UNIVERSITI PUTRA MALAYSIA

DISTRIBUTED JOINT POWER CONTROL, BEAMFORMING AND SPECTRUM LEASING FOR COGNITIVE TWO-WAY RELAY NETWORKS

HAVZHIN IRANPANAH

FK 2017 132

DISTRIBUTED JOINT POWER CONTROL, BEAMFORMING AND SPECTRUM LEASING FOR COGNITIVE TWO-WAY RELAY NETWORKS

By

HAVZHIN IRANPANAH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

June 2017

To my parents, Maryam and Soleiman

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

DISTRIBUTED JOINT POWER CONTROL, BEAMFORMING AND SPECTRUM LEASING FOR COGNITIVE TWO-WAY RELAY NETWORKS

By

HAVZHIN IRANPANAH

June 2017

Chairman : **Professor Borhanuddin bin Mohd Ali, PhD**
Faculty : **Engineering**

Cognitive Radio (CR), as a promising technological solution to the spectrum underutilization problem, is becoming increasingly important as demand for various wireless applications and services rises. Protection of primary users from inflicted interference induced by the secondary users and, in the meantime, improvement of the network utility of the secondary users, thus remains the difficult challenge in underlay CR network.

In the first part of the thesis, distributed power control and beamforming algorithm is proposed in which users operating in the underlay mode can strategically adapt their power levels and maximize their own utilities. This is subject to the primary user (PU) interference constraint as well as its own resource and target signal-to-interference-and-noise-ratio (SINR) constraints. The strategic competition among multiple decision makers is modeled as a noncooperative game where each secondary user (SU) acts selfishly to maximize its own utility. An adaptive method is proposed to determine appropriate pricing function. The problem of beamforming optimization under amplify-and-forward (AF) protocol is addressed as a generalized eigenvalue problem with respect to the utility function of SUs. The existence of a unique Nash equilibrium (NE) was proved and several numerical simulations were conducted to quantify the effect of various system parameters on the performance of the proposed method.

In the second part of the thesis, maximization of the total revenue is formulated as an optimization problem that finds the optimal price and congestion threshold in the congestion-based pricing scheme. A search method with numerous advantages over conventional algorithms, has been designed to solve the optimization problems with an enhanced global optimality and convergence speed. Once the number of iterations conditioning along each dimension corresponds with the length of price interval, the convergence of algorithm is achieved. A key factor in the accuracy of Dynamic Response Pricing (DRP), the length of the demand response window, as observed in

numerical results, indicates that the convergence of DRP to optimal threshold pricing is completed with a 98 percent accuracy in a 15 time-unit demand response.

Finally, ADRP was introduced as an adaptive model of DRP, with numerical simulations of ADRP available for realistic call records data set. Simulation results show that optimal current channel occupancy and price is well tracked by ADRP. In order to know how much revenue may be lost because of the time-varying demand patterns, the first scenario was examined and the results show that 2734 monetary units per day for weekday were gained by the optimal threshold pricing, while this number for ADRP is 2652. In the second scenario, these values are 6595 and 6322 for optimal threshold pricing and ADRP, respectively. Comparing these results with optimal threshold pricing shows that ADRP loses just 3 percent and 4 percent of total revenue in first and second scenario, respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

GABUNGAN KAWALAN KUASA, BEAMFORMING TERAGIH DAN PAJAKAN SPEKTRUM UNTUK RANGKAIAN GEGANTI DUA-HALA KOGNITIF

Oleh

HAVZHIN IRANPANAH

Jun 2017

Pengerusi : **Professor Borhanuddin bin Mohd Ali, PhD**
Fakulti : **Kejuruteraan**

Radio kognitif (RK), sebagai satu penyelesaian teknologi yang baik kepada masalah spektrum tidak digunakan dengan sepenuhnya, menjadi semakin penting memandangkan permintaan bagi pelbagai aplikasi dan perkhidmatan wayarles semakin meningkat. Sementara melindungi pengguna-pengguna utama dari interferens yang dicetuskan oleh pengguna-pengguna sekunder, peningkatan utiliti rangkaian pengguna-pengguna sekunder juga perlu diambil kira, maka ia tetap kekal sebagai cabaran yang sukar di rangkaian RK.

Penyelidikan ini terdiri daripada dua bahagian. Pertama sekali, satu jaringan penyampaian dua-hala kognitif di mana berbilang pasang pengguna sekunder (SUs) bertukar maklumat atas bantuan geganti berbilang telah dikaji. Seterusnya, satu algoritma penentuan harga baru yang berdasarkan waktu nyata telah diperkenalkan untuk pajakan spektrum yang dinamik dengan menggunakan ”Adaptive Demand Response Pricing” (ADRP). Satu kawalan kuasa teragih dan algoritma beamforming yang membolehkan para pengguna beroperasi dalam mod lapik bawah juga telah dicadangkan supaya para pengguna dapat menyesuaikan aras kuasa mereka secara strategik, di samping memaksimumkan utiliti mereka yang tertakluk kepada kekangan gangguan dari pengguna utama (PU), kekangan dari sumber sendiri, dan kekangan ”signal-to-interference-and-noise-ratio” (SINR) dari sasarannya.

Pertandingan strategik di kalangan berbilang pembuat keputusan dimodelkan sebagai berbilang adakah dicontohi sebagai satu permainan tak berkooperasi di mana setiap pengguna sekunder (SU) bertindak secara kendiri untuk memaksimumkan utilitinya. Satu kaedah adaptif telah dicadangkan untuk menentukan fungsi penentuan harga yang sesuai. Masalah pengoptimuman beamforming di bawah protokol amplify-and-forward (AF) dikenali sebagai satu masalah generalizedeigenvalue yang berkenaan dengan fungsi utiliti SUs. Kewujudan satu keseimbangan Nash (NE) yang unik dibuktikan dan beberapa simulasi angka dijalankan untuk mengukur kesan pelbagai parameter sistem terhadap prestasi kaedah yang dicadangkan. Dalam bahagian

kedua, pemaksimuman jumlah pendapatan telah dirumuskan sebagai satu masalah pengoptimuman yang bertujuan untuk mencari harga optimum dan ambang dalam skim penentuan harga yang berasaskan ambang.

Satu kaedah carian, yang mendatangkan pelbagai kebaikan berbanding denagn algoritma konvensional, direka secara khususnya bagi tujuan menyelesaikan masalah pengoptimuman dengan keoptimuman global yang ditingkatkan dan kelajuan penumpuan. Sebaik sahaja jumlah lelaran yang dikondisikan di sepanjang setiap dimensi adalah sepadan dengan panjang selang, maka algoritma penumpuan berjaya dibuktikan. Satu faktor utama dalam menentukan ketepatan ”Demand Response Pricing” (DRP), iaitu panjang tetingkap ”demand response” yang diperhatikan dalam keputusan berangka, menunjukkan bahawa penumpuan DRP kepada penentuan harga ambang optimum disiapkan dengan ketepatan 98 peratus apabila tetingkap ”demand response” ialah 15 unit masa (di mana 1 unit masa adalah sepadan dengan tempoh panggilan selepas 5 lelaran). Akhir sekali, ADRP telah diperkenalkan sebagai satu model adaptif DRP, dengan simulasi angka ADRP yang boleh digunakan untuk set data rakaman panggilan realistik. Keputusan simulasi menunjukkan bahawa ambang dan harga semasa yang optimum hampir diikuti oleh ADRP.

Bagi mendapatkan satu idea umum tentang jumlah pendapatan yang mungkin rugi atas permintaan SU yang berubah-ubang dan tidak dapat dikenalpasti, senario pertama telah diperiksa di mana 2734 unit kewangan telah diperolehi setiap hari dari Isnin hingga Jumaat dengan penentuan harga ambang optimum, manakala ADRP pula menunjukkan nilai 2652. Dalam senario kedua, nilai-nilai ini adalah 6595 dan 6322 untuk penentuan harga ambang optimum dan ADRP masing-masing. Perbandingan antara keputusan ini dengan penentuan harga ambang optimum menunujukkan bahawa ADRP hanya rugi 3 peratus dan 4 peratus dari jumlah pendapatan dalam senario pertama dan kedua masing-masing.

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude and respect to my supervisor, Prof. Dr. Borhanuddin bin Mohd Ali, for his continuous support, invaluable comments and guidance throughout my studies at Universiti Putra Malaysia. It is a great honor to work under his supervision.

I would also like to thank the rest of my thesis committee: Dr. Fazirulhisyam Hashim, Dr. Hafizal Mohamad, for their insightful comments and suggestions.

Last but not least, I am grateful to my parents and my brothers for their love and sacrifice. Please accept my deepest bow.

I certify that a Thesis Examination Committee has met on 20 June 2017 to conduct the final examination of Havzhin Iranpanah on his thesis entitled "Distributed Joint Power Control, Beamforming and Spectrum Leasing for Cognitive Two-Way Relay Networks" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

Mohd Fadlee bin A Rasid, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Aduwati binti Sali, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohamad Yusoff bin Alias, PhD
Professor
Multimedia University
Malaysia
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 30 November 2017

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science.

The members of the Supervisory Committee were as follows:

Borhanuddin bin Mohd Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairperson)

Fazirulhisyam Hashim, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Hafizal Mohamad, PhD
Wireless Network and Protocol
Malaysian Institute of Microelectronic Systems Berhad
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ____________________ Date: ____________________

Name and Matric No: Havzhin Iranpanah, GS33355

Declaration by Members of Supervisory Committee

This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________________
Name of Chairman of Supervisory Committee
Professor Borhanuddin bin Mohd Ali

Signature: ______________________________
Name of Member of Supervisory Committee
Dr. Fazirulhisyam Hashim

Signature: ______________________________
Name of Member of Supervisory Committee
Dr. Hafizal Mohamad

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADRP	Adaptive Demand Response Pricing
AF	Amplify and Forward
ANC	Analog Network Coding
AWGN	Additive White Gaussian Noise
BC	Broadcasting Phase
BNC	Binary Network Coding
BR	Best Response
CDMA	Code Division Multiple Access
CF	Compress and Forward
CR	Cognitive Radio
CRN	Cognitive Radio Network
CSI	Channel State Information
DF	Decode and Forward
DRP	Demand Response Pricing
DSA	Dynamic Spectrum Access
DSL	Dynamic Spectrum Leasing
FCC	Federal Communications Commission
KKT	Karush-Kuhn-Tucker
MABC	Multiple Access Broadcasting
MAC	Media Access Control
MAC	Multiple Access Phase
MIMO	Multiple Input Multiple Output
NE	Nash Equilibrium
NEP	Nash Equilibrium Point
NP	non-deterministic polynomial-time
NUM	Network Utility Maximization
OFDM	Orthogonal Frequency Division Multiplexing
OSA	Opportunistic Spectrum Access
PU	Primary User
QoS	Quality of Service
SDP	Semi-Definite Programming
SINR	Signal to Interference and Noise Ratio
SNR	Signal-to-noise Ratio
SU	Secondary User
TDBC	Time Division Broadcasting
UWB	Ultra Wide-Band
VI	Variational Inequality
ZFB	Zero-Forcing Beamforming

CHAPTER 1

INTRODUCTION

1.1 Preface

Over the last two decades, due to the wide use of wireless technology in various areas of human life and due to the growing need for services and data rates, accessing wireless spectrum [4] is faced with the problem of scarcity on the one hand and underutilization on the other extreme. The reports by FCC indicate that licensed frequency band especially cellular spectrum and TV spectrum have not been exploited adequately in time and space [1]. The measurement in [5] particularly emphasizes that for $15-85\%$ of the cases based on spatial location, the licensed spectrum is underutilized. Identical trends have been offered by industrial and academic organizations in their measurement studies. As can be seen in Fig (1.1), one part of the spectrum carries considerable amount of traffic while the other part is virtually unutilized. The term used to refer to the unutilized part of spectrum is white space and it can be defined in terms of time, frequency, and maximum transmission power at a particular location [6]. On the other hand, by introducing new data services which require higher bit rate and consequently higher bandwidth, the inadequacy of the required bandwidth turns out to be a serious problem. For instance, in the 2.4 GHz unlicensed band which carries the traffic of IEEE 802.11 b/g/n protocol, on one hand we are faced with high traffic and on the other, with high demand of multimedia services like video requiring very wide band and high service quality. In order to solve this problem Cognitive Radio has been proposed to improve the efficiency of the spectrum. In fact, the static spectrum allocation is transformed into dynamic spectrum allocation by the cognitive radio and cognitive based networking. It was suggested that Cognitive radio be built on a radio software, introduced by Mitola in 1999, in such a way that efficient spectrum utilization can be caused by providing an opportunity by different approaches of spectrum sharing for the secondary net-

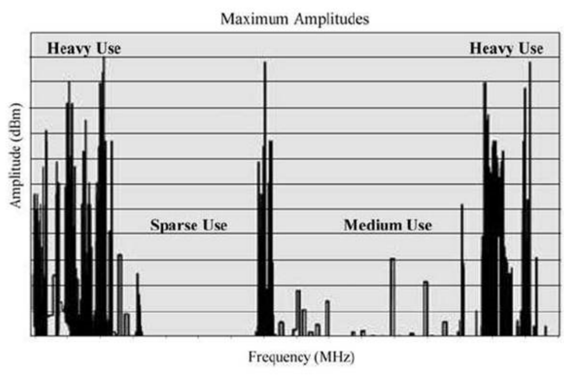

Figure 1.1: Spectrum Underutilization [1].

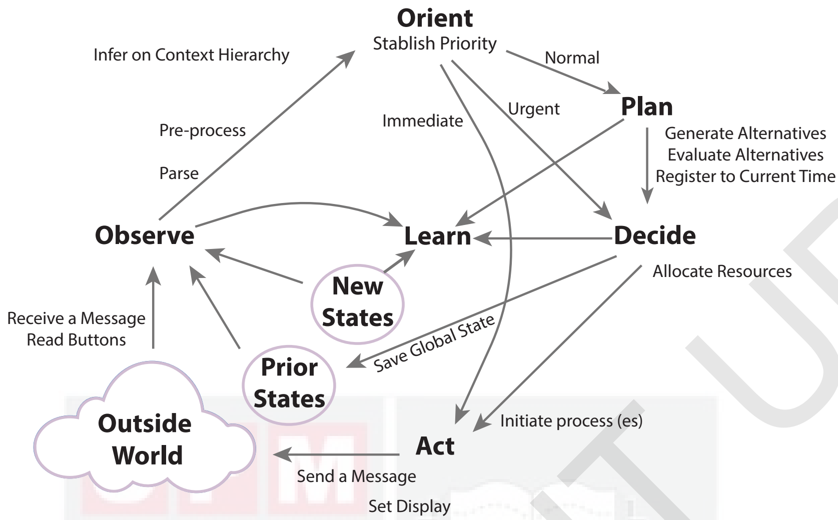

Figure 1.2: Cognitive Radio Structure [2].

work to use the spectrum [7, 8]. In order to approximate the accessible resources and application requirements, cognitive user ought to have the ability to sense the environment and by doing so adopt the required performance parameters regarding user request and available resources [9].

1.2 Cognitive Radio Structure

In further explaining the concept of cognitive radio, one can mention that these networks are capable of making decisions. That is, based on the information obtained from spectrum and traffic as well as licensed and unlicensed user actions, they can adjust parameters like power and frequency, etc (Figure 1.2). In addition, cognitive radio has the ability of learning, which means that, according to previous information, such as the state of channel or parameters transmitted by users, it can obtain the kind of pattern from network conditions.

Finally, since the cognitive radio network operates along with traditional telecommunication networks, they should be compatible with different protocols in order to perform various modulations and signaling throughout different networks. In order to achieve networks with such features, it is essential to focus more on the software than hardware section of the radio [10]. Accordingly, the unlicensed users are able to send at a time when the licensed users are unable to transmit. From then on, licensed and unlicensed users are referred to as primary and secondary users, respectively.

There are generally two different aspects that are considered for the use of spectrum by secondary users along with primary users in cognitive radio networks. Firstly,

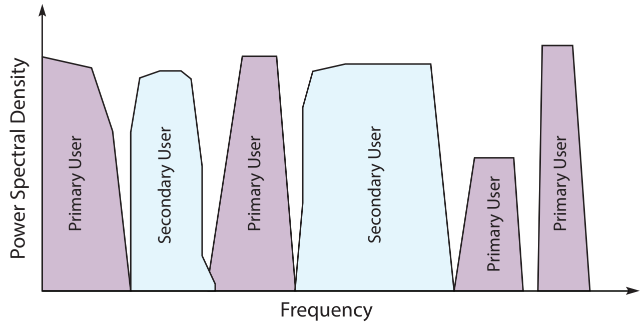

Figure 1.3: Overlay Transmission in Cognitive Radio Networks [3].

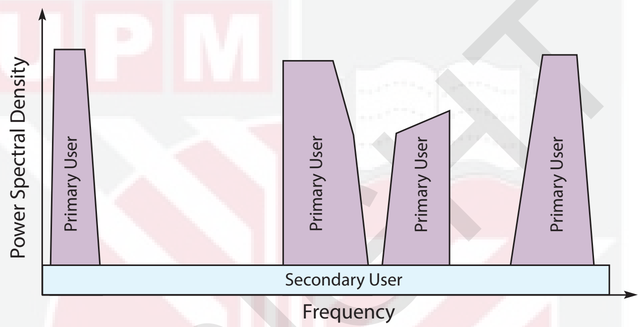

Figure 1.4: Underlay Transmission in Cognitive Radio Networks [3].

secondary users are allowed to use telecommunication resources, either time or frequency, even in MIMO systems, only at a time when they sense, through signal processing methods, that the primary users are inactive. The frequencies in which the primary users are inactive are called spectrum holes and this method is known as overlay transmitting (Figure 1.3). In other cases which are less addressed, secondary users send information simultaneously with the primary users subject to the condition that secondary users should fully comply with the QoS of primary users. Usually in this case, this given QoS is considered to be an interference threshold that is calculated based on minimum required bit rate and outage probability of the bit rate [4, 11]. This method is known as underlay transmitting (see Figure 1.4). In underlay transmission techniques of CDMA and OFDM as well as beamforming in multiple antenna systems, interference on primary users is controlled. This will be described in detail in the following chapters.

1.3 Resource Allocation and Quality of Service Provisioning

Resource allocation algorithms can be divided into central and distributed categories. In central algorithms, there exists a central station which based on general information of the entire network, calculates the transmitting parameters such as power or frequency and sends the feedbacks to the users [12]. In addition, there are algorithms that are based on large-scale collaboration among users. These algorithms, as discussed in [13], usually solve the problem of network utility maximization. The solution requires to transfer large amounts of control messages between users. This is undesirable because large amounts of control messages are transmitted as control messages should be transferred within a network that is designed based on spectrum shortage. In addition, due to its non-convex feature, solving network utility maximization incurs high computational complexity. Based on the evidence presented, central approaches are not advisable to design resource allocation algorithms in cognitive radio networks, and this is the motivation for the movement toward distributed algorithms, since a high participation in the centralized algorithms leads to high signaling cost and bandwidth consumption. However, in decentralized algorithm, a selfish behavior may be seen that is based only on user information or at least local information. As a result, there is a need to control selfish behavior, this can be accomplished via different methods of controlling distributed resources. On the other hand, in designing networks based on distributed algorithms, optimality of resource allocation should be addressed in terms of distribution of the algorithm in order to establish appropriate balance between these two criteria.

1.3.1 Pricing in Power Control and Dynamic Spectrum Leasing

This thesis mainly focuses on the study of two components of radio resource management which are power control and dynamic spectrum leasing. The problem of power control and beamforming will be discussed in chapter 3 and dynamic spectrum leasing problem will be discussed in chapter 4.

'Pricing' is the underlying concept that interweaves chapters 3 and 4 together. In chapter 3, the pricing concept is used to monetize the transmission power as well as a penalized factor in order to optimally distribute the transmission power among SUs. This means that the interference that SU inflicts on PU will determine how much the proposed pricing scheme charges each user and the pricing function coefficient is determined based on overall welfare of the network. The pricing scheme here can serve different purposes like obtaining various tradeoffs between fairness, stability, degrading the performance of primary network and efficiency in a multi-user two-way relay network.

In chapter 4, the pricing concept is used to monetize the spectrum cost by spectrum provider to two types of customers i.e. SUs and PUs. The service provider's revenue and the SUs' tendency to lease the spectrum are two factors under the direct influence of this parameter. To specify spectrum price, an occupancy-based policy is applied on SUs to determine their access to the shared spectrum. SUs will be either rejected or accepted by these policies depending on the profitability of the revenue function and the total number of active calls in the system upon arrival.

1.4 Problem Statement and Motivation

As discussed previously in Section 1.3, the desired resource allocation algorithm in CRN must:

1. consider the uncertainty in measurement of different network parameters.
2. be distributed and have an appropriate convergence speed.
3. gives priority to primary users in every circumstance.
4. allows for cognitive capabilities of secondary users.
5. maintains the QoS of secondary users as much as possible.

Challenge 1: The distributed optimization problem is not often categorized as a convex optimization problem; therefore, determining the optimized solution requires complex calculations [14, 15, 16, 17, 18].

Challenge 2: A closed form solution is not normally available for the optimization solution in such problems.

A distributive resource allocation algorithm in CRN networks that uses the decomposition technique are faced with the following difficulties respectively:

1.1) If the optimization problem is not convex, the distributed algorithms based on binary method will not converge into global optimum [19].

1.2) If the optimization problem is not convex, the existence of Nash equilibrium in the game is not mathematically provable [20].

2.1) If the solution of optimization problem for each user is not available in closed form, we cannot use conventional methods to analyse the uniqueness of the Nash equilibrium.

2.2) If the variables of the problem are co-dependent on each other, it is not easily possible to propose a distributive algorithm to reach to of Nash equilibrium point, which requires signaling between network users.

Three main challenges need to be addressed for dynamic spectrum leasing in Chapter 4:

1. A provider has to guarantee that the QoS requirement of each PU will be fully satisfied and does not significantly degrade their system performance, because SUs activity may lead to punishment by the aggrieved primary network in the

face of monetary loss due to blocking of new calls seeking admission. On the other hand, increased call admission control on SUs reduces the revenue obtained from spectrum leasing. Most literature consider the demand of primary and secondary users to be responsive to price. In other words, all arrival rates are elastic to pricing schemes. However, this study considers only the demand of the secondary network to be elastic to pricing strategies; therefore, the arrival rate of PUs is not elastic.

2. Most of the related literature assume that the call duration distribution is exponential. A recent study [21], however, expounds Pareto distribution, and concludes that the assumption of exponential call duration distribution does not hold in practice. The importance of call duration distribution is its unpredictability, necessitating a successful spectrum pricing policy that is valid for a wide range of network settings and robust to their innate uncertainties.

3. Another presumption of the related literature is that the user demand is known. A precise knowledge of the ever-changing arrival rates is, however, impractical to obtain. Uncertainty in SUs demand function is challenging to manage because the function that aims to maximize average revenue depends on unidentified demand function.

1.5 Research Aim and Objectives

The aim of this thesis is to propose a game theoretic model of radio resource management in cognitive two-way relay networks that optimize the Network Utility Maximization and enhance the QoS of SUs. This thesis brings together two component of radio resource management which are power control and dynamic spectrum leasing to construct a framework that can be used to monetize the transmission power and the spectrum price. Thus, this thesis seeks to accomplish the following objectives:

1. To design a joint power control and beamforming algorithm in cognitive two-way multi-user multi-relay networks by taking SUs' cognitive abilities and uncertainties of different network parameters into account in a way that the control game is convergent to a unique Nash equilibrium point with Pareto improvement in Network Utility Maximization. The incorporated beamforming must be obliged to enhance the quality of service of SUs while constantly maintaining the priority of primary users with low computational complexity.

2. To design congestion-based spectrum pricing algorithms that aim to monetize the spectrum price through maximizing the average revenue of the spectrum provider with unidentified demand function; prompt converging to the optimal solution by exploiting the unimodal probability distribution characteristic of the threshold pricing schemes. This will include a specifically-designed algorithm for cases where the demand response pattern of secondary networks

and the arrival rate of primary networks change throughout the day, which will create a robust, adaptive spectrum pricing scheme.

1.6 Research Contributions

The main contributions of Chapter 3 work are as follows:

1. The problem of power control for cognitive two-way multi-user multi-relay networks that are modeled as a noncooperative game is addressed and the Nash equilibrium point (NEP) with respect to the Network Utility Maximization (NUM) is achieved. This includes a novel distributed pricing scheme without imposition of additional signaling on the system which enforces each selfish SU to make an efficient decision. By doing so, SUs increase their utility function in order to increase NUM in a global sense as well as increasing the convergence speed.

2. A distributed beamforming algorithm under amplify-and-forward protocol using generalized eigenvalue solution that improves the QoS of SUs in terms of SINR, meanwhile satisfying the interference constraint of PUs.

3. The spectrum leasing price, profitability and channel availability are modeled as a congestion based pricing strategy; and a Dynamic Response Pricing (DRP) algorithm is proposed in which it does not require any knowledge of the demand function or any parameter of the demand curve and build its output decision on the basis of the demand response measurements. In order to derive a practical pricing policy, the DRP algorithm is extended to ADRP by combining sequential demand response measurements and myopic price optimization. Such an optimization would award spectrum providers with maximum average revenue, thus providing guidance to determine whether admission of a new SU in a particular channel availability threshold level can be profitable. ADRP is a low computational complexity real-time algorithm which is suitable for online implementation and will get arbitrary close to the optimal solution in case of time dependent arrival rate and demand function. The proposed algorithms make the concord of elastic and non-elastic networks possible while still remaining invariant to call duration distribution and only rely on the continues optimization of the defined objective function with two factors of threshold and price.

1.7 Thesis Outline

The remainder of the thesis is structured as follows. The literature review is surveyed in Chapter 2. The distributed power control and beamforming algorithm in cognitive two-way relay networks is proposed in Chapter 3. Then, the existence of a unique Nash equilibrium is proved and several numerical simulations are conducted to quantify the effect of various system parameters on the performance of the proposed methods. In Chapter 4, the DRP algorithm is proposed to address the problem of dynamic spectrum leasing with unidentified demand pattern. We extend the model to adaptive demand response case where the arrival rate of secondary and primary networks varies over time. Afterwards, the numerical simulation results available for realistic call records data set are compared to demonstrate the optimality, effectiveness and convergence speed of the proposed algorithms. The thesis is concluded by Chapter 5 where a summary of results and a look at possible future directions for research in this area are carried out.

To have an overall view of the proposed hierarchical network model, Fig. (1.5) is illustrated to demonstrate the design process of integrated joint power control and beamforming together with dynamic spectrum leasing algorithm.

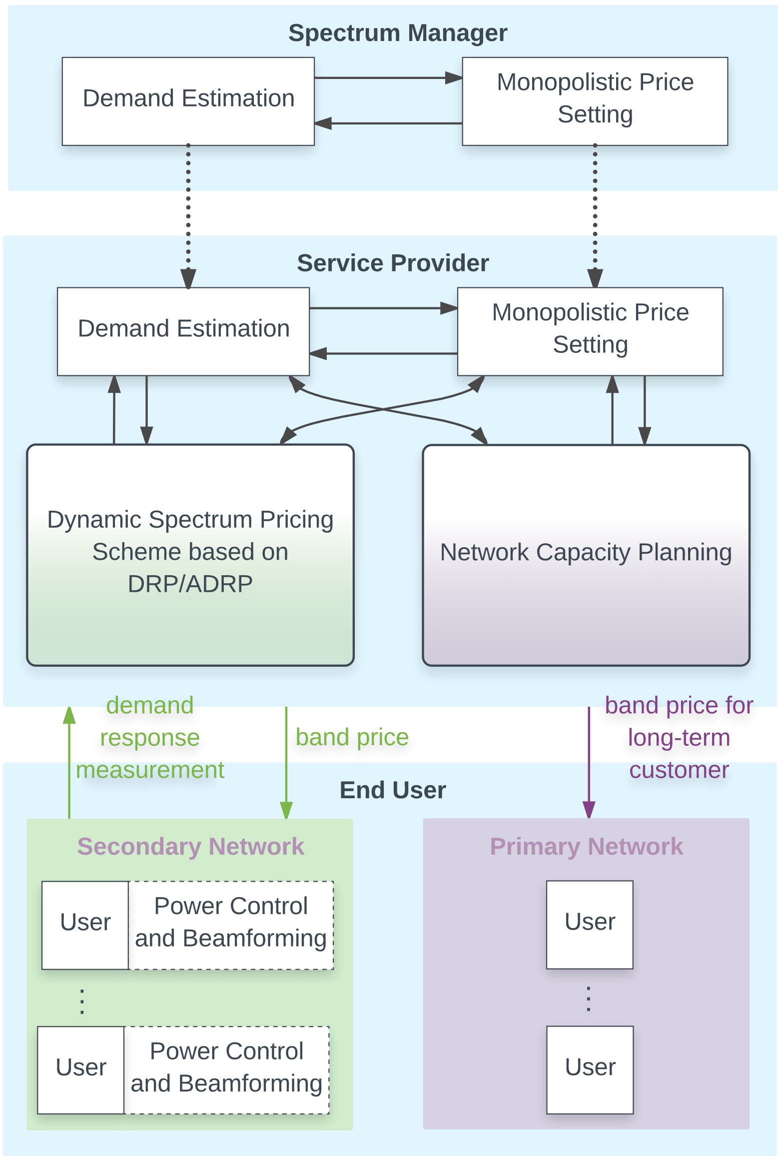

Figure 1.5: Hierarchical Network Model of Dynamic Spectrum Leasing

BIBLIOGRAPHY

[1] FCC Spectrum Policy Task Force. Report of the spectrum efficiency working group, 2002.

[2] Simon Haykin. Cognitive radio: brain-empowered wireless communications. *IEEE journal on selected areas in communications*, 23(2):201–220, 2005.

[3] Danijela Cabric, Shridhar Mubaraq Mishra, and Robert W Brodersen. Implementation issues in spectrum sensing for cognitive radios. In *Signals, systems and computers, 2004. Conference record of the thirty-eighth Asilomar conference on*, volume 1, pages 772–776. IEEE, 2004.

[4] Andrea Goldsmith, Syed Ali Jafar, Ivana Marić, and Sudhir Srinivasa. Breaking spectrum gridlock with cognitive radios: An information theoretic perspective. *Proceedings of the IEEE*, 97(5):894–914, 2009.

[5] FCC Spectrum Policy Task Force. Fcc spectrum policy task force report. *ET Docket*, (02-135), 2002.

[6] Kok-Lim Alvin Yau, Peter Komisarczuk, and Paul D Teal. Cognitive radio-based wireless sensor networks: Conceptual design and open issues. In *2009 IEEE 34th Conference on Local Computer Networks*, pages 955–962. IEEE, 2009.

[7] Joseph Mitola. Cognitive Radio—An Integrated Agent Architecture for Software Defined Radio. 2000.

[8] Joseph Mitola and Gerald Q Maguire. Cognitive radio: making software radios more personal. *IEEE personal communications*, 6(4):13–18, 1999.

[9] David Maldonado, Bin Le, Akilah Hugine, Thomas W Rondeau, and Charles W Bostian. Cognitive radio applications to dynamic spectrum allocation: a discussion and an illustrative example. In *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005.*, pages 597–600. IEEE, 2005.

[10] Seung-Jun Kim and Georgios B Giannakis. Rate-optimal and reduced-complexity sequential sensing algorithms for cognitive ofdm radios. *EURASIP journal on Advances in Signal Processing*, 2009:2, 2009.

[11] Natasha Devroye, Patrick Mitran, and Vahid Tarokh. Achievable rates in cognitive radio channels. *IEEE Transactions on Information Theory*, 52(5):1813–1827, 2006.

[12] R Cendrillion, M Moonen, J Verliden, T Bostoen, and W Yu. Optimal multiuser spectrum management for digital subscriber lines. In *IEEE Intl. Conf. on Comm*, 2004.

[13] Patrick Mitran, Long Le, Catherine Rosenberg, and André Girard. Resource allocation for downlink spectrum sharing in cognitive radio networks. In *Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th*, pages 1–5. IEEE, 2008.

[14] Peyman Setoodeh and Simon Haykin. Robust transmit power control for cognitive radio. *Proceedings of the IEEE*, 97(5):915–939, 2009.

[15] Aharon Ben-Tal, Stephen Boyd, and Arkadi Nemirovski. Extending scope of robust optimization: Comprehensive robust counterparts of uncertain problems. *Mathematical Programming*, 107(1-2):63–89, 2006.

[16] Aharon Ben-Tal and Arkadi Nemirovski. Robust solutions of uncertain linear programs. *Operations research letters*, 25(1):1–13, 1999.

[17] Aharon Ben-Tal and Arkadi Nemirovski. Selected topics in robust convex optimization. *Mathematical Programming*, 112(1):125–158, 2008.

[18] Antonio Pascual-Iserte, Daniel Pérez Palomar, Ana I Pérez-Neira, and Miguel Ángel Lagunas. A robust maximin approach for mimo communications with imperfect channel state information based on convex optimization. *IEEE Transactions on Signal Processing*, 54(1):346–360, 2006.

[19] Wei Yu and Raymond Lui. Dual methods for nonconvex spectrum optimization of multicarrier systems. *IEEE Transactions on Communications*, 54(7): 1310–1322, 2006.

[20] Jong-Shi Pang, Gesualdo Scutari, Daniel P Palomar, and Francisco Facchinei. Design of cognitive radio systems under temperature-interference constraints: A variational inequality approach. *Signal Processing, IEEE Transactions on*, 58(6):3251–3271, 2010.

[21] Daniel Willkomm, Sridhar Machiraju, Jean Bolot, and Adam Wolisz. Primary user behavior in cellular networks and implications for dynamic spectrum access. *IEEE Communications Magazine*, 47(3):88–95, 2009.

[22] J Neel, R Menon, A MacKenzie, and J Reed. Using game theory to aid the design of physical layer cognitive radio algorithms. In *Conference on Economics, Technology and Policy of Unlicensed Spectrum*, pages 16–17, 2005.

[23] Rekha Menon, Allen B MacKenzie, J Hicks, R Michael Buehrer, and Jeffrey H Reed. A game-theoretic framework for interference avoidance. *IEEE Transactions on Communications*, 57(4):1087–1098, 2009.

[24] Ali Tajer, Narayan Prasad, and Xiaodong Wang. Distributed beamforming and rate allocation in multi-antenna cognitive radio networks. In *2009 IEEE International Conference on Communications*, pages 1–6. IEEE, 2009.

[25] Eduard Jorswieck and Rami Mochaourab. Beamforming in underlay cognitive radio: Null-shaping design for efficient nash equilibrium. In *2010 2nd International Workshop on Cognitive Information Processing*, pages 476–481. IEEE, 2010.

[26] Rui Wang, Vincent KN Lau, Cui Ying, Kaibin Huang, Bin Chen, and Xia Yang. Decentralized fair resource allocation for relay-assisted cognitive cellular downlink systems. In *2009 IEEE International Conference on Communications*, pages 1–5. IEEE, 2009.

[27] Juncheng Jia, Jin Zhang, and QT Zhang. Relay-assisted routing in cognitive radio networks. In *2009 IEEE International Conference on Communications*, pages 1–5. IEEE, 2009.

[28] Lang Xie, Jie Xiang, and Yan Zhang. Revenue-based admission control for cognitive radio cellular systems. In *Communications and Networking in China, 2008. ChinaCom 2008. Third International Conference on*, pages 1200–1204. IEEE, 2008.

[29] Diego Pacheco-Paramo, Vicent Pla, and Jorge Martinez-Bauset. Optimal admission control in cognitive radio networks. In *2009 4th International Conference on Cognitive Radio Oriented Wireless Networks and Communications*, pages 1–7. IEEE, 2009.

[30] John George, Ahmed Sultan, and Mohammed Nafie. Distributed power and admission control for cognitive radios in spectrum underlay networks. In *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, pages 1–6. IEEE, 2009.

[31] Alvin Kok-Lim Yau, Peter Komisarczuk, and Paul D Teal. C 2 net: A cross-layer quality of service (qos) architecture for cognitive wireless ad hoc networks. In *Telecommunication Networks and Applications Conference, 2008. ATNAC 2008. Australasian*, pages 306–311. IEEE, 2008.

[32] Khajonpong Akkarajitsakul, Ekram Hossain, and Dusit Niyato. Distributed resource allocation in wireless networks under uncertainty and application of bayesian game. *IEEE Communications Magazine*, 49(8), 2011.

[33] Leila Musavian and Sonia Aissa. Cross-layer analysis of cognitive radio relay networks under quality of service constraints. In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pages 1–5. IEEE, 2009.

[34] Roy D Yates and Ching-Yao Huang. Integrated power control and base station assignment. *Vehicular Technology, IEEE Transactions on*, 44(3):638–644, 1995.

[35] Roy D Yates. A framework for uplink power control in cellular radio systems. *Selected Areas in Communications, IEEE Journal on*, 13(7):1341–1347, 1995.

[36] Cem U Saraydar, Narayan B Mandayam, and David J Goodman. Efficient power control via pricing in wireless data networks. *Communications, IEEE Transactions on*, 50(2):291–303, 2002.

[37] Jianwei Huang, Randall A Berry, and Michael L Honig. Auction-based spectrum sharing. *Mobile Networks and Applications*, 11(3):405–418, 2006.

[38] Juncheng Jia and Qian Zhang. A non-cooperative power control game for secondary spectrum sharing. In *Communications, 2007. ICC'07. IEEE International Conference on*, pages 5933–5938. IEEE, 2007.

[39] Ashraf Al Daoud, Tansu Alpcan, Sachin Agarwal, and Murat Alanyali. A stackelberg game for pricing uplink power in wide-band cognitive radio networks. In *Decision and Control, 2008. CDC 2008. 47th IEEE Conference on*, pages 1422–1427. IEEE, 2008.

[40] Gan Zheng. Joint beamforming optimization and power control for full-duplex MIMO two-way relay channel. *IEEE Transactions on Signal Processing*, 63(3):555–566, 2015.

[41] Qunwei Li and Pramod K Varshney. Resource Allocation and Outage Analysis for An Adaptive Cognitive Two-Way Relay Network. *arXiv preprint arXiv:1511.07469*, 2015.

[42] Wei Zhong, Gang Chen, Shi Jin, and Kai-Kit Wong. Relay selection and discrete power control for cognitive relay networks via potential game. *IEEE Transactions on Signal Processing*, 62(20):5411–5424, 2014.

[43] S Vahidian, E Soleimani-Nasab, S Aissa, and M Ahmadian-Attari. Bidirectional AF Relaying with Underlay Spectrum Sharing in Cognitive Radio Networks. *IEEE Transactions on Vehicular Technology*, PP(99):1, 2016. ISSN 0018-9545. doi: 10.1109/TVT.2016.2578180.

[44] Ashraf Al Daoud, Murat Alanyali, and David Starobinski. Secondary pricing of spectrum in cellular CDMA networks. In *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, pages 535–542. IEEE, 2007.

[45] Yiping Xing, Rajarathnam Chandramouli, and Carlos Cordeiro. Price dynamics in competitive agile spectrum access markets. *Selected Areas in Communications, IEEE Journal on*, 25(3):613–621, 2007.

[46] Dusit Niyato and Ekram Hossain. Competitive spectrum sharing in cognitive radio networks: a dynamic game approach. *Wireless Communications, IEEE Transactions on*, 7(7):2651–2660, 2008.

[47] Hui Yu, Lin Gao, Zheng Li, Xinbing Wang, and Ekram Hossain. Pricing for uplink power control in cognitive radio networks. *IEEE Transactions on Vehicular Technology*, 59(4):1769–1778, 2010.

[48] Kwang-Cheng Chen and Ramjee Prasad. Cognitive radio networks. 2009.

[49] Xin Kang, Ying-Chang Liang, and Arumugam Nallanathan. Optimal power allocation for fading channels in cognitive radio networks under transmit and interference power constraints. In *Communications, 2008. ICC'08. IEEE International Conference on*, pages 3568–3572. IEEE, 2008.

[50] Chen Sun, Yohannes D Alemseged, Ha Nguyen Tran, and Hiroshi Harada. Transmit power control for cognitive radio over a Rayleigh fading channel. *Vehicular Technology, IEEE Transactions on*, 59(4):1847–1857, 2010.

[51] Peng Wang, Ming Zhao, Limin Xiao, Shidong Zhou, and Jing Wang. Power Allocation in OFDM-Based Cognitive Radio Systems. In *GLOBECOM*, pages 4061–4065, 2007.

[52] Xiang Nian Zeng, Ali Ghrayeb, and Mazen Hasna. Joint optimal threshold-based relaying and ML detection in network-coded two-way relay channels. *Communications, IEEE Transactions on*, 60(9):2657–2667, 2012.

[53] Yuan Wu and Danny H K Tsang. Distributed power allocation algorithm for spectrum sharing cognitive radio networks with QoS guarantee. *INFOCOM 2009, IEEE*, pages 981–989, 2009.

[54] Xin Kang, Hari Krishna Garg, Ying-Chang Liang, and Rui Zhang. Power allocation for OFDM-based cognitive radio systems with hybrid protection to primary users. In *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, pages 1–6. IEEE, 2009.

[55] Gaurav Bansal, Md Jahangir Hossain, and Vijay K Bhargava. Optimal and suboptimal power allocation schemes for OFDM-based cognitive radio systems. *Wireless Communications, IEEE Transactions on*, 7(11):4710–4718, 2008.

[56] Seyed Hamid Safavi, Mehrdad Ardebilipour, and Soheil Salari. Relay beamforming in cognitive two-way networks with imperfect channel state information. *Wireless Communications Letters, IEEE*, 1(4):344–347, 2012.

[57] Ali Afana, Ali Ghrayeb, Vahid Asghari, and Sofiéne Affes. Cooperative two-way selective relaying in spectrum-sharing systems with distributed beamforming. In *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pages 2976–2981. IEEE, 2013.

[58] Beibei Wang, Yongle Wu, and K J Ray Liu. Game theory for cognitive radio networks: An overview. *Computer networks*, 54(14):2537–2561, 2010.

[59] Fan Wang, Marwan Krunz, and Shuguang Cui. Price-based spectrum management in cognitive radio networks. *Selected Topics in Signal Processing, IEEE Journal of*, 2(1):74–87, 2008.

[60] Karama Hamdi, Keyvan Zarifi, Khaled Ben Letaief, and Ali Ghrayeb. Beamforming in relay-assisted cognitive radio systems: A convex optimization approach. In *Communications (ICC), 2011 IEEE International Conference on*, pages 1–5. IEEE, 2011.

[61] Rui Wang, Meixia Tao, and Yuan Liu. Optimal linear transceiver designs for cognitive two-way relay networks. *Signal Processing, IEEE Transactions on*, 61(4):992–1005, 2013.

[62] Nan Feng, Siun-Chuon Mau, and Narayan B Mandayam. Pricing and power control for joint network-centric and user-centric radio resource management. *Communications, IEEE Transactions on*, 52(9):1547–1557, 2004.

[63] Gesualdo Scutari, Daniel P Palomar, and Sergio Barbarossa. Optimal linear precoding strategies for wideband non-cooperative systems based on game theorypart II: algorithms. *Signal Processing, IEEE Transactions on*, 56(3): 1250–1267, 2008.

[64] Luyong Zhang, Sen Zhang, Lin Wu, Yujun Liu, and Chengshi Zhao. A Nash game algorithm for distributive power control with faster convergence in cognitive radio. In *Proceedings of the 9th international conference on Communications and information technologies*, pages 93–96. IEEE Press, 2009.

[65] Joseph Mitola III. Cognitive radio architecture evolution. *Proceedings of the IEEE*, 97(4):626–641, 2009.

[66] Ekram Hossain and Vijay K Bhargava. Cognitive wireless communication networks. 2007.

[67] Raul Etkin, Abhay Parekh, and David Tse. Spectrum sharing for unlicensed bands. *Selected Areas in Communications, IEEE Journal on*, 25(3):517–528, 2007.

[68] James O'Daniell Neel. Analysis and design of cognitive radio networks and distributed radio resource management algorithms. 2006.

[69] Christian H W Oey, Ivan Christian, and Sangman Moh. Energy-and cognitive-radio-aware routing in cognitive radio sensor networks. *International Journal of Distributed Sensor Networks*, 2012, 2012.

[70] Tung T Kim, Mikael Skoglund, and Giuseppe Caire. Quantifying the loss of compress–forward relaying without wyner–ziv coding. *IEEE Transactions on Information Theory*, 55(4):1529–1533, 2009.

[71] Francisco Facchinei and Jong-Shi Pang. Finite-dimensional variational inequalities and complementarity problems. 2007.

[72] Juncheng Jia and Shukui Zhang. Cooperative transmission in cognitive radio ad hoc networks. *International Journal of Distributed Sensor Networks*, 2012, 2012.

[73] Cuiran Li and Jianli Xie. Repeated game-inspired spectrum sharing for clustering cognitive ad hoc networks. *International Journal of Distributed Sensor Networks*, 2013, 2013.

[74] Ian F Akyildiz, Won-Yeol Lee, Mehmet C Vuran, and Shantidev Mohanty. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey. *Computer Networks*, 50(13):2127–2159, 2006.

[75] Bin Cao, Qinyu Zhang, Jon W Mark, Lin X Cai, and H Vincent Poor. Toward efficient radio spectrum utilization: user cooperation in cognitive radio networking. *Network, IEEE*, 26(4):46–52, 2012.

[76] Osvaldo Simeone, Igor Stanojev, Stefano Savazzi, Yeheskel Bar-Ness, Umberto Spagnolini, and R Pickholtz. Spectrum leasing to cooperating secondary ad hoc networks. *Selected Areas in Communications, IEEE Journal on*, 26(1): 203–213, 2008.

[77] Lingjie Duan, Jianwei Huang, and Biying Shou. Investment and pricing with spectrum uncertainty: a cognitive operator's perspective. *IEEE Transactions on Mobile Computing*, 10(11):1590–1604, 2011.

[78] Gaurav S Kasbekar and Saswati Sarkar. Spectrum pricing games with random valuations of secondary users. *Selected Areas in Communications, IEEE Journal on*, 30(11):2262–2273, 2012.

[79] Peng Lin, Juncheng Jia, Qian Zhang, and Mounir Hamdi. Dynamic spectrum sharing with multiple primary and secondary users. *Vehicular Technology, IEEE Transactions on*, 60(4):1756–1765, 2011.

[80] Alexander W Min, Xinyu Zhang, Jaehyuk Choi, and Kang G Shin. Exploiting spectrum heterogeneity in dynamic spectrum market. *Mobile Computing, IEEE Transactions on*, 11(12):2020–2032, 2012.

[81] Dusit Niyato, Ekram Hossain, and Zhu Han. Dynamics of multiple-seller and multiple-buyer spectrum trading in cognitive radio networks: A game-theoretic modeling approach. *Mobile Computing, IEEE Transactions on*, 8 (8):1009–1022, 2009.

[82] Lingjie Duan, Jianwei Huang, and Biying Shou. Duopoly competition in dynamic spectrum leasing and pricing. *Mobile Computing, IEEE Transactions on*, 11(11):1706–1719, 2012.

[83] Shuqin Li, Jianwei Huang, and Shuo-Yen Robert Li. Dynamic profit maximization of cognitive mobile virtual network operator. *IEEE Transactions on Mobile Computing*, 13(3):526–540, 2014.

[84] Hong Xu, Jin Jin, and Baochun Li. A secondary market for spectrum. *INFOCOM, 2010 Proceedings IEEE*, pages 1–5, 2010.

[85] Sorabh Gandhi, Chiranjeeb Buragohain, Lili Cao, Haitao Zheng, and Subhash Suri. A general framework for wireless spectrum auctions. In *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, pages 22–33. IEEE, 2007.

[86] Xia Zhou, Sorabh Gandhi, Subhash Suri, and Haitao Zheng. eBay in the sky: Strategy-proof wireless spectrum auctions. In *Proceedings of the 14th ACM international conference on Mobile computing and networking*, pages 2–13. ACM, 2008.

[87] Xia Zhou and Heather Zheng. Trust: A general framework for truthful double spectrum auctions. *INFOCOM 2009, IEEE*, pages 999–1007, 2009.

[88] Lin Chen, Stefano Iellamo, Marceau Coupechoux, and Philippe Godlewski. An auction framework for spectrum allocation with interference constraint in cognitive radio networks. *INFOCOM, 2010 Proceedings IEEE*, pages 1–9, 2010.

[89] Ian A Kash, Rohan Murty, and David C Parkes. Enabling spectrum sharing in secondary market auctions. *IEEE Transactions on Mobile Computing*, 13(3): 556–568, 2014.

[90] Milind M Buddhikot. Understanding dynamic spectrum access: Models, taxonomy and challenges. In *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, pages 649–663. IEEE, 2007.

[91] Joe M Butler and William T Webb. An implementation of spectrum usage rights for liberalization of the radio spectrum. *Communications and Networks, Journal of*, 8(2):163–168, 2006.

[92] Reed E Hundt and Gregory L Rosston. Spectrum flexibility will promote competition and the public interest. *Communications Magazine, IEEE*, 33 (12):40–43, 1995.

[93] Nan Feng, Siun-Chuon Mau, and Narayan B Mandayam. Joint network-centric and user-centric radio resource management in a multicell system. *Communications, IEEE Transactions on*, 53(7):1114–1118, 2005.

[94] Frank P Kelly, Aman K Maulloo, and David KH Tan. Rate control for communication networks: shadow prices, proportional fairness and stability. *Journal of the Operational Research society*, 49(3):237–252, 1998.

[95] Nolan H Miller. Notes on microeconomic theory. *Externalities and Public Goods.[Online]. Available: https://business. illinois. edu/nmiller/documents/notes/notes8. pdf*, 2003.

[96] Dusit Niyato and Ekram Hossain. Market-equilibrium, competitive, and co-operative pricing for spectrum sharing in cognitive radio networks: Analysis and comparison. *IEEE Transactions on Wireless Communications*, 7(11): 4273–4283, 2008.

[97] Ioannis Ch Paschalidis and John N Tsitsiklis. Congestion-dependent pricing of network services. *Networking, IEEE/ACM Transactions on*, 8(2):171–184, 2000.

[98] Ioannis Ch Paschalidis and Yong Liu. Pricing in multiservice loss networks: static pricing, asymptotic optimality, and demand substitution effects. *IEEE/ACM Transactions on Networking (TON)*, 10(3):425–438, 2002.

[99] Xiaojun Lin and Ness B Shroff. Simplification of network dynamics in large systems. *Networking, IEEE/ACM Transactions on*, 13(4):813–826, 2005.

[100] Huseyin Mutlu, Murat Alanyali, and David Starobinski. Spot pricing of secondary spectrum access in wireless cellular networks. *IEEE/ACM Transactions on Networking (TON)*, 17(6):1794–1804, 2009.

[101] Noah Gans and Sergei Savin. Pricing and capacity rationing for rentals with uncertain durations. *Management Science*, 53(3):390–407, 2007.

[102] Ali O Ercan, Jiwoong Lee, Sofie Pollin, and Jan M Rabaey. A revenue enhancing Stackelberg game for owners in opportunistic spectrum access. In *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, pages 1–8. IEEE, 2008.

[103] Omar Besbes and Assaf Zeevi. Dynamic pricing without knowing the demand function: Risk bounds and near-optimal algorithms. *Operations Research*, 57 (6):1407–1420, 2009.

[104] Zhi-Quan Luo and Shuzhong Zhang. Dynamic spectrum management: Complexity and duality. *IEEE Journal of Selected Topics in Signal Processing*, 2 (1):57–73, 2008.

[105] Daniel Pérez Palomar and Mung Chiang. A tutorial on decomposition methods for network utility maximization. *IEEE Journal on Selected Areas in Communications*, 24(8):1439–1451, 2006.

[106] Martin J Osborne and Ariel Rubinstein. *A course in game theory*. MIT press, 1994.

[107] Shaolei Ren and Mihaela der Schaar. Pricing and distributed power control in wireless relay networks. *Signal Processing, IEEE Transactions on*, 59(6): 2913–2926, 2011.

[108] Lingjie Duan, Jianwei Huang, and Biying Shou. Cognitive Mobile Virtual Network Operator: Investment and Pricing with Supply Uncertainty. In *INFOCOM*, pages 785–793, 2010.

[109] Jocelyne Elias and Fabio Martignon. Joint spectrum access and pricing in cognitive radio networks with elastic traffic. In *Communications (ICC), 2010 IEEE International Conference on*, pages 1–5. IEEE, 2010.

[110] Enrique Campos-Nánez and Stephen D Patek. On-line tuning of prices for network services. In *INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications. IEEE Societies*, volume 2, pages 1231–1241. IEEE, 2003.

[111] Beibei Wang, Zhu Han, and K J Ray Liu. WLC41-4: Stackelberg Game for Distributed Resource Allocation over Multiuser Cooperative Communication Networks. In *Global Telecommunications Conference, 2006. GLOBECOM'06. IEEE*, pages 1–5. IEEE, 2006.

[112] Jianwei Huang, Zhu Han, Mung Chiang, and H Vincent Poor. Auction-based resource allocation for cooperative communications. *Selected Areas in Communications, IEEE Journal on*, 26(7):1226–1237, 2008.

[113] Utku Ozan Candogan, Ishai Menache, Asuman Ozdaglar, Pablo Parrilo, and Others. Near-optimal power control in wireless networks: A potential game approach. In *INFOCOM, 2010 Proceedings IEEE*, pages 1–9. IEEE, 2010.

[114] Wei Yu. Multiuser water-filling in the presence of crosstalk. In *Information Theory and Applications Workshop, 2007*, pages 414–420. IEEE, 2007.

[115] J Nicholas Laneman, David N C Tse, and Gregory W Wornell. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *Information Theory, IEEE Transactions on*, 50(12):3062–3080, 2004.

[116] Mischa Dohler and A H Aghvami. A crash-course on cooperative wireless networks. In *IEEE Intl. Conf. Commun. Half-Day Tutorial*, 2008.

[117] Amir Ghasemi and Elvino S Sousa. Fundamental limits of spectrum-sharing in fading environments. *Wireless Communications, IEEE Transactions on*, 6 (2):649–658, 2007.

[118] Irina Gaynanova, James Booth, and Martin T Wells. Penalized versus constrained generalized eigenvalue problem. *arXiv preprint arXiv:1410.6131*, 2014.

[119] Victor Y Pan and Zhao Q Chen. The complexity of the matrix eigenproblem. In *Proceedings of the thirty-first annual ACM symposium on Theory of computing*, pages 507–516. ACM, 1999.

[120] Dario Andrea Bini, Yuli Eidelman, Luca Gemignani, and Israel Gohberg. Fast qr eigenvalue algorithms for hessenberg matrices which are rank-one perturbations of unitary matrices. *SIAM Journal on Matrix Analysis and Applications*, 29(2):566–585, 2007.

[121] Gregory Staple and Kevin Werbach. The end of spectrum scarcity [spectrum allocation and utilization]. *IEEE spectrum*, 41(3):48–52, 2004.

[122] Václav Valenta, Roman Maršálek, Geneviève Baudoin, Martine Villegas, Martha Suarez, and Fabien Robert. Survey on spectrum utilization in Europe: Measurements, analyses and observations. In *2010 Proceedings of the Fifth International Conference on Cognitive Radio Oriented Wireless Networks and Communications*, pages 1–5. IEEE, 2010.

[123] Giovanni Giambene. *Queuing theory and telecommunications*. Springer, 2005.

[124] Heejun Roh, Chenglong Shao, Sinjae Lee, Wonjun Lee, and Ding-Zhu Du. Secondary user games with spectrum leasing market in cooperative cognitive radio networks. In *Computer Communications Workshops (INFOCOM WKSHPS), 2013 IEEE Conference on*, pages 87–88. IEEE, 2013.

[125] Miguel López-Ben\'\itez and Fernando Casadevall. Time-dimension models of spectrum usage for the analysis, design, and simulation of cognitive radio networks. *IEEE transactions on vehicular technology*, 62(5):2091–2104, 2013.

[126] Miguel López-Ben\'\itez and Fernando Casadevall. Improved energy detection spectrum sensing for cognitive radio. *IET communications*, 6(8):785–796, 2012.

[127] Chen Peipei, Zhang Qinyu, Zhang Yalin, and Wang Ye. Performance analysis of spectrum sharing mechanisms in cognitive radio networks. *EURASIP Journal on Wireless Communications and Networking*, 2011(1):129, 2011.

[128] Anita Garhwal and Partha Pratim Bhattacharya. A survey on dynamic spectrum access techniques for cognitive radio. *arXiv preprint arXiv:1201.1964*, 2012.

[129] Emir Kavurmacioglu and David Starobinski. Network dimensioning with carrier aggregation. In *Dynamic Spectrum Access Networks (DySPAN), 2015 IEEE International Symposium on*, pages 336–347. IEEE, 2015.

[130] Pinki Yadav and Partha Pratim Bhattacharya. An effective dynamic spectrum access method for use in cognitive radio. *IJCSMC*, 2(2):12–20, 2013.

[131] Scott Kirkpatrick, C Daniel Gelatt, Mario P Vecchi, and Others. Optimization by simmulated annealing. *science*, 220(4598):671–680, 1983.

[132] Suren Dadallage, Changyan Yi, and Jun Cai. Joint Beamforming, Power, and Channel Allocation in Multiuser and Multichannel Underlay MISO Cognitive Radio Networks. *IEEE Transactions on Vehicular Technology*, 65(5):3349–3359, 2016.

[133] Emile H L Aarts and Peter J M Van Laarhoven. Simulated annealing: Theory and applications. *Reidel, Dordrecht*, 9717:5, 1987.

[134] Thomas Bonald. The erlang model with non-poisson call arrivals. *ACM SIGMETRICS Performance Evaluation Review*, 34(1):276–286, 2006.

[135] Grigorios Zachariadis and Javier A Barria. Demand management for telecommunications services. *Computer Networks*, 51(12):3507–3524, 2007.

PUBLICATION

Havzhin Iranpanah, Borhanuddin M Ali, Fazirulhisyam Hashim, and Hafizal Mohamad. Distributed power control and beamforming for cognitive two-way relay networks using a game-theoretic approach. In Telecommunication Technologies (ISTT), 2016 IEEE 3rd International Symposium on, pages 81-86. IEEE, 2016.

UNIVERSITI PUTRA MALAYSIA

STATUS CONFIRMATION FOR THESIS / PROJECT REPORT AND COPYRIGHT

ACADEMIC SESSION : First Semester 2017

TITLE OF THESIS / PROJECT REPORT :

Distributed Joint Power Control, Beamforming and Spectrum Leasing for Cognitive Two-Way Relay Networks

NAME OF STUDENT : Havzhin Iranpanah

I acknowledge that the copyright and other intellectual property in the thesis/project report belonged to Universiti Putra Malaysia and I agree to allow this thesis/project report to be placed at the library under the following terms:

1. This thesis/project report is the property of Universiti Putra Malaysia.
2. The library of Universiti Putra Malaysia has the right to make copies for educational purposes only.
3. The library of Universiti Putra Malaysia is allowed to make copies of this thesis for academic exchange.

I declare that this thesis is classified as :

*Please tick (√)

[ ]	**CONFIDENTIAL**	(Contain confidential information under Official Secret Act 1972).
[ ]	**RESTRICTED**	(Contains restricted information as specified by the organization/institution where research was done).
[√]	**OPEN ACCESS**	I agree that my thesis/project report to be published as hard copy or online open access.

This thesis is submitted for :

[ ]	**PATENT**	Embargo from __________ (date) until __________ (date)

Approved by:

(Signature of Student)	(Signature of Chairman of Supervisory Committee)
New IC No/ Passport No.:	Name:
Date :	Date :

[Note : If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization/institution with period and reasons for confidentially or restricted.]