UNIVERSITI PUTRA MALAYSIA

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

HAVZHIN IRANPANAH

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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

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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

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June 2017

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

Cognitive Radio (CR), as a promising technological solution to the spectrum under-utilization 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

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Jun 2017

Pengerusi : **Professor Borhanuddin bin Mohd Ali, PhD**
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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.

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

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.

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I hereby confirm that:

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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.

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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-

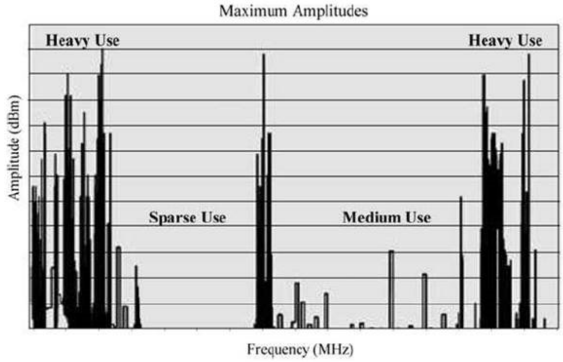

Figure 1.1: Spectrum Underutilization [1].

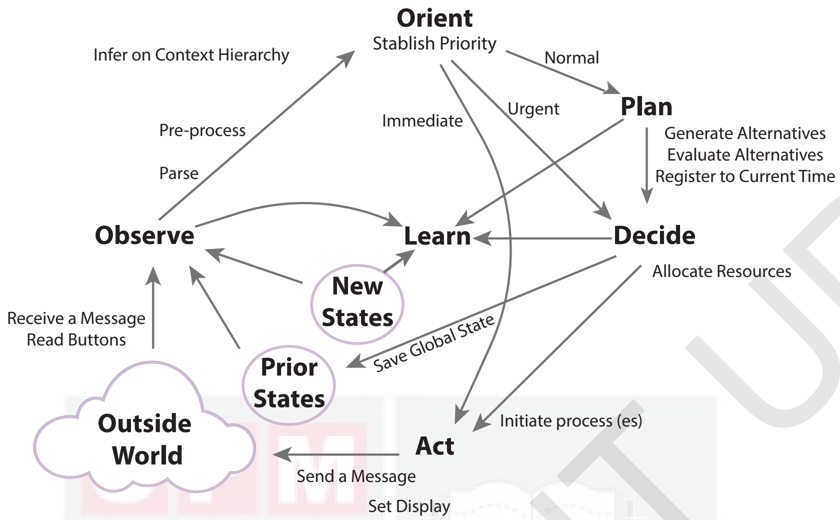

Figure 1.2: Cognitive Radio Structure [2].

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,

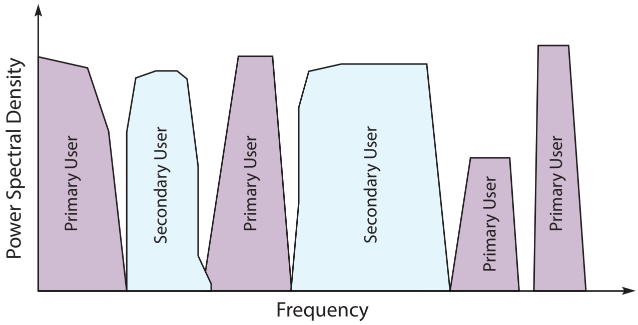

Figure 1.3: Overlay Transmission in Cognitive Radio Networks [3].

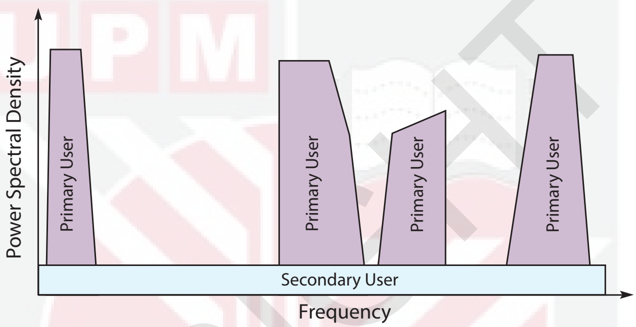

Figure 1.4: Underlay Transmission in Cognitive Radio Networks [3].

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.

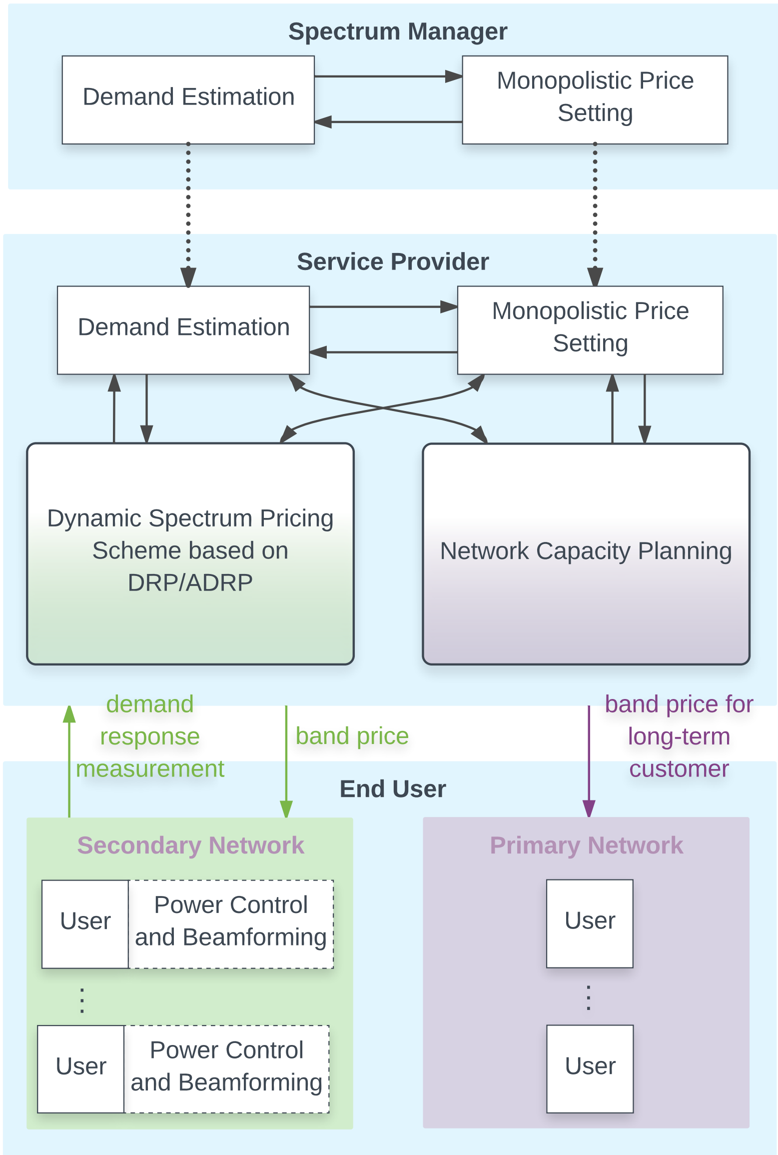

Figure 1.5: Hierarchical Network Model of Dynamic Spectrum Leasing

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