of spectrum-access devices in a harmonised manner.

- Another significant challenge is to introduce security and privacy features in future spectrum-sharing frameworks to guarantee confidentiality of corporate and personal data. For example, privacy-preserving techniques for necessary information exchange during the negotiation phase of spectrum-sharing schemes need to be developed so that sensitive data are not compromised.

Appendix A

List of Acronyms

A to G

CBLSA	Cross Border Licensed Shared Access
CBRS	Citizens Broadband Radio Service
CEPT	The European Conference of Postal and Telecommunications Administrations
CoMP	Coordinated Multipoint
CRN	Cognitive Radio Network
DSRC	Dedicated Short Range Communications
ECC	ECC
ETSI	ETSI
FC	Femtocell
FNPRM	Further Notice of Proposed Rule Making
FUE	Femtocell User Equipment

H to P

IMT-Advanced	International Mobile Telecommunications Advanced
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
ITU-R	International Telecommunication Union Radio Standards Sector
KPI	Key Performance Indicators
LSA	Licensed Shared Access
MC	Macrocell
MFCN	Mobile/Fixed Communications Networks
MNO	Mobile Network Operator
MUE	Macrocell User Equipment
NPRM	Notice of Proposed Rule Making
OSI	Open Systems Interconnection

Q to Z

QoS	Quality of Service
RF	Radio Frequency
RSPG	Radio Spectrum Policy Group
SAS	Spectrum Access System
SRB	Spectrum Resource Block
U-NII	Unlicensed National Information Infrastructure

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