A SOFTWARE FRAMEWORK FOR PRIORITIZED SPECTRUM ACCESS IN HETEROGENEOUS COGNITIVE RADIO NETWORKS

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A Software Framework for Prioritized Spectrum Access in Heterogeneous Cognitive Radio Networks

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Doctoral Dissertation in Telecommunication Systems

Department of Communication Systems
Blekinge Institute of Technology
SWEDEN
To my family...
Abstract

Today, the radio spectrum is rarely fully utilized. This problem is valid in more domains, e.g., time, frequency and geographical location. To provide an efficient utilization of the radio spectrum, the Cognitive Radio Networks (CRNs) have been advanced. The key idea is to open up the licensed spectrum to unlicensed users, thus allowing them to use the so-called spectrum opportunities as long as they do not harmfully interfere with licensed users. An important focus is laid on the limitation of previously reported research efforts, which is due to the limited consideration of the problem of competition among unlicensed users for spectrum access in heterogeneous CRNs.

A software framework is introduced, which is called PRioritized Opportunistic spectrum Access System (PROAS). In PROAS, the heterogeneity aspects of CRNs are specifically expressed in terms of cross-layer design and various wireless technologies. By considering factors like ease of implementation and efficiency of control, PROAS provides priority scheduling based solutions to alleviate the competition problem of unlicensed users in heterogeneous CRNs. The advanced solutions include theoretical models, numerical analysis and experimental simulations for performance evaluation. By using PROAS, three particular CRN models are studied, which are based on ad-hoc, mesh-network and cellular-network technologies. The reported results show that PROAS has the ability to bridge the gap between research results and the practical implementation of CRNs.
It is a pleasure to express my deep gratitude and appreciation to those who have contributed to the conducting of this thesis. Foremost, I would like to thank my main advisor Prof. Adrian Popescu for accepting me as a Ph.D student, and for his guidance and immense knowledge that helped me grow up in the research career. I also would like to thank my co-advisor TeknDr. David Erman for his invaluable supervision, and Prof. Markus Fiedler for firmly supporting me along the way.

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Yong Yao

Karlskrona, June 2014
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Acronyms

ACO Ant Colony Optimization
AI Artificial Intelligence
API Application Programming Interface
BS Base Station
BER Bit Error Rate
BTH Blekinge Institute of Technology
CCC Common Control Channel
CDMA Code Division Multiple Access
CI Computational Intelligence
CR Cognitive Radio
CRMN Cognitive Radio Mesh Network
CTMC Continuous Time Markov Chain
AC-L Allocated Channel for Local
AC-R Allocated Channel for Relay
DM Decision-Making
DTMC Discrete Time Markov Chain
e2e end-to-end
FCA Fuzzy Channel Availability
FTP Fuzzy Transmission Performance
FCC Federal Communication Commission
GR Gateway Router
GSL GNU Scientific Library
LAPI Lower Application Programming Interface
MAC Media Access Control
MDP Markov Decision Processes
<table>
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<th>Abbreviation</th>
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<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
<tr>
<td>MR</td>
<td>Mesh Router</td>
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<td>NS-2</td>
<td>Network Simulator 2</td>
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<td>OSA</td>
<td>Opportunistic Spectrum Access</td>
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<tr>
<td>OS</td>
<td>Operation System</td>
</tr>
<tr>
<td>ODM</td>
<td>Overlay Decision Maker</td>
</tr>
<tr>
<td>POMDP</td>
<td>Partially Observed Markov Decision Process</td>
</tr>
<tr>
<td>PPM</td>
<td>Prediction by Partial Match</td>
</tr>
<tr>
<td>PST</td>
<td>Probabilistic Suffix Tree</td>
</tr>
<tr>
<td>PU</td>
<td>Primary User</td>
</tr>
<tr>
<td>PROAS</td>
<td>PRioritized Opportunistic spectrum Access System</td>
</tr>
<tr>
<td>PCC</td>
<td>Primary Central Coordinator</td>
</tr>
<tr>
<td>PBS</td>
<td>Primary Base Station</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>QoE</td>
<td>Quality of Experience</td>
</tr>
<tr>
<td>RSS</td>
<td>Received Signal Strength</td>
</tr>
<tr>
<td>SU</td>
<td>Secondary User</td>
</tr>
<tr>
<td>STL</td>
<td>Standard Template Library</td>
</tr>
<tr>
<td>SCC</td>
<td>Secondary Central Coordinator</td>
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<tr>
<td>TSIE</td>
<td>Two-Step Information Exchange</td>
</tr>
<tr>
<td>UAPI</td>
<td>Upper Application Programming Interface</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wide Band</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal Software Radio Peripheral</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<td>WMN</td>
<td>Wireless Mesh Network</td>
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Chapter 1

Introduction

This chapter defines the research scope of the PhD thesis. The concepts of Cognitive Radio (CR), Cognitive Radio Networks (CRNs) and spectrum decision are described. A critical problem created by that the unlicensed users compete for the shared spectrum opportunities in CRNs is discussed. The heterogeneity aspects of CRNs is described. The need of alleviating the competition problem in heterogeneous CRNs is addressed. The corresponding contributions of this thesis are presented.

1.1 Introduction

As a result of the existing policy for static frequency allocation, today’s licensed spectrum is rarely fully utilized in the domains of time, frequency and geographical location [1–3]. Spectral under-utilization is contrasting the increasing demand for radio resources (i.e., spectrum bands), which is due to the rapid growth of populations, wireless devices and services. This conflict reveals the serious problem of spectrum scarcity inherently
CHAPTER 1. INTRODUCTION

challenging in wireless communication systems. To overcome the problem, attractive technologies like Cognitive Radio (CR) have been advanced [4,7].

1.1.1 Cognitive Radio Networks

CR was first coined by Mitola in 1999 [7], and it is envisioned to act as a highly intelligent radio unit where transmission parameters like frequency range, transmit power and modulation type are altered by learning the radio environment. Recently, CR has been accepted as an emerging technology to improve the performance of radio communication systems. This novel communication paradigm leads to an enabling framework “Cognitive Radio Networks (CRNs)”, which is first suggested by the Federal Communication Commission (FCC) [1].

The key idea of CRNs is to open the licensed spectrum bands to unlicensed users [5]. Hence, they can access the so-called spectrum opportunities as long as they do not harmfully interfere with licensed users. In CRNs, the licensed users are called Primary Users (PUs). For unlicensed users, they are equipped with CR devices and are known as Secondary Users (SUs). By using CR technology, the SUs are capable of autonomous adaptation to radio environment changes.

![Figure 1.1: Example of spectrum availability.](image)

So far, various solution approaches have been advanced for the imple-
1.1. INTRODUCTION

mentation of CRNs, A detailed taxonomy of these approaches is reported in [6]. Therein, one typical approach is called Opportunistic Spectrum Access (OSA) [8], as shown in Figure 1.1. In this approach, the licensed spectrum bands are authorized to PUs. If and when a band is not used by PUs, it becomes available for the use by SUs, creating so the so-called spectrum opportunity or available channel. When a PU occupies a band, the SU using the same band must vacate this band. Otherwise, the PUs data transmission would be impaired. The focus of this thesis is on the OSA based CRNs.

1.1.2 Spectrum Decision

Today, some of the most active areas of research in CRNs refer to the methods used to detect, to select and to access available channels. The detection can be done by either spectrum sensing\textsuperscript{1} or by database based solutions [11–13]. Since SUs may obtain information about multiple channels available at a time moment, this results in an important research task called spectrum decision [4], which significantly influences the transmission performance of SUs in CRNs.

Spectrum decision is often referred to as a process with the help of which SUs decide which available channel should be selected for access. It can be carried out either at a SU side or at the SU coordinator side. At a SU coordinator, it can be like a secondary base station or a support node [13, 30]. The goal of doing spectrum decision is to decide on the best channel, which could optimize the transmission performance of SUs.

\textsuperscript{1}The spectrum sensing is related to the actions of doing frequency scanning on licensed spectrum and detecting the existence of PUs. The advanced sensing techniques are like, e.g., matched filter detection, energy detection [11, 12].
CHAPTER 1. INTRODUCTION

In a longer perspective, it is expected that CRNs will go beyond the OSA approach and new technologies and policies will be developed for CRNs. The goal is to allow the access to a portfolio of different spectrum types like, e.g., licensed spectrum, unlicensed spectrum and leased spectrum. The SUs are further expected to be able to dynamically change the operating spectrum within the particular spectrum portfolio, and to do this on a “just-in-time” basis. The resources of the spectrum pool can be characterized in terms of context, location and technology. Various parameters like price, QoS/QoE, energy saving and competition may be used in selecting the particular spectrum [13].

1.2 Motivation

Many studies done so far on the spectrum decision in CRNs have focused on the protection assurance for PUs. That is, the data transmissions of SUs are not allowed to harmfully interfere with the ones of PUs. Therefore, the transmission activity of PUs has been considered as a dominant factor in affecting the effectiveness of spectrum decision. However, the above mentioned diversity property of radio resources indicates more complexity in the design and development of viable spectrum decision strategies. In the thesis, this complexity is connected with the heterogeneous aspects of CRNs and also with the competition problem of SUs in CRNs.

1.2.1 Heterogeneity Aspects

Specifically, the heterogeneity aspects of CRNs is expressed in terms of vertical and horizontal properties of wireless communication system, as shown in Figure 1.2.
1.2. MOTIVATION

On one hand, the vertical property means that the data transmission of SUs may operate at several layers such as physical layer, Media Access Control (MAC) layer, network layer and so on. Hence, a major operational requirement for SUs is to effectively coordinate multiple layers, also known as cross-layer design. For instance, since the spectrum sensing may be imperfectly performed at physical layer, a simple CR MAC protocol may frequently create transmission collisions between SUs and PUs. On the other hand, the horizontal property refers to different wireless techniques like, e.g., Bluetooth, IEEE 802.11, Code Division Multiple Access (CDMA) and IEEE 802.22 [9]. These techniques can be modified and used in CRNs [28–30].

The heterogeneity aspects of CRNs are further associated with various

Figure 1.2: Heterogeneity aspects of CR networks.
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characteristics of spectrum bands (i.e., channels). These characteristics can be represented by either using instant parameters like transmit power and bandwidth [5], or by using statistical parameters like the average duration of channel being available for SUs [19–21]. Naturally, when the spectrum decision is carried out, different parameters can be considered as various decision criteria. Hence, the spectrum decision maker must have a capability that jointly takes into account these different parameters.

1.2.2 Competition Problem

In a CRN, different SUs may share the same set of available channels during a particular time period. Several of them may want to access the available channel at the same time. In this case, if their spectrum decision strategies are only based on the information about the transmission activity of PUs, they may select the same channel and compete for the utilization of this particular channel. This phenomenon is known as the competition problem of SUs, and these SUs are called SU competitors.

Generally, the competition problem of SUs is associated with the inefficient utilization of available channels. As the channel capacity is limited, a single channel may not satisfy the requirements of all involved SU competitors. If a channel is overcrowded due to a large number of SU competitors, the QoS performance of the whole system degrades [20]. The conclusion therefore is that there is strong need for new scientific solutions that also consider the problem of internal competition among SUs in accessing the same available channels in CRNs.
1.3. RELATED WORK

1.2.3 Suggested Solution

Today, an important challenge for the research and industrial communities is to bridge the gap between research results and the large-scale deployment of CRNs. Sustained research efforts are needed to provide technological solutions able to take advantage of the great potential and commercial promises of CRNs. Therefore, a new software framework is suggested, which combines case studies, system modelling, numerical analysis, simulation experiments and portable Application Programming Interfaces (APIs).

In the suggested software framework, different mathematic tools like Markov Chains and Fuzzy Logic are used to deal with the heterogeneity aspects of CRNs. The corresponding numerical analysis can be validated by the simulator that is integrated in the framework. By considering factors like ease of implementation and efficiency of control, priority scheduling based algorithms are developed to alleviate the competition problem of SUs. By using portable APIs, these developed algorithms can be conveniently applied in other existing studies/investigations on heterogenous CRNs, like, e.g., network topology designing, testbed development, performance evaluation.

1.3 Related Work

The related work done on spectrum decision, heterogeneity aspects of CRNs and the competition problem of SUs is as follows.

To date, a large amount of spectrum decision strategies have been suggested for SUs. For instance, in [5], the authors characterized the channels with parameters like received signal strength, interference, path loss, wireless link error, link layer delay. Based on these parameters, SUs can select
CHAPTER 1. INTRODUCTION

the most available channels to access. However, this strategy gives rise to a multiple-constraint based decision making problem. The mathematic tool fuzzy logic is useful for solving this problem because of the capability of coping with various criteria for decision making purposes. For instance, in [18] the authors adopted parameters like mobile speed and signal strength received at SU side to represent the channel availability. Moreover, by introducing a set of fuzzy rules, the authors constructed a fuzzy logic based decision system to help SUs in doing channel selection.

Clearly, the above described spectrum decision strategies rely on the instant information. They are not flexible for SUs to adapt to the radio environment varying over time. The conclusion therefore is that statistical information about radio environment changes is desirable for SUs to do spectrum decision. For instance, the authors of [19] suggested a two-state free-busy Markov chains based model to theoretically study the interaction between PUs and SUs. Alternatively, in [22] the authors suggested a hybrid free-busy model, in which the duration of the state free is fixed and the duration of the state busy is exponentially distributed. In [21], the authors adopted the hybrid free-busy model to investigate the blocking and dropping probabilities of the data transmission of SUs\(^2\).

To be called cognitive, the SUs should also have the ability of learning from the radio environment changes. To provide this ability, Computational Intelligence (CI) based algorithms can be applied in spectrum decision strategies as indicated in recent literature. For instance, in [23], the authors suggested a biologically-inspired algorithm to achieve efficient spectrum sharing among SUs. To do this, they first defined a handoff event so that a SU vacates a channel and switches to another available channel. The

\(^2\)The blocking event means there are no channels available for SUs, and the dropping event means that a SU is dropped out from an available channel due to the channel occupancy by PUs.
authors formulated then the decision of performing a handoff as a function of two parameters. The first parameter is defined as the (total) transmit power permitted by a channel. The second parameter is defined as the transmit power required by a SU when the SU wants to access a channel. These two parameters are respectively referred to as response threshold and stimuli intensity, which are introduced in adaptive task allocation model [24]. As a result, SUs can automatically access the most available channels in accordance with the largest handoff-decision value. However, the biologically-inspired algorithm may lead to a high handoff rate of SUs. To reduce the handoff rate, the authors of [25] suggested an improved algorithm. In this algorithm, the values of two parameters response threshold and stimuli intensity are derived with respect to a free-busy Markov process. Moreover, in [26, 27], the authors applied the game theory in CRNs, so that SUs can behave in a socially constructive way when they want to select available channels.

Studies focused on the heterogeneity aspects of CRNs and competition problem of SUs have also been reported in recent literature. For instance, in [15] the authors studied the resource allocation in Orthogonal Frequency Division Multiplexing (OFDM) based CRNs. The spectrum decision done for SUs is under the consideration of different practical limitations and parameters like, e.g., imperfect spectrum sensing, limited transmission power, different traffic demands of SUs. The authors also suggested a barrier-based method to achieve the optimal power distribution among SUs. In [30], the authors suggested an adaptive spectrum sharing scheme for applying the CDMA based cognitive MAC protocol in the uplink communications over CRNs. This scheme addresses the joint problem of spectrum sensing, data transmission and power allocations for SUs to do channel selection. It enables SUs to efficiently use the available channels while stringently limiting

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3This model is used to study the cooperation behavior in insect colonies [24].
the interference to PUs. In [28], the authors studied the transmission performance of OSA model for using the modified IEEE 802.11 MAC protocol. Their results highlight the importance of taking a cross-layer view for SUs to do spectrum decision. By a cross-layer view, we mean the need of jointly designing physical-layer spectrum sensing and MAC-layer channel access. Similarly, the authors of [29] also considered a modified IEEE 802.11-based CRNs, where the data transmissions of users (both PUs and SUs) operate on a time-slotted basis. They suggested a new channel selection algorithm for SUs to transmit variable length based packets. The selection criterion depends on the remaining time of channel availability within each particular time slot.

Furthermore, in [16] the authors considered a heterogenous CRN consisting of both centralized and distributed network topologies. They formulated the problem of allocating spectrum resources to SUs in CRN as a cooperative game. They also suggested an iterative power water-filling scheme to achieve the Nash Equilibrium (NE). In [17], the authors considered heterogeneous SUs in distributed cooperative CRNs. These SUs have different types of data transmissions in term of real-time and non-real-time traffics. To deal with their competition for channel access, the authors suggested a priority scheme by reserving a number of available channels to the real-time traffic based SUs rather than the non-real-time traffic based SUs. The optimum number of the reserved channels is determined by the joint consideration of different parameters like, e.g., QoS providing, spectrum sensing results.

The above studies show the requirement for intelligent and efficient spectrum decision strategies in heterogeneous CRNs. This requirement is mainly driven by various factors like instant and statistical information about radio environmental parameters, mathematic tools (e.g., fuzzy-logic,
Markov decision process), cross-layer design, different wireless technologies, Quality of Service (QoS) provision, competition problem for SUs, and so on. An important research focus of the PhD thesis is, however, regarding the limitation of the reported results, which is basically due to the limited framework that is not able to integrate all these factors. To the best of our knowledge, there has been so far few investigations along with this research line.

1.4 Contributions of the PhD Thesis

A new software framework is advanced for implementing the prioritized spectrum access in heterogeneous CRNs. More specifically, we suggest a set of priority schemes to schedule the unlicensed data transmissions carried out by SUs. These schemes provide the SUs with different access priorities when they want to use the same available channels. The goal is to alleviate the competition problem of SUs in heterogeneous CRNs. The major contributions of the PhD thesis are as follows:

- Study the OSA based CR transmission model under four particular CRN topologies, i.e., infrastructure based CRNs, CR cellular networks, CR ad-hoc networks and CR mesh networks.
- Introduce the need of priority scheduling for alleviating the competition problem of SUs. Suggest effective priority schemes for SUs to do prioritized spectrum access in heterogeneous CRNs.
- Conduct the system modelling and numerical analysis of heterogeneous CRNs. Evaluate the transmission performance of SUs under the suggested priority schemes. Design and conduct simulation experiments to validate the numerical results.
CHAPTER 1. INTRODUCTION

1.5 Outline

The rest of the thesis is organized as follows. Chapter 2 presents the characteristics of heterogeneous CRNs, with emphasize on the competition problem of SUs and the priority scheduling based solution. Chapter 3 is about the description of a software framework, which is advanced for supporting priority scheduling in heterogenous CRNs. Chapter 4 is regarding a queueing buffer based priority scheme, which is suggested to deal with the handover procedure in CR cellular networks. In Chapter 5, a single-hop based CR ad-hoc network is studied, where a queueing buffer based priority scheme is suggested for SU to cope with different types of traffic. In Chapter 6, the end-to-end (e2e) transmission performance of SUs with imperfect spectrum sensing in CR mesh networks is studied. In Chapter 7, a fuzzy logic based hybrid spectrum decision strategy is suggested for SUs to efficiently share the available channels in CR ad-hoc networks. Finally, Chapter 8 concludes the research and presents the future work.
Chapter 2

Characteristics of Heterogeneous Cognitive Radio Networks

This chapter is about the description of heterogeneous CRNs from different perspectives like physical, MAC, network and application layers. First, several fundamental research problems related to the CR transmission model are presented. Then, the four typical CRN topologies are studied. They are the infrastructure based networks, cellular networks, ad-hoc networks and mesh networks. Based on this, the competition problem of SUs in heterogeneous CRNs is discussed. The need for applying priority scheduling in heterogeneous CRNs is addressed.

2.1 Transmission Model

In OSA based CRNs, an available channel (i.e., spectrum opportunity) can be occupied by PUs, even when it is used by SUs. In order to not
harmfully interfere to PUs, SUs have to leave the occupied channel, the so-called protection mechanism of PUs. This protection mechanism, however, interrupts the ongoing data transmission of SUs. Therefore, an important task in the design of CRNs is to develop viable transmission models for SUs. By this, we mean the way how a SU carries out the data transmission over an available channel under the protection mechanism of PUs. The implementation must consider different layers, e.g., physical layer, MAC layer, network layer.

In this section, the study is focused on the MAC layer of CRNs. Simply put, we consider a simple CRN system, where only a single SU exists. Two particular cases, i.e., single-channel case and multiple-channel case, are studied as follows.

### 2.1.1 Single-Channel Case

In this case, the CRN system is assumed to provide a single channel shared by multiple PUs\(^1\) and a single SU. This channel is denoted by \(\mathcal{C}\). The transmission activities of the PUs and the SU in channel \(\mathcal{C}\) are studied below.

**Transmission activity of PUs**

The two-state *free-busy* model is widely used to study the transmission activity of PUs [19–21]. As shown in Figure 2.1, the states “free” and “busy” represent “PU being absent” and “PU being present” in channel \(\mathcal{C}\), respectively. Depending on the time periods of these two states, the

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\(^{1}\)Development of channel allocation policies or solutions for PUs is out-of-scope of this thesis.
transmission activity of PUs can be classified in two categories: dynamic-based and static-based. By dynamic activity, we mean that the transmission activity of PUs changes very often and the time periods of the state free or busy in channel $C$ can be scaled at second or minute level. By static activity, we mean that the time periods of the state free or busy in channel $C$ usually last for several hours or days.

**Transmission activity of the SU**

When the SU wants to access the channel $C$, it needs to first identify the channel availability. Once the channel $C$ is identified to be available (i.e., being free), the SU can then use it to transmit data. The identification can be accomplished by spectrum sensing or by database based solutions [13]:

- The spectrum sensing is expected to work in the radio environment where the transmission activity of PUs is dynamic-based. In this environment, the SU frequently senses the radio signal of PUs, and thus detects the existence of PUs in channel $C$. Due to hardware/software limitations at the SU side, the results of spectrum sensing may be imperfect. This imperfection is typically expressed in terms of overlook and misidentification errors, as shown in Figure 2.2. Overlook means that the free channel $C$ is sensed to be busy, while misidentification
CHAPTER 2. CHARACTERISTICS OF HETEROGENEOUS COGNITIVE RADIO NETWORKS

![Diagram showing channel state in reality and sensing results with states "busy" and "free" in reality, as well as "Overlook" and "Misidentification" in sensing results.]

Figure 2.2: Sensing errors: overlook and misidentification.

means that the busy channel $C$ is sensed to be free.

The database based solutions are expected to work in radio environments where the transmission activity of PUs is static-based. In this environment, the particular time periods of PUs occupying the channel $C$ may be prescribed in a database. By communicating with the database, the SU knows the historical information about the transmission activity of PUs in channel $C$. Such information can be then used by the SU to predict the future channel availability. The goal is to alleviate the collision with PUs.

**Time-slotted transmission scheme and blocking event**

The PUs can return to channel $C$ at an arbitrary time moment. At the same time, if the SU transmits data over channel $C$, this may create the transmission collision between the PUs and the SU. To alleviate this collision, a feasible solution is advanced as the data transmission of either PUs or SU operates in a time-slotted manner, the so-called *time-slotted transmission scheme*. 

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2.1. TRANSMISSION MODEL

Specifically, the data transmission of either PUs or SU is partitioned into multiple time slots. Each time slot has an identical length in the time domain. PUs are assumed be either absent or present in channel $C$ during the whole slot duration of each particular slot. While, every SU time slot consists of two action phases: sensing phase and transmission phase, as show in Figure 2.3. During the first phase, the SU performs the spectrum sensing on channel $C$. If the channel is sensed to be free, the SU uses channel $C$ to transmit the data to a receiver (e.g., an access point or another SU) during the second phase. The successful transmission can be acknowledged by the receiver at the end of the second phase. If the channel

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For the database based solutions, the SU communicates with the database during the first phase.

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For the SU, each time slot consists of two action phases.

**Figure 2.4:** Example of time-slotted transmission: five identical time slots are denoted by $k-2$, $k-1$, $k$, $k+1$ and $k+2$. 

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C is sensed to be busy, the SU keeps quiet until the beginning of the next time slot. As a result, the SU’s data transmission is temporarily blocked, the so-called blocking event, as shown in Figure 2.4.

2.1.2 Multiple-Channel Case

In this case, multiple channels are assumed to be shared by multiple PUs and a single SU in the CRN system. Similar to the single-channel case, the free-busy model is used to model the transmission activity of PUs in each channel. Further, both the PUs and the SU are assumed to use the time-slotted transmission scheme.

Channel selection

Each channel is assumed to be allowed for the use by one PU at a time. At a particular time moment, since the PUs may not use all channels, one or more channels\(^3\) may become available for the use by the SU. Therefore, when the SU wants to access an available channel, it needs not only to identify the channel availabilities of all channels, but also to select the best channel. The channel selection can be done by using suitable spectrum decision strategies as mentioned in Section 1.3.

Spectrum handoff and dropping event

Since each channel is exclusively reserved for PUs, the data transmission of the SU over an available channel may be interrupted due to the channel occupancy by a PU. By channel occupancy, we mean the event that a PU

\(^3\)At different time moments, there may exist different sets of available channels, as shown in Figure 2.5.
returns to a channel when it is used by the SU. The channel occupancy can be detected by the SU during the sensing phase in each time slot. To cope with the interruption by PUs, the SU can attempt to use another available channel. If this attempt is successful, the SU can then switch its data transmission to the newly selected channel. Otherwise, the SU needs to stop its data transmission until another available channel is found.

Accordingly, the successful switching of data transmission from the previously used channel to the newly selected channel is called *spectrum handoff*. While, the event of stopping the data transmission due to lack of available channel is called *dropping event*. Figure 2.5 shows an example of the process that the SU switches its data transmission among different available channels during a particular time period.

![Figure 2.5: Example of spectrum handoff, together with a dropping event.](image)

Note that the underlying meaning of dropping event is different from the one of blocking event. On one hand, the dropping event indicates a
fact that the SU failed in attempting spectrum handoff from one available channel to another one. Hence, it may occur only in multiple-channel case. On the other hand, the blocking event means that the SU can not access any available channel to transmit data. Therefore, it may occur in either single-channel case or multiple-channel case CRN. Detailed statistical analysis of both blocking and dropping events of SUs in CRNs are presented in chapters 4, 5 and 6 and 7.

**Proactive channel access**

There are two typical strategies for SUs to do spectrum handoff under the time-slotted transmission scheme. They are the *passive-based* and the *proactive-based* strategies. By passive strategy, we mean that the SU performs the spectrum handoff only when the channel occupancy by PUs is detected.

In the proactive-based strategy, the SU may carry out the spectrum handoff in any time slot even when there is no interruption by PUs. This strategy is also called proactive channel access [52]. Specifically, the SU first identifies the available channels during the sensing phase in each time slot. It also predicts the future channel availability of these available channels according to the historical statistics of the PUs transmission activity. The SU selects then the best channel, which has the smallest possibility of being occupied by PUs in the near future. As a result, the SU is capable of keeping the data transmission over the best channels within a long time period\(^4\).

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\(^4\)Different available channels may be selected as the best channel in different time slot.
2.2 Network Topologies

In this section, we consider more general CRN systems, where multiple SUs exist and share multiple channels with PUs. The transmission activity of these SUs is more complex than in the single SU case. This is because different SUs may have various responsibilities in the transmission process\(^5\), which particularly rely on the CRN topologies.

Naturally, establishing a suitable CRN topology is equivalent to making an effective management of network entities, so that the viable transmission model for SUs can be fulfilled. Examples of network entities in CRNs are PUs, SUs, licensed channels. In the following, four typical CRN topologies are studied. They are the infrastructure based CRNs, the CR cellular networks, the CR ad-hoc networks and the CR mesh networks.

2.2.1 Infrastructure Based Cognitive Radio Networks

In an infrastructure based CRN, the transmission activities of PUs and SUs are usually managed by two central nodes, respectively. Each of them can be like, e.g., a base station, an access point. Simply put, these two central nodes are called Primary Central Coordinator (PCC) and Secondary Central Coordinator (SCC) for PUs and SUs, respectively.

The deployment of PCC and SCC depends on the practical networking implementation. For instance, both PCC and SCC can be integrated together, or they can be deployed independently from each other (so-called separated deployment), as shown in Figure 2.6. On one hand, if PCC and

\(^5\)For instance, in centralized CRNs, a SU may transmit/receive signalling messages or real-time traffic. In distributed CRNs, a SU may either take a role as data transmitter/receiver or serve as a relay node.
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SCC are integrated together, their radio ranges may be totally overlapped. In this case, the channel availabilities are spatial invariant for all SUs within the radio range of SCC. Namely, at a particular time moment, there may exist a particular set of available channels, which is the subset of all licensed channels. This particular set of available channels is the same for every SU at that particular time moment. On the other hand, if PCC and SCC are deployed independently from each other, the channel availabilities may be spatial-varying at different SU sides.

To communicate with PCC and SCC, PUs and SUs need to be located within their radio ranges, respectively. The communication between the PUs and PCC exclusively operates over a set of licensed channels, and it can be done with respect to the traditional wireless technologies (like, e.g., IEEE 802.11, FDMA/TDMA). For SCC, it is responsible for collecting the information about channel availabilities for SUs. The collection can be done

Figure 2.6: In both deployments, two PUs $a$ and $b$ use two channels 1 and 2, respectively. Therefore, in the separated deployment, channel 1 is not available for SU $x$ as interfering to PU $a$, but it is available for SU $y$ due to no interference with PU $a$. 
by using two different solution approaches. The first solution approach is to perform spectrum sensing at the SCC side. Since the SCC may have no hardware/software limitations, its sensing results are more accurate than the ones obtained at the SU side [30]. The second solution approach is that the SCC exchanges the statistical information about the PUs transmission activity with the PCC.

Once the SCC obtains a set of available channels⁶, it has two main responsibilities as follows:

- **Communicating with SUs**: the data transmission between SUs and SCC can be classified in two categories, as *signalling communication* and *data-oriented communication*. On one hand, the signalling communication consists of several different actions like, e.g., a SU registers the channel access at the SCC side, a SU requests an available channel from SCC, SCC allocates available channels to different SUs, SCC informs a SU to leave a channel due to the PU’s return. The signalling communication can be done over a dedicated Common Control Channel (CCC) that is reserved for all SUs [13, 14]. On the other hand, once a particular SU is assigned with an available channel, this particular SU can transmit/receive the data to/from SCC over this particular channel, the so-called data-oriented communication.

- **Performing spectrum decision**: SCC carries out this action when it receives the channel request from a particular SU. The goal of this action is to select the best channel for the particular SU with respect to its QoS requirement. If a PU returns to a channel that is previously allocated to the particular SU, SCC needs to inform this particular SU to leave the channel. The goal is to protect the PUs transmission. In

⁶By collecting the information about channel availabilities at SCC, this can be considered as the function of database supporting.
order to keep the ongoing data transmission, the particular SU needs to do the spectrum handoff by requesting another available channel from SCC.

2.2.2 Cognitive Radio Cellular Networks

The main difference between classic cellular networks and Cognitive Radio Cellular Networks (CRCNs) is in the support of CR technology in CRCNs. Such support opens for a promising strategy to resolve the exponential data traffic growth in the current cellular network [67].

IEEE 802.22

Today, a practical solution to the implementation of CRCNs is given by the first CR standard IEEE 802.22 [9], which is primarily designed to use CR technology in rural broadband wireless access. In this standard, three mechanisms are used for protecting the licensed data transmission. They are the spectrum sensing based solution, the database based solution and the specially designed beacon based solution. However, since IEEE 802.22 operates in the TV Whitespace 54-862 MHz, the geographical locations of PUs in IEEE 802.22 based CRCNs are usually fixed. Therefore, in this thesis we consider a more general network topology of CRCNs, where both PUs and SUs show mobility behavior.

Cognitive radio cells

As shown in the example in Figure 2.7, CRCNs consist typically of three different types of entities, namely, the Base Station (BS), the licensed channels and the users of type PU and SU. The wireless access for users is provided
by multiple BSs. Each BS has an identical radio range that covers a limited area, the so-called CR cell. In other words, a CR cell can be considered as a single infrastructure based CRN.

![Network Topology of CR Cellular Networks](image)

**Figure 2.7:** Example of network topology of CR cellular networks.

In each particular CR cell, the data transmissions of users go through a BS located in the particular cell. Further, the BS adopts the Fixed Channel Assignment (FCA) strategy to manage licensed channels, which means that a prescribed set of channels is allocated to the BS. To avoid the radio interference among different CR cells, two neighboring CR cells usually use different sets of channels. Moreover, the channel availabilities in each CR cell are spatially invariant for all SUs within the particular cell.

Several fundamental research problems that need to be resolved in CR-CNs are regarding, e.g., the identification of channel availability, the protection of the PUs transmission. The study on CRCNs is further complicated by the presence of mobility behavior of users, which is associated with individual users (i.e., either PUs or SUs).
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Handover procedure

Similar to the situation existent in classical cellular networks (where only PUs exist), an user in CRCNs shows a mobility behavior. Meaning, it may move across the boundary of a source cell to a neighboring target cell, as shown in Figure 2.8. In this case, if the data transmission of the particular user is in progress, the wireless (access) service needs to be handed over from the source cell to the target cell. The user must release in this case the used channel and the associated resources in the source cell and, at the same time, requires an idle channel in the target cell. Such procedure of switching channels between two neighboring cells is called inter-cell handover.

![Figure 2.8](image)

**Figure 2.8:** Example of the SU’s handover procedure: a SU is moving from cell x to cell y, while releasing channel 1 to BS x and requiring channel 4 from BS y.

Intra-handoff and inter-handoff

In CRCNs, the handover procedure regards both PUs and SUs. It also results in the switching of data transmission between different channels,
which has the same consequence as the successful spectrum handoff of SUs. To differentiate between the two concepts *spectrum handoff* and *handover procedure*, we use two new denotations *intra-handoff* and *inter-handoff*:

- **Intra-handoff**: means that the switching of data transmission in different channels is done only by SUs within the same cell.

- **Inter-handoff**: means that the switching of data transmission in different channels is done by an user (either a PU or a SU) when it performs the handover procedure from a source cell to a neighboring target cell.

The actions of the intra- and inter-handoff of SUs have prompted the development of two important functions in the design of CRCNs. The first function is to deal with the channel sharing between PUs and SUs in each CR cell. The second function is connected with the mechanism of allocating available channels not only to the SUs initially located within a CR cell, but also to the SUs handed over from its neighboring CR cells. These two functions are further studied in detail in Chapter 4.

### 2.2.3 Cognitive Radio Ad-Hoc Networks

Basically, a CRN is composed of two networking systems, namely, a primary network and a secondary network. They are associated with the PUs and SUs, respectively. In the following, the denotation Cognitive Radio Ad-Hoc Networks (CRAHNs) means that the secondary network topology is ad-hoc based, while the primary network is considered to be either infrastructure based or ad-hoc based.
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Relay node

Usually, there is no central node deployed in CRAHNs to manage the transmission activities of SUs. Therefore, the data transmission between two SUs usually needs other SUs serving as relay nodes, the so-called relay SUs.

![Diagram of data transmission between source and destination SUs](image)

**Figure 2.9:** Data transmission between the source and destination SUs in CR ad-hoc networks.

As shown in Figure 2.9, the data transmission from a source SU to a destination SUs operates in a multiple-hop manner. Each hop indicates the transmission between two neighboring SUs\(^7\). Subsequently, supporting the data transmission between two SUs in CRAHNs is equivalent to establishing an available end-to-end (e2e) routing path through multiple relay SUs.

\(^7\)Differing from the concept of neighboring CR cells in CRCNs, two neighboring SUs mean that they are located close to each other. Therefore, they can perceive the radio signal from each other.
2.2. NETWORK TOPOLOGIES

Channel identification

Given a particular e2e routing path between two SUs in a CRAHN, one critical task is to identify the channel availability along this routing path. Two related characteristics are described below:

- **Hop by hop based**: the identification of channel availability needs to be carried out at every relay SU along the routing path. This is mainly because the primary network may have diverse topologies at different geographical areas within the CRAHN. Therefore, the channel availability is usually spatial-varying for different SUs. This means that, if the spectrum sensing performed by multiple SUs is perfect, they may obtain different sets of available channels at the same time moment.

- **Affected by mobility behavior**: similar to the classical ad-hoc networks, a relay SU along the particular e2e routing path may show mobility behavior. As a consequence, this relay SU may become unavailable for providing the relay service, so that the particular e2e routing path needs to be re-established.

2.2.4 Cognitive Radio Mesh Networks

Today’s rapid growth of Internet services raises the need of ubiquitous access for end users over wireless networks. A feasible solution is the Wireless Mesh Network (WMN) based framework. In this framework, the conventional cellular network is evolved into the multi-hop based sub-cellular networks, each of which is served by a Mesh Router (MR). Due to the traditional policy of static frequency allocation, most WMNs are designed to operate in the unlicensed spectrum. To improve the spectrum utiliza-
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tion, the CR technology is suggested for the WMN, the so-called Cognitive Radio Mesh Network (CRMN) [34]. With CR, both MRs and SUs can opportunistically access the available licensed channels being vacated by PUs\textsuperscript{8}.

![Diagram of CR mesh networks]

\textbf{Figure 2.10:} Example of network topology of CR mesh networks. The dashed circle indicates the radio range of PU network.

\section*{Gateway router}

An example of a CRMN is shown in Figure 2.10. In this CRMN, there are several MRs, which are located within the radio range of a primary network. These MRs are not directly connected to the Internet. Therefore, the transmission between two neighboring MRs\textsuperscript{9} need to operate in a single-hop ad-hoc manner. To supply the Internet service to MRs, a special type

\textsuperscript{8}Similar to CRAHNs, the network topologies of the primary and secondary networks are also separately considered, and only the secondary network is considered to be mesh network based.

\textsuperscript{9}By neighboring, we mean that they can perceive the radio signal from each other.
of router called Gateway Router (GR) is deployed in the CRMN. The GR is typically connected to the Internet, and it can provide wireless access to its neighboring MRs.

Given a particular MR in CRMNs, a set of SUs, which are located with its radio range, are associated with it. If these SUs want to transmit or to receive data through the Internet, they need to establish an e2e routing path\(^{10}\) from this particular MR to a GR. This particular MR is called source MR. The available e2e routing path may consist of several other MRs, which serve as relay nodes, the so-called relay MRs. Differing from the CRAHNs, the geographical locations of relay MRs are usually fixed in CRMNs. In other words, there is no mobility behavior associated with the relay MRs in CRMNs.

**Routing availability**

As shown in Figure 2.11, for an established e2e routing path in CRMNs, its availability for SUs relies on the routing availability of each MR along the whole path.

For every MR, its routing availability indicates a status of whether or not it can support the e2e data transmission between the SUs and the GR. The identification of routing availability is a complex task, because it needs to consider the transmission activities of both PUs and SUs.

For simplicity purposes, three assumptions are adopted: i) the PU network topology is infrastructure based, ii) each MR provides a set of channels to SUs, and iii) two neighboring MRs have different sets of channels. The routing availability of a particular MR is described as:

\(^{10}\)Similar to CRAHNs, an available e2e routing path indicates that the SUs can transmit data over this path under the protection mechanism of PUs.
When all channels in CRMNs are occupied by PUs, there is no available channel for the particular MR to communicate with its neighbouring MRs and the SUs associated with it.

If the particular MR is a source MR, then: i) if all channels provided by it are occupied by PUs, the ongoing data transmission of SUs are dropped and the new data transmission of SUs are blocked, and ii) if these channels are fully used by the PUs and SUs, the new data transmission of SUs are blocked.

If the particular MR is a relay MR, then: if all channels provided by it are occupied by PUs, its relay service is stopped. Otherwise, i) if the ongoing relayed data transmission of a SU is interrupted by PUs, this SU attempts the spectrum handoff, and ii) if the spectrum handoff is unsuccessful, the SU tries to find another relay MR to replace the particular MR.
2.3 Competition in Heterogenous Cognitive Radio Networks

The above mentioned models of CR transmission and CRN topologies indicate that the development of heterogenous CRNs is an important and complicated research task. In this section, the study is focused on alleviating the limitation of previously reported research efforts, due to the limited consideration of resolving the competition problem of SUs in heterogenous CRNs. Accordingly, a competition example is described as follows.

2.3.1 Competition Example

Given a set of SUs and another set of available channels in CRNs, solving the competition problem of SUs refers to how to solve the efficient channel allocation to multiple SUs when they share the same available channels. As an example shown in Figure 2.12, we consider a simple CRCN system to address the competition problem of SUs.

![Figure 2.12: Example of competition in CR cellular networks.](image)

In the figure, the CRCN system consists of two neighboring CR cells,
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denoted by $C_x$ and $C_y$. The two BSs $B_x$ and $B_y$ are deployed in these two cells, respectively. These two BSs concurrently cope with the data transmissions of PUs and SUs.

In the system, there are three SUs $S_a$, $S_b$ and $S_c$. In particular, two SUs $S_a$ and $S_b$ are assumed to statically stay within the two cells $C_x$ and $C_y$, respectively. While, the third SU $S_c$ is assumed to move from cell $C_x$ to cell $C_y$. When SU $S_c$ is moving, it is also assumed to have two different types of traffics transmitted through the BSs. They are the real-time traffic (e.g., voice streaming) and the non-real-time traffic (e.g., file downloading). The competitions among these three SUs are described blow:

- When SU $S_c$ stays within cell $C_x$, it may compete with SU $S_a$ for the channel allocation at the BS $B_x$ side. Since they are located in the same CR cell, they have equal priority to obtain an available channel from BS $B_x$.

- When SU $S_c$ is moving across the overlapping area of two cells, the inter-handoff from BS $B_x$ to BS $B_y$ occurs. In this case, if SU $S_b$ has an ongoing data transmission with BS $B_y$, both two SUs $S_b$ and $S_c$ may compete for the channel allocation at the BS $B_y$ side. Typically, by comparing the blocking of the traffic of SU $S_b$, the blocking of the inter-handoff traffic of SU $S_c$ may have more impact on the system performance from mobile user point of view [10, 64]. Therefore, SU $S_c$ should have higher priority than SU $S_b$ for channel allocation at the BS $B_y$ side.

- Since SU $S_c$ simultaneously copes with both real-time and non-real-time traffics, these two types of traffics may compete for the medium access of the channel allocated to SU $S_c$. Such competition exists when SU $S_c$ stays within either cell $C_x$ or cell $C_y$. Usually, due to
2.3. COMPETITION IN HETEROGENEOUS COGNITIVE RADIO NETWORKS

the high demand on QoS performance, the real-time traffic should be given priority over the non-real-time traffic.

2.3.2 Prioritized Spectrum Access

Based on the above competition example, we classify the competition problem of SUs in two categories: the channel allocation based competition and the medium access based competition. This classification is determined in accordance with the type of competitors (i.e., either the SU users or the SU traffic) during the competition process. Ultimately, the motivation comes down to assigning different priorities to different competitors. For the same type of competitors, if a particular competitor is given priority over others, its request for channel access is regarded as more important than the requests of others. Accordingly, its associated data transmission over an allocated channel is called prioritized spectrum access.

Priority scheduling

To support the prioritized spectrum access of SUs in CRNs, a feasible solution is given by priority scheduling. By this, we mean a group of schemes that give the prescribed priorities to individual competitors, the so-called priority schemes. By recalling the classical wireless networks, there are two typical priority schemes. They are the channel reservation based priority scheme and the queueing buffer based priority scheme [64,65].

For instance, in [64], the authors suggested a loss-system based queueing model for classical cellular networks. They further used the channel reservation based priority scheme to reduce the blocking probability of inter-handoff traffic. In [65], the queueing buffer based priority scheme
CHAPTER 2. CHARACTERISTICS OF HETEROGENEOUS COGNITIVE RADIO NETWORKS

was discussed. By this, the authors introduced a finite queueing buffer to save only inter-handoff traffic when all channels in the target cell are busy.

Several studies on priority scheduling in CRNs has been reported in recent literature. For example, the authors of [61] considered an infrastructure based CRN, where the SUs are categorised as low- and high-priority classes. They adopted the channel reservation based priority scheme to manage the data transmission of these two different SU classes. The goal was to accommodate more high-priority SUs ahead of low-priority ones when they simultaneously attempt spectrum handoff. In a previous work [57], a loss-system based queueing model was suggested for CRCNs. The channel reservation based priority scheme to manage the inter-handoff SU traffic was adopted as well.

Other solutions

To solve the competition problem of SUs in CRNs, several other solution approaches have been advanced like, e.g., Markov chain based perdition, game theoretic modelling [20,26,27].

In [20], the authors suggested a forecasting strategy for SUs. In this strategy, the transmission activities of PUs and SUs were first assumed to follow a continuous-time Markov chain model. A Kalman filter approach was developed to estimate the number of SUs on a particular channel. The estimation was based on the power level measurements performed at each SU side. It was further used to determine whether or not the particular channel was overcrowded with SUs. The determination results can help SUs to predict the future channel utilization.

In [26], the authors provided an overview of game theoretic modelling of CRN. Specifically, they presented a comprehensive explanation on how the
game theory can be used in designing spectrum sharing protocols. They also presented the corresponding state-of-the-art research contributions on CRNs with emphasis on four scenarios, i.e., non-cooperative spectrum sharing, spectrum trading and mechanism design, cooperative spectrum sharing, and stochastic spectrum sharing games. In [27], the authors reported the application of game theory to the research on IEEE 802.22-based CRNs. They suggested a hierarchical spectrum trading model to analyze the interaction among service providers (e.g., base stations), PUs and SUs. They also proposed a joint spectrum bidding and service pricing model for service providers to maximize their profits.

Naturally, both the Markov chains based prediction and the game theoretic modelling are complicated in numerical analysis and practical implementation for CRNs. This is mainly due to the high time complexity of the associated algorithms, e.g., prediction, trading and bidding in games.

**2.3.3 Solution Adopted**

In this PhD thesis, the priority scheduling based solution is adopted to alleviate the competition problem of SUs in heterogeneous CRNs. Compared with other solution approaches, the priority scheduling has several advantages like, e.g., ease of implementation, efficiency of control. The detailed solution approach is described as follows.

**Software framework**

Given the heterogeneity aspects of CRNs, they may affect the effectiveness of the priority scheduling on the transmission performance of SUs. This is because the data transmission of SUs depends on the specific CR trans-
mission model and the particular network topologies. Subsequently, the priority scheduling based solution needs to be flexible in adapting to the heterogeneity aspects of CRNs. To provide such flexibility, we suggest a new software framework, which is called PRioritized Opportunistic spectrum Access System (PROAS).

In PROAS, the priority scheduling is integrated together with an intelligent spectrum decision strategy. This strategy takes into account various parameters related to the heterogeneous aspects of CRNs. PROAS also includes several other modules used for scientific investigations on CRNs. These modules are the queueing theory based modelling, the numerical analysis and experimental simulations for performance evaluation. The detailed description of features and structure of PROAS are presented in Chapter 3. By using PROAS, four particular case studies are presented in Chapters 4, 5, 6 and 7. The reported results show that PROAS has the ability to bridge the gap between research results and the practical implementation of CRNs.

Case studies

In Chapter 4, a CR cellular network is considered, where the queueing buffer based priority scheme is used to give priority to inter-handoff SU traffic. The transmission performance of SUs is studied by using Markov chains based modelling approach. A fuzzy-logic based hybrid decision making algorithm is suggested to select the best solution for inter-handoff prioritization. The goal is to optimize the transmission performance of SUs by leveraging their requirements on service-completion throughput and waiting time in the queue.

In Chapter 5, a single-hop based data transmission is considered be-
Summary

The OSA based CR transmission model has been described. Accordingly, four particular CRN topologies have been studied. Further, the competition between two SUs by sharing a licensed channel with PUs. The medium access based competition among different types of SU traffics is presented, and a queueing buffer based priority scheme is suggested for them. This scheme also takes into consideration the factor of imperfect spectrum sensing performed at the SU side. Based on these, a two-stage parallel server, i.e., a $M/H_2/1$, based queueing model is developed to study the transmission performance of SUs.

In Chapter 6, a CR mesh network is considered, where the SU traffic (in terms of multiple packets) may be blocked by mesh routers due to the hardware limitation. Since this blocking event further creates packet retransmission from the source SU, the QoS performance of the whole e2e routing path may degrade. To solve this problem, a queueing buffer based priority scheme is suggested. By using this scheme, the mesh routers can accept the relayed SU packets with higher priority than other types of packets. The uplink e2e transmission performance of SUs is studied under both the suggested priority scheme and the imperfect spectrum sensing.

Additionally, there exists a particular case for both channel allocation and medium access based competition of SUs. That is, for the same type of SU competitors, they may have equal priority among each other for data transmission. In this particular case, either fair channel allocation for the SU users or fair medium access for the SU traffics is an intuitively desirable property of CRNs. Therefore, in Chapter 7 a fuzzy-logic based solution is suggested to support CRNs to fairly server the SU competitors.
CHAPTER 2. CHARACTERISTICS OF HETEROGENEOUS COGNITIVE RADIO NETWORKS

problem of SUs in CRNs has been presented, and the need of carrying out priority scheduling has been addressed. Based on these, a new software framework PRioritized Opportunistic spectrum Access System (PROAS) has been suggested. This software framework can provide flexible priority scheduling to heterogenous CRNs. The goal is to alleviate the competition problem of SUs in heterogeneous CR networks.
In heterogeneous CR networks, there are three preliminary requirements for SUs to do prioritized spectrum access. These are: dealing with the heterogeneity aspects of CR networks, providing SUs with priority scheduling, and helping SUs in doing spectrum decision. To meet these requirements, a software-based framework called PRIoritized Opportunistic spectrum Access System (PROAS) is suggested. In this chapter, the scientific design and practical implementation of PROAS are presented. A new spectrum decision strategy advanced in PROAS is also presented. The key idea of this strategy is to set up an uniform decision criterion for channel selection by using the mathematic tool fuzzy logic. The uniform decision criterion makes the spectrum decision maker be able to jointly consider various channel characterization parameters and to intelligently employ different decision making algorithms.
CHAPTER 3. SOFTWARE FRAMEWORK

3.1 Framework Design

From a scientific viewpoint, there are two important tasks in the design of PROAS. The first task is to identify a way that can scientifically represent the heterogeneity aspects of CRNs. Such a way should be practically implemented by software programming. The second task is to integrate the priority scheduling into the spectrum decision. The reason for doing this is because the priority scheduling is used by SUs to do channel selection, while the channel selection is eventually carried out by the spectrum decision maker\(^1\).

3.1.1 Representation of Heterogeneity Aspects

We consider the elements involved in doing CR based communication. By element, we mean an individual entity in CRNs, which can be, e.g., a PU, a SU, a channel, a CR network model, a decision making algorithm. As shown in Figure 3.1, we classify various elements in three sets: active unit, information base, and algorithm factory. The relationships among these three sets are shown in Figure 3.2(a).

- The active unit includes the mobile user, radio channel, CR transmission model and CR coordinator. The mobile users consists of two types, i.e., PUs and SUs. When PUs and SUs carry out the data transmission, the corresponding network topology can be organized in either ad-hoc based or infrastructure based manner. Accordingly, the channel availability for SUs can be either spatial invariant or spatially varying \([8]\). Furthermore, the CR coordinator indicates the

\(^1\)The spectrum decision maker can be deployed at every SU side, the central controller side, or at both SU and controller sides.
3.1. FRAMEWORK DESIGN

Figure 3.1: Classification of elements involved in CR communications.
function of allocating available channels to SUs, and it can be deployed in either centralization or decentralization way in CRNs. By centralization way, we mean the CR coordinator can be like a support node [13] or a SU base station [30]. By decentralization way, we mean the function of CR coordinator is carried out at every SU side, for instance, the CR ad-hoc networks.

(a) Triangle relationship

(b) Various decision making algorithms

Figure 3.2: Three sets involved in spectrum decision.

- The information base consists of two different parts, namely, the information content and the way of collecting information. On one hand, the information content is about the characteristics of CRNs. We further classify the information content in two categories. The first category is regarding the instant channel characterization, which is in terms of different parameters like, e.g., signal-to-noise ratio and channel bandwidth. The second category is regarding the statistical channel characterization, which is in terms of different parameters like, e.g., the average arrival and departure rates of PUs, the average
idle time on channels. On the other hand, the action of collecting information can be done through solutions like, e.g., spectrum sensing by SUs, information exchange among SUs, and collaborative sensing between SUs and base stations. For instance, a SU base station can periodically perform spectrum sensing, and it can broadcast the sensing results to SUs via a common control channel.

- The algorithm factory contains various algorithms used for doing spectrum decision. According to the related work presented in Section 1.3, several examples of decision making algorithms are shown in Figure 3.2(b). Notice that different algorithms may have different characteristic features. For instance, a key characteristic feature related to fuzzy logic is given by the fuzzy membership degree. Moreover, individual decision making algorithms may have respective decision criteria, each of which prescribes a way to judge which channel is most available for SUs. For example, from QoS and QoE point of view, we can define a decision criterion as the smallest delay between the SU transmitter and the SU receiver pair, the lowest energy consumed at a SU side, or the largest number of available channels provided by a SU base station.

Subsequently, the heterogeneity aspect of CR networks can be represented by the above described three sets and the triangle relationships among them (Figure 3.2(a)).

3.1.2 Integration of Priority Scheduling into Spectrum Decision

Subsection 3.1.1 indicates that the spectrum decision maker is faced with two important tasks. The first task is to choose one or more decision making
algorithms provided by the algorithm factory, and thus to process the characteristics (existent in the information base) with respect to corresponding decision criteria. The second task is to use the chosen algorithms to do decision making to select the most available channels. These two tasks are called information processing and decision making, respectively.

To integrate the priority schemes into the spectrum decision, we suggest a priority pool that includes several prescribed priority schemes. According to the specific transmission requirements of SUs, the spectrum decision maker can select the particular priority schemes from the priority pool and use them when doing channel selection. Based on this, we show in Figure 3.2(b) the integration mechanism of priority scheduling into spectrum decision in heterogeneous CR networks.

3.1.3 Scientific Functionalities

PROAS mainly has six scientific functionalities: spectrum decision, priority scheduling, learning and prediction, cooperation among SUs, queueing modelling approach, and CRN simulator. Short description of these functionalities is presented below.

Spectrum Decision

Spectrum decision is an important scientific functionality of PROAS. This is because of its crucial function of determining the most available channels for SUs to access. By using spectrum sensing and spectrum analysis, SUs can obtain information about the channel availability. The information can be either instant or statistical channel characterization in terms of different parameters. The parameter values can be collected by spectrum
3.1. FRAMEWORK DESIGN

decision maker, which further conducts channel selection by using various
decision making algorithms. The decision results provide SUs with the
most available channels. Detailed implementation of spectrum decision
functionality is presented in Section 3.3.

Priority Scheduling

The importance of priority scheduling for heterogeneous CRNs was ad-
dressed in Subsection 2.3.2. Two schemes are widely used for supporting
priority scheduling in classical wireless network systems. The first scheme
is associated with the channel reservation for data transmission with high
priority. The second scheme is based on using a finite queue to save the data
transmission with high priority. Both these schemes are adopted in PROAS
to help SUs in carrying out prioritized spectrum access. Further studies on
priority scheduling for heterogeneous CRNs are developed in Chapters 4, 5
and 6.

Learning and Prediction

To identify the channel availability, SUs need to observe different param-
eters of channels. Such observation is usually connected with actions like,
e.g., spectrum sensing, exchanging information with the SU base station.
However, the continuous observation is inefficient in terms of energy con-
sumption and hardware demanding. Therefore, the observation is usually
done on a periodic time basis, for instance, the time-slot based spectrum
sensing. By doing this, the observation results may however correspond
to partial characterization about CRN environment. To approach the full
knowledge of channel availability, we suggest the SUs to learn from his-
torical observation results. By using the learned knowledge, the decision
maker is capable of estimating in advance the channel availability in the near future. The corresponding estimation process is known as prediction.

Secondary Users Cooperation

In CRNs, the SUs can share the same information about the radio environment. When several SUs need the channel at the same time, a simple decision maker may lead to the same available channel. In this case, the multiple SUs likely compete for the channel utilization over a single channel. If a large number of SUs simultaneously use a particular channel, the channel may become overcrowded, and thus QoS performance for SUs degrades. Therefore, it is necessary that the SUs access different available channels as much as possible. Furthermore, to avoid SUs overcrowding in available channels, we suggest SUs to work in a cooperative manner. This means that the SUs need to exchange the information about channel utilization via the common control channel or by using signalling protocol based solutions [32]. As a result, SUs can behave in self-organizing manner to efficiently share the available channels.

Queueing Modelling

The particular spectrum decision strategy may affect the overall performance of the whole CRN system. Investigation of related performance characteristics is usually based upon theoretical analysis or simulation experiment. In PROAS, queueing modelling is used to carry out theoretical analysis. The considered queueing models are, e.g., m-server loss system, finite user-population system and finite queueing-buffer system. For instance, in Chapter 4 a queueing buffer based model is developed to study the performance of SUs prioritized spectrum access under the joint consid-
3.2 FEATURES AND STRUCTURE

operation of intra- and inter- spectrum handoff.

Cognitive Radio Network Simulator

To validate the numerical performance evaluation, a CRN simulator is developed to conduct experimental simulation. The simulator consists of two parts. The first part is regarding the definition and configuration of a particular CRN topology, together with relevant parameters. For instance, a particular CRN topology can be configured as an ad-hoc network, where the channel availability is spatially invariant for all SUs. Further, if the two-state free-busy model is used to model the transmission activity of PUs, relevant parameters are, e.g., the arrival rates of PUs. The second part is to simulate the dynamic behaviours of both PUs and SUs, and to deal with the interactions\(^2\) among PUs and SUs. To do this, the discrete-event based simulation is used in PROAS.

3.2 Features and Structure

On one hand, the aforementioned decision making algorithms and priority schemes lay the ground for researchers to develop heterogeneous CRNs. So far, most of suggested algorithms/schemes were designed to work independently from each other, and they were used for different research goals. On the other hand, recent research on CRNs concentrates on setting up practical CRN systems [13]. This raises two important questions for the practical development of PROAS:

\(^2\)The associated interactions among PUs and SUs can be, e.g., a PU accesses/releases a channel, a SU vacates a channel due to the channel occupancy by PUs.
CHAPTER 3. SOFTWARE FRAMEWORK

- Do we need to implement all suggested decision making algorithms and priority schemes, or instead to suggest new ones?

- If the newly suggested algorithms and schemes are evaluated to be useful for doing prioritized spectrum access, then how to easily make them applicable to the existent CRN systems?

These questions motivate us to develop PROAS with good compatibility for different PROAS users. Along with this research line, the features and structure of PROAS are presented in the following.

3.2.1 Features

The main features of PROAS are as follows:

- Setting up an uniform decision criterion. This is done by using Computational Intelligence (CI) techniques, such as Fuzzy Logic and Neural Network. Fuzzy Logic is considered because of the capability of dealing with various criteria for decision making purpose.

- Setting up an overlay manager. The overlay manager provides the PROAS users with several alternative CRN models, based on which the theoretical analysis, simulation evaluation and practical experiment can be done. Each model defines the types of elements in active units (see Figure 3.2(a)). For instance, a model can be defined as a decentralized CRN with spatially invariant channel availability, with using time-slotted transmission scheme. For a particular model, the overlay manager intelligently provides spectrum decision maker with different channel characterization parameters, suitable spectrum decision making algorithms and flexible priority schemes.
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- Provision of the Upper Application Programming Interface (UAPI). The UAPIs are platform-independent interfaces to PROAS users. In other words, the PROAS users can conveniently embed PROAS into their own research tasks called upper objectives. The upper objectives can be, e.g., simulation based study of CR networks, testbed setting up, performance evaluation, algorithm development.

- Provision of the Lower Application Programming Interface (LAPI). The LAPIs help PROAS users in updating old decision making algorithms and priority schemes existing in PROAS and adding new ones into PROAS. Once the new algorithms are added into PROAS, they are available for the use by all PROAS users. In particular, the updated and added algorithms can be evaluated by experiments or simulations on the basis of specific upper objectives. Therefore, the functionalities of PROAS for heterogeneous CRNs can be improved and extended.

3.2.2 Structure

We abstractly illustrate the structure of PROAS in Fig 3.3. In the figure, the components in the area of grey color compose the PROAS. The connections among these components are described below:

- The arrows of type (1) indicate that PROAS is applied to upper objectives like testbed development, simulation experiments.

- The arrows of type (2) indicate the process of doing spectrum decision. Specifically, the information about channel characterization

\[\text{3. The SDSS users can be, e.g., academic/industrial researchers.}\]

\[\text{4. For instance, the simulation experiments which are developed by using Network Simulator 2 (NS-2) [33].}\]
is first obtained by doing spectrum sensing and spectrum analysis. This information is then collected by PROAS. After the information collection, PROAS provides the selected channels to the upper objectives.

- The arrows of type (3) imply that new spectrum decision algorithms
and new priority schemes are added into the PROAS. The evaluation of these new algorithms and schemes can be done by the “Upper Objectives” with using PROAS.

• The arrows of type (4) show the internal functions of PROAS. For instance, the fuzzy logic module is responsible for processing all input information about channel characterization with respect to the uniform decision criterion. After doing this, the fuzzy logic module sends the processed information to the overlay decision maker. The overlay decision maker uses this processed information to do hybrid decision making based on different decision making algorithms. At the meantime, the priority scheduling is also carried out. Moreover, the communication between the fuzzy logic module and the overlay decision maker is bidirectional. This implies that the decision making inside PROAS is a self-learning process.

3.3 Spectrum Decision Strategy

In CRNs, different decision making algorithms may have different decision criteria. These decision criteria may provide different constraints to spectrum decision maker. Therefore, if multiple decision making algorithms are jointly taken into account, the spectrum decision becomes a multiple-constraint based decision making problem. Towards solving this problem, a three-dimension model is used to represent the channel characterization, and an overlay decision maker is constructed by using fuzzy logic and graph theory.
3.3.1 Channel Characterization

We consider a CRN with \( M \) radio channels denoted by \( c_1, c_2, ..., c_m, ..., c_M \). Every channel is assumed to be characterized by a number \( N \) of parameters, each with label of \( e_1, e_2, ..., e_N \), respectively. Further, these \( N \) parameters are assumed to be independent from each other.

Let \( a_{e_n}^{m}(t) \) denote the observed value of a specific characterization parameter \( e_n \) on channel \( c_m \) at time \( t \), where \( n \in \{1, 2, ..., N\} \) and \( m \in \{1, 2, ..., M\} \). At time \( t \), the characterization of \( M \) channels under \( N \) parameters can be represented by a matrix, denoted by \( A(t) \):

\[
A(t) = \begin{bmatrix}
a_{e_1}^1(t) & a_{e_2}^1(t) & \cdots & a_{e_N}^1(t) \\
a_{e_1}^2(t) & a_{e_2}^2(t) & \cdots & a_{e_N}^2(t) \\
\vdots & \vdots & \ddots & \vdots \\
a_{e_1}^m(t) & a_{e_2}^m(t) & \cdots & a_{e_N}^m(t) \\
\vdots & \vdots & \ddots & \vdots \\
a_{e_1}^M(t) & a_{e_2}^M(t) & \cdots & a_{e_N}^M(t)
\end{bmatrix}
\] (3.1)

The matrix \( A(t) \) is called the channel characterization at time \( t \). Furthermore, we assume that the observation of characterization parameters is done on a periodic time basis with uniform duration \( \delta \). We also assume that the observation starts at time point \( t_0 \) and ends at time point \( t_H \), where \( t_H \) and \( t_0 \) satisfy the equation:

\[
(t_H - t_0) = H \delta
\] (3.2)

Thus, we can obtain a set of channel characterization matrixes at discrete
time points \( \{t_0, t_1, ..., t_H\} \), which is expressed as:

\[
\{A(t_0), A(t_1), ..., A(t_H)\}
\]

(3.3)

For a particular parameter, we further assume that, for each channel, it keeps the same characterization during the time interval \([t_h; t_{h+1}]\), where \( h = 0, 1, 2, ..., H - 1 \). Subsequently, the characterization of \( M \) channels during the time period \([t_0; t_H]\) can be represented by a three-dimension model. The three dimensions are associated with three domains, namely, time, frequency (i.e., channels) and parameter. An example of modelling of five channels under multiple parameters such as PU channel occupancy, delay and bandwidth is illustrated in Figure 3.4.

Based on the channel characterization model, the spectrum decision maker deals with two main problems: learning from historical information

Figure 3.4: Modelling of channel characterization in interval \([t_0, t_H]\).
and doing decision making according to multiple constraints \[20, 56\]. The first problem can be dealt with by using algorithms like, e.g., Markov Chain based prediction approach, machine learning, neural network. Furthermore, the learned knowledge can be considered as one kind of characterization parameter as well. The second problem requires an overlay decision maker that acts on various characterization parameters. Note that only the second problem is within the scope of this chapter.

To solve the second problem, we suggest a new decision making strategy by using the mathematic tool fuzzy logic [41]. This strategy is focused on setting up an uniform decision criterion, which helps the decision maker in integrating different parameter values together into a single value. For a particular channel, such integrated value numerically represents the channel availability for SUs. Further, the largest integrated value indicates the most available channel. The suggested spectrum decision strategy is presented in detail in the following.

### 3.3.2 Uniform Decision Criterion

Since different parameters may vary in distinct metrics and measures, this gives rise to a multiple-constraint based decision problem of finding the most available channel for SUs. Fuzzy-logic is suggested to solve this problem. We first introduce a parameter named as Fuzzy Channel Availability (FCA).

**Proposition:** *Fuzzy Channel Availability is a fuzzy-logic based parameter used to represent three different levels of channel availability for SUs. The three levels are respectively formalized as three fuzzy sets, namely, “high-level”, “medium-level” and “low-level” channel availabilities.*

The use of Fuzzy Channel Availability (FCA) is to map different types
of parameter values to an uniform type, i.e., fuzzy membership degree. Let $\sigma_{e_n}$ denote the set of all possible values by observing the parameter $e_n$ on all channels during a long time period. For the $m^{th}$ channel at time $t$, the observed value associated with the parameter $e_n$ is given by $a_{e_n}^m(t) \in \sigma_{e_n}$. By considering fuzzy set theory, we introduce a function $g_{e_n}$ acting as characteristic function of set $\sigma_{e_n}$. Specifically, $g_{e_n}$ is generalized to a membership function in such a way that, for every $a_{e_n}^m(t) \in \sigma_{e_n}$, we assign $g_{e_n}(a_{e_n}^m(t))$ a value from the unit interval $[0,1]$. 

For example, at time $t$, we define a fuzzy set $B$ that is determined by the set of pairs:

$$B = \{(a_{e_n}^m(t), g_{e_n}(a_{e_n}^m(t)))\}, \quad a_{e_n}^m(t) \in \sigma_{e_n}, \; g_{e_n}(a_{e_n}^m(t)) \in [0,1]$$  \hspace{1cm} (3.4)

where $g_{e_n}(a_{e_n}^m(t))$ is called the fuzzy membership degree that quantifies the grade of membership of $a_{e_n}^m(t)$ to $B$. For instance, the case of $g_{e_n}(a_{e_n}^m(t)) = 0$ means that $a_{e_n}^m(t)$ is not a member of $B$, whereas the case of $g_{e_n}(a_{e_n}^m(t)) = 1$ means that $a_{e_n}^m(t)$ is a full member of $B$. In addition, the case of $0 < g_{e_n}(a_{e_n}^m(t)) < 1$ implies that $a_{e_n}^m(t)$ belongs only partially to $B$.

### 3.3.3 Numerical Decision Factor

We adopt the notations $\alpha_{e_n}$, $\beta_{e_n}$, and $\gamma_{e_n}$ to denote three fuzzy sets “high-level”, “medium-level” and “low-level” under parameter $e_n$, respectively. Accordingly, their fuzzy membership functions are denoted by $g_{e_n}^{\alpha}$, $g_{e_n}^{\beta}$, and $g_{e_n}^{\gamma}$, respectively. For a given channel $c_m$ at time $t$, we have:

$$[FCA|e_n,m,t] = \{[\alpha_{e_n}|m,t], [\beta_{e_n}|m,t], [\gamma_{e_n}|m,t]\}$$  \hspace{1cm} (3.5)
where

\[
\begin{align*}
[\alpha_{em}|m,t] &= \{(a_{em}^m(t), g_{\alpha_{em}}(a_{em}^m(t)))\} \\
[\beta_{em}|m,t] &= \{(a_{em}^m(t), g_{\beta_{em}}(a_{em}^m(t)))\} \\
[\gamma_{em}|m,t] &= \{(a_{em}^m(t), g_{\gamma_{em}}(a_{em}^m(t)))\}
\end{align*}
\]  
(3.6)

and \(a_{em}^m(t) \in \sigma_{en}\), and the values of \(g_{\alpha_{em}}^a(a_{em}^m(t)), g_{\beta_{em}}^b(a_{em}^m(t))\) and \(g_{\gamma_{em}}^\gamma(a_{em}^m(t))\) are in the interval \([0.0,1.0]\) with regard to the equation (3.4).

In equation (3.6), \(g_{\alpha_{em}}^a(a_{em}^m(t)), g_{\beta_{em}}^b(a_{em}^m(t))\) and \(g_{\gamma_{em}}^\gamma(a_{em}^m(t))\) are called fuzzy membership degrees of \(a_{em}^m(t)\) to fuzzy sets \(\alpha_{en}, \beta_{en},\) and \(\gamma_{en}\), respectively. The three fuzzy membership degrees further form a vector:

\[
V_{em}^m(t) = (g_{\alpha_{em}}^a(a_{em}^m(t)), g_{\beta_{em}}^b(a_{em}^m(t)), g_{\gamma_{em}}^\gamma(a_{em}^m(t)))
\]  
(3.7)

We call \(V_{em}^m(t)\) the FCA-based characterization of the observed parameter \(e_{n}\) in channel \(c_{m}\) at time \(t\). Since \(V_{\sigma}(t)\) is a three-coordinate vector, it is not convenient to carry out the numerical computing regarding decision making. This has prompted the development of a method to compound three coordinates into a joint value referred to as the channel availability.

To obtain the joint value, we adopt a fuzzy-comparison based algorithm developed by Saaty [41]. The algorithm is based on using a paired-comparison of three fuzzy sets’ importance in deciding on which channel is most available.

Let \(\pi_\times, \pi_+,\) and \(\pi_-\) denote the importance of “high-level”, “medium-level”, and “low-level”, respectively. For example:

- Since high-level has strong importance over low-level, we assign \(\frac{\pi_\times}{\pi_-}\) with 5.
3.3. SPECTRUM DECISION STRATEGY

- Since high-level and medium-level respectively have stronger importance than medium-level and low-level, we assign both \( \frac{\pi_x}{\pi_+} + \frac{\pi_-}{\pi_-} \) with 3.

- Since high-level, medium-level, or low-level has equal importance over itself, we have \( \frac{\pi_x}{\pi_-} = \frac{\pi_+}{\pi_-} = \frac{\pi_-}{\pi_-} = 1 \).

Similar to [42], a fuzzy-comparison matrix, denoted by \( \Pi \), is obtained by:

\[
\Pi = \begin{bmatrix}
\frac{\pi_-}{\pi_-} & \frac{\pi_+}{\pi_-} & \frac{\pi_x}{\pi_-} \\
\frac{\pi_-}{\pi_+} & \frac{\pi_+}{\pi_+} & \frac{\pi_x}{\pi_+} \\
\frac{\pi_-}{\pi_x} & \frac{\pi_+}{\pi_x} & \frac{\pi_x}{\pi_x}
\end{bmatrix}
= \begin{bmatrix}
1 & 3 & 5 \\
1/3 & 1 & 3 \\
1/5 & 1/3 & 1
\end{bmatrix}
(3.8)
\]

The matrix \( \Pi \) is used to determine the numerical values of \( \pi_x, \pi_+ \), and \( \pi_- \), respectively. Given the eigen value \( \lambda \) and eigen vector \( \Omega \) of matrix \( \Pi \), they satisfy the eigen equation and characteristic equation as:

\[
\Pi \Omega = \lambda \Omega
\]
\[
det(\Pi - \lambda I) = 0
\]

where \( I \) is an unit matrix. The largest real eigen value corresponds to an eigen vector, denoted by \( \Omega^* \) and it is given by:

\[
\Omega^* = \{ \omega^*_x, \omega^*_+, \omega^*_- \} \simeq \{0.94, 0.31, 0.19\}
(3.10)
\]

where the three coordinates \( \omega^*_x \), \( \omega^*_+ \) and \( \omega^*_- \) are associated with \( \pi_x \), \( \pi_+ \) and \( \pi_- \), respectively.

Consequently, three coordinates of \( V_\sigma(t) \) can be composed in the term of a linear combination:

\[
\xi^m_{e_n}(t) = g^\alpha_{e_n}(a^m_{e_n}(t))\omega^*_x + g^\beta_{e_n}(a^m_{e_n}(t))\omega^*_+ + g^\gamma_{e_n}(a^m_{e_n}(t))\omega^*_-
(3.11)
\]
We call $\xi_{en}^m(t)$ the FCA-based decision factor of parameter $e_n$ on channel $c_m$ at time $t$. We can further compute different FCA-based decision factors $\xi_{e_1}^m(t), \xi_{e_2}^m(t), \ldots, \xi_{e_N}^m(t)$, which correspond to parameters $e_1, e_2, \ldots, e_N$, respectively.

### 3.3.4 Hybrid Decision Making

Although the computed FCA-based decision factors of different parameters have the same value type, their respective weights for doing decision making still need to be configured. Assume that every parameter $e_n \in \{e_1, e_2, \ldots, e_N\}$ can be assigned with a weight value $w_n$. A *weight vector*, denoted by $W$, is then given by:

$$W = (w_1, w_2, \ldots, w_n, \ldots, w_N) \quad (3.12)$$

where $n = 1, 2, \ldots, N$.

Moreover, let $\eta_m(t)$ denote the numerical channel availability (for SUs) of channel $c_m$ at time $t$. If the decision maker jointly takes into account the multiple parameters $e_1, e_2, \ldots, e_n$, $\eta_m(t)$ can be computed as:

$$\eta_m(t) = \xi_{e_1}^m(t)w_1 + \xi_{e_2}^m(t)w_2 + \ldots + \xi_{e_n}^m(t)w_n + \ldots + \xi_{e_N}^m(t)w_N \quad (3.13)$$

Therefore, the most available channel in this particular model is based on the decision with the largest value of $\eta_m(t)$, which is given by:

$$\eta_m^*(t) = \max\{\eta_1(t), \eta_2(t), \ldots, \eta_M(t)\} \quad (3.14)$$

where $m = 1, 2, \ldots, M$. 

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3.4 Summary

A new software framework PRioritized Opportunistic spectrum Access System (PROAS) has been described. The goal of PROAS is to provide priority scheduling to SUs in heterogenous CRNs, so that the competition among these SUs for the utilization of spectrum resources (i.e., channels) can be alleviated. The framework design, features and structure of PROAS have been described. Based on these elements, an intelligent spectrum decision strategy has been advanced in PROAS. The detailed decision making algorithm in this strategy has been presented. In specific, a new parameter called Fuzzy Channel Availability (FCA) was introduced from the fuzzy logic point of view. By using FCA, different types of channel characterization parameters were mapped into an uniform type. For each channel, the corresponding parameters values can be integrated into a joint value, such that the most available channel is determined by the largest joint value.
CHAPTER 3. SOFTWARE FRAMEWORK
Chapter 4

Case Study I: Cognitive Radio Cellular Networks

In this chapter, the Cognitive Radio Cellular Networks (CRCNs) base model is considered, where a mobile user with a call in progress shows mobility behavior of moving across different CR cells. In this model, the particular CR cell is assumed to give priority to inter-handoff calls over the calls originating within it. A finite queue is used in every cell for SUs and a fixed number of queueing slots are reserved for the inter-handoff SU calls. With these considerations, the transmission performance of SUs is studied by using Markov chains based modelling approach. The numerical analysis is validated by simulation experiments. A fuzzy-logic based hybrid decision making algorithm is suggested to select the best solution for inter-handoff prioritization. The goal is to optimize the transmission performance of SUs by leveraging their requirements on service-completion throughput and waiting time in the CR cell.
CHAPTER 4. CASE STUDY I: COGNITIVE RADIO CELLULAR NETWORKS

4.1 Introduction

As described in Section 2.2.2, the main difference between classic cellular networks and CRCNs is given by the support of CR technology in CRCNs. While, similar to classic cellular networks, a mobile user (either a PU or a SU) in CRCNs also shows mobility behavior. If this particular user has a call in progress\(^1\), an inter-handoff event occurs for the case of moving across the boundary of a source cell to a neighboring target cell.

The challenge of SUs inter-handoff in CRCNs was discussed in [67], where SUs intra-handoff and inter-handoff were referred to as intra-cell spectrum mobility and inter-cell user mobility. The authors also suggested a new network architecture to support spectrum/user mobility management. However, they did not consider the effects of the PUs inter-handoff activity and the inter-handoff priority scheme on the SUs transmission performance.

Due to the highly complicated dynamics in CRNs, the Markov chains based modelling is widely used in recent literature. For instance, in [54, 55, 59–61], the authors suggested various Continuous Time Markov Chains (CTMC) based queueing models to study the transmission performance of SUs in infrastructure based CRNs. They adopted a channel model based on which the licensed spectrum was divided into several frequency bands and every band was further divided into identical number of sub-bands. All bands are exclusively reserved as data transmission channels for PUs. All sub-bands in the bands not occupied by PUs are available as data transmission channels for SUs. When a newly arrived PU occupies a band, all SUs in the same band are dropped and they attempt the intra-handoff to access other available sub-bands.

---

\(^1\)By a call, we mean the data transmission between an user and the base station through a channel within a CR cell.
Moreover, in [54, 55] the authors reported a loss-system based queueing model for the study of SU intra-handoff in CRNs. In this model, a newly arrived PU call is blocked if all bands are being used by PU calls, and a newly arrived SU call is blocked if all bands are being used by both PU and SU calls. In [59], a finite buffer was employed to queue a newly arrived SU call when there is no available sub-band for this call. The goal was to decrease the blocking probability of SU calls. The authors also studied the SUs transmission performance in terms of service-completion throughput and average queueing time in the buffer. However, the authors did not study the performance optimization based on these two parameters. In [60], a finite user population was assumed for PUs and SUs, respectively. The authors of [61] also studied a loss queueing system. They further categorized the SU calls into low- and high-priority classes. The goal was to accommodate more high-priority SUs ahead of low-priority ones when SUs intra-handoff occurs.

Although the above-mentioned studies provide solid investigations on CRNs, their focus is generally laid on individual research topics, like, e.g., priority scheduling in classical cellular networks, inter-handoff activity of SUs in CRCNs, intra-handoff activity of SUs in infrastructure based CRNs, queueing modelling of CRNs. In this chapter, a comprehensive study on the handover procedure in CRCNs is reported, by jointly taking into consideration the relevant research topics altogether. A fuzzy-logic based optimization strategy is also suggested for the configuration of optimal priority scheduling in CRCNs. To the best of our knowledge, there are few investigations so far along with this research line.
4.2 System Model

By recalling Section 2.2.2, a general CRCN system is considered in the study, where both PUs and SUs may move across different CR cells.

4.2.1 Channel Model

For each particular CR cell, the licensed spectrum is partitioned into \( m \) identical frequency bands and each band is divided into \( n \) identical sub-bands (Figure 4.1). Every band is reserved for one PU at a particular time, while every sub-band in the available bands can be used by one SU at a time. A PU band may accommodate more SU sub-bands. The consideration for the difference in frequency bands allocated to the PUs on one side and the SUs on the other side is as follows. PUs are paying subscribers whose expected QoS/QoE must be provided, whereas SUs are non-paying subscribers whose primary focus is on providing the access to the media and less on expected performance. It is therefore assumed that the SUs accept this model.

Moreover, the availabilities of \( nm \) sub-bands are assumed to be spatially invariant for all SUs in the particular CR cell. This means that the sub-band availability (i.e., PU being present or absent) at a time is the same at every SU [8]. A common control channel [13] is assumed to be used by the
base station for coordinating all mobile units in the CR cell.

4.2.2 Priority Model

In a CR cell, the BS has two important responsibilities. The first responsibility is to deal with the channel sharing between two categories of users, i.e., PUs and SUs. Naturally, PUs have higher priority in accessing resources (e.g., channels) than SUs. This is because of the need to protect the PUs transmission.

The second responsibility of the BS is to concurrently allocate the existent resources to three categories of calls\(^2\), as follows:

- **Initial calls**: these are the calls initially originated within the cell. They are associated with either PUs or SUs.

- **Intra-handoff calls**: theses are the calls attempting the intra-handoff due to the channel occupancy by PUs. They are associated with only SUs.

- **Inter-handoff calls**: these are the calls handed over from neighboring cells. They are associated with either PUs or SUs when carrying out the inter-handoff.

Clearly, the three categories of calls compete for the use of resources provided by the BS. For the same user type (i.e., either PUs or SUs), the competitions among their calls are presented in Table 4.1. They are as follows:

\(^2\)By a call, it means the data transmission between an user and the BS through a channel.
Table 4.1: Competition among different categories of calls.

<table>
<thead>
<tr>
<th>Competition</th>
<th>Involved user</th>
<th>Priority comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial vs Intra-handoff</td>
<td>Only SUs</td>
<td>Low - High</td>
</tr>
<tr>
<td>Initial vs Inter-handoff</td>
<td>PUs, or SUs</td>
<td>Low - High</td>
</tr>
<tr>
<td>Intra- vs Inter-handoff</td>
<td>Only SUs</td>
<td>Equal</td>
</tr>
</tbody>
</table>

- **Initial calls vs Intra-handoff calls**: this competition is associated with only SUs. Compared with the resource allocation to initial SU calls, allocating resources to intra-handoff SU calls during the call in progress demands for resource switching, with the consequence of higher influence on the user and system performance. Therefore, the intra-handoff SU calls should be given priority over the initial SU calls.

- **Initial calls vs Inter-handoff calls**: this competition is associated with either PUs or SUs. During the handover procedure, the inter-handoff calls require the CRCN system to maintain their ongoing data transmission. Similar to the consequence mentioned above, the inter-cell handoff calls should be also given priority in resource allocation over the initial SU calls.

- **Intra-handoff calls vs Inter-handoff calls**: this competition is associated with SUs only. For simplicity purposes, in this model both intra- and inter-handoff SU calls are assumed to have equal priority in resource allocation.

Subsequently, the suggested priority assignment\(^3\) is shown in Table 4.2, where more stars the particular call category has, the higher the priority

\(^3\)For some emergency calls like fire-alarm, the channel allocation may follow the prescribed rules, which are out of scope for the research focus.
Table 4.2: Priorities assigned to different categories of calls for the resource allocation in CRCNs.

<table>
<thead>
<tr>
<th>User</th>
<th>Initial</th>
<th>Intra-handoff</th>
<th>Inter-handoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
<td>⋆ ⋆ ⋆</td>
<td>Not applicable</td>
<td>⋆ ⋆ ⋆ ⋆</td>
</tr>
<tr>
<td>SU</td>
<td>⋆</td>
<td>⋆ ⋆</td>
<td>⋆ ⋆</td>
</tr>
</tbody>
</table>

for resource allocation is.

Moreover, different parameters are used in the modelling of a CR cell as indicated in Table 4.3. The PUs and SUs models are described as follows.

4.2.3 Primary User Model

In a CR cell, PUs can exclusively occupy the bands even when they are used by SUs. In other words, the SUs behavior does not affect the transmission performance of PUs. Hence, the performance characteristics of PUs in the presence of inter-handoff can be studied with respect to classical cellular networks. It is also important to study the effect of PUs inter-handoff on the transmission performance of SUs. Because of these, only the band reservation scheme for the inter-handoff PU calls is considered.

PU calls are assumed to arrive independently in Poisson streams at mean rates $\lambda_1$ and $\lambda_2$ for initial and for inter-handoff PUs, respectively. When an inter-handoff PU call arrives and at least one band is idle, the PU call is accepted and a band is allocated to it. Otherwise, the inter-handoff PU call is blocked. By an idle band we mean that there is no other PU using it, yet this band may be used by SUs. Similar to [64], a parameter $g$ is denominated as the number of reserved bands for inter-handoff PU calls.
### Table 4.3: Parameters used in the modelling of a CR Cell

<table>
<thead>
<tr>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>Number of identical bands in the licensed spectrum in the cell.</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of identical sub-bands in each band.</td>
</tr>
<tr>
<td>$g$</td>
<td>Number of reserved bands for inter-handoff PU calls.</td>
</tr>
<tr>
<td>$q$</td>
<td>Queue length, i.e, the maximum number of queueing places when the queue is empty.</td>
</tr>
<tr>
<td>$h$</td>
<td>Number of reserved queueing places for inter-handoff SU calls, $h &lt; q$.</td>
</tr>
<tr>
<td>$(i, j)$</td>
<td>A pair of values indicating a system state that $i$ connected SUs and $j$ ongoing PUs coexist in the cell.</td>
</tr>
<tr>
<td>$S$</td>
<td>System state space.</td>
</tr>
<tr>
<td>$\pi_{i,j}$</td>
<td>Steady-state probability of Markov state $(i, j)$.</td>
</tr>
<tr>
<td>$\lambda_1$</td>
<td>Mean arrival rate of initial PU calls to the cell.</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td>Mean arrival rate of inter-handoff PU calls to the cell.</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>Mean service-completion rate of PU calls in the cell.</td>
</tr>
<tr>
<td>$\mu_2$</td>
<td>Mean departure rate of PUs outgoing of the cell.</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>Mean arrival rate of initial SU calls to the cell.</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>Mean arrival rate of inter-handoff SU calls to the cell.</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>Mean service-completion rate of SU calls in the cell.</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>Mean departure rate of SUs outgoing of the cell.</td>
</tr>
<tr>
<td>$\bar{\lambda}_j$</td>
<td>Mean rate of accessing bands by PUs, depending on the values of $j$ and $g$.</td>
</tr>
<tr>
<td>$\bar{\mu}_j$</td>
<td>Mean rate of releasing bands by PUs, depending on the value of $j$.</td>
</tr>
<tr>
<td>$\bar{\gamma}_{i,j}$</td>
<td>Mean rate of accessing sub-bands by SUs, depending on the values of $i$, $j$, $g$, $h$, and $q$.</td>
</tr>
<tr>
<td>$\bar{\delta}_{i,j}$</td>
<td>Mean rate of releasing sub-bands by SUs, depending on the values of $i$, $j$ and $q$.</td>
</tr>
</tbody>
</table>
4.2. SYSTEM MODEL

When an initial PU call arrives, this is accepted when at least \((g + 1)\) bands are idle. Otherwise, the initial PU call is blocked. In the case of \(g > 0\), the system gives priority to inter-handoff PU calls. To avoid that initial PU calls are blocked altogether, \(g\) must be less than the total number of bands, i.e., \(g < m\).

Additionally, if a newly arrived PU call (for either initial or inter-handoff) is assigned a band for data transmission, the PU call is said to become an ongoing PU call. The time periods of ongoing PU calls completing service are assumed to be exponentially distributed with mean value \(1/\mu_1\) per band. While, the ongoing PU calls may do the inter-handoff activity, so that they leave the particular cell and are handed over to the neighboring cells. Simply put, such activity is also called departing from that particular CR cell. The departure of ongoing PU calls is assumed to follow an exponential distribution with mean rate \(\mu_2\).

4.2.4 Secondary User Model

As indicated in Figure 4.2, a finite queue with length \(q\) is introduced in the considered CR cell, which is used for two purposes. The first purpose is to queue the newly arrived SU calls when there are no idle sub-bands available for them. An idle sub-band means it is not used by other SUs and nor by PUs. The second purpose is to queue the dropped SU calls due to the band occupancy by PUs. Each idle queueing place in the queue can be used for a single SU call at a time.

As shown in Fig 4.3, the arrivals of SU calls are assumed to independently follow Poisson streams with mean rates \(\gamma_1\) and \(\gamma_2\) for initial and for inter-handoff SUs, respectively. When a new SU call (for either initial or inter-handoff) arrives and there is an idle sub-band available, this sub-band
is allocated to the particular SU call. Otherwise, the newly arrived SU call needs to be queued. Further, it is assumed that \( h \) out of \( q \) queueing slots are reserved for the inter-handoff SU calls. Hence, if at least one queueing place is idle, the newly arrived inter-handoff SU call is queued. Otherwise, the inter-handoff SU call is blocked. If the number of idle queueing slots is larger than \( h \), the newly arrived initial SU call is queued. Otherwise, the initial SU call is blocked. Moreover, if \( 0 < h < q \), the inter-handoff SU calls are prioritized and the initial SU calls are not blocked altogether to the queue. Simply put, a SU call using a sub-band for data transmission
is called ongoing SU call, and a SU call being queued is called queued SU call. A queued SU call needs to pause its data transmission until an idle sub-band becomes available. Both ongoing and queued SU calls are called connected SU calls, indicating that they are coordinated by the base station.

The time periods of ongoing SU calls completing service are assumed to be exponentially distributed with the mean value $1/\delta_1$ per sub-band. A SU with a connected call may depart from the CR cell and moves to a neighboring CR cell. The SU departure is assumed to follow the exponential distribution with mean rate $\delta_2$. An ongoing SU call may be dropped from
an available band due to a newly arrived PU call. This particular ongoing call is said to become a dropped SU call. If an idle sub-band is available in another band, the particular sub-band is allocated to the dropped SU call. Otherwise, the dropped SU call needs to be queued. The dropped SU calls are given the same priority as the inter-handoff SU calls. In other words, if the queue is not full, a dropped SU call can be queued. Otherwise, the particular dropped SU call is forced to be terminated.

4.3 Queueing Model

Based on the above described model of the CR cell system, a CTMC queueing model is built up. This model has three characteristics: system state, state transition and steady-state probability.

Let an integer pair \((i,j)\) denote a system state when \(i\) connected SU calls and \(j\) ongoing PU calls coexist in the system. The system state space is given by \(S = \{(i,j)\}\), where the values of \(i\) and \(j\) are constrained by \(i \in [0, nm + q], j \in [0, m]\) and \((i + nj) \in [0, nm + q]\).

4.3.1 State Transition

The state transition of the system is triggered by several activities. These are the PU’s activity, SU’s activity without interruption by PUs, and SU’s feedback in response to the band occupancy by PUs (Figure 4.2). Their models are as follows.

Primary user activity

PUs have three different activities:
4.3. QUEUEING MODEL

- A newly arrived PU occupies an idle band for either an initial or an inter-handoff PU call.

- PU releases the used band at the service completion.

- PU with an ongoing call departs from the cell and it releases the used band in that particular cell.

The first activity indicates the arrival of PU calls into the system. Both the second and the third activities indicate PU calls leaving the system.

For \( j \) ongoing PU calls in the system, we let \( \tilde{\lambda}_j \) and \( \tilde{\mu}_j \), denote the arrival and the leaving rates of PU calls, respectively. The value of \( \tilde{\lambda}_j \) depends on the four parameters \( j, \lambda_1, \lambda_2 \) and \( g \). The value of \( \tilde{\mu}_j \) depends on the three parameters \( j, \mu_1 \) and \( \mu_2 \). \( \tilde{\lambda}_j \) and \( \tilde{\mu}_j \) are given by:

\[
\tilde{\lambda}_j = \begin{cases} 
\lambda_1 + \lambda_2, & 0 \leq j \leq m - g - 1 \\
\lambda_2, & m - g \leq j < m \\
0, & \text{others}
\end{cases} \quad (4.1)
\]

\[
\tilde{\mu}_j = \begin{cases} 
 j(\mu_1 + \mu_2), & 0 < j \leq m \\
0, & \text{others}
\end{cases} \quad (4.2)
\]

Given that \( i \) connected SU calls and \( j \) ongoing PU calls are in the system, a newly arrived SU call is treated in four different ways:

- For \((i + nj) < nm\), a sub-band is allocated to the call for either initial or inter-handoff SU.

- For \(nm \leq (i + nj) < (mn + q - h)\), the call is queued for either initial or inter-handoff SU.
• For \((nm + q - h) \leq (i + n j) < (nm + q)\), if the call is related to an inter-handoff SU, this call is queued. Otherwise, the call is blocked.

• For \((i + n j) = (nm + q)\), the call is blocked for either initial or inter-handoff SU.

Similar to PUs, we let \(\tilde{\gamma}_{i,j}\) denote the arrival rate of SU calls into the system. The value of \(\tilde{\gamma}_{i,j}\) depends on the six parameters \(i, j, \gamma_1, \gamma_2, q\) and \(h\). Let \(\tilde{\delta}_{i,j}\) denote the leaving rate of SU calls from the system. If \((i + n j) \leq nm\), then all \(i\) connected SU calls are ongoing ones and they may leave the system because of either service-completion or departure. As such, their leaving rate is equal to \(i(\delta_1 + \delta_2)\). If \(nm < (i + n j) \leq (nm + q)\), there are \(n(m - j)\) ongoing SU calls and the rest of \([i - n(m - j)]\) connected SUs are queued. In this case, all \(i\) connected SU calls may leave the system due to departure, while only \(n(m - j)\) ongoing SU calls may leave the system due to service-completion. Subsequently, \(\tilde{\gamma}_{i,j}\) and \(\tilde{\delta}_{i,j}\) are given by:

\[
\tilde{\gamma}_{i,j} = \begin{cases} 
\gamma_1 + \gamma_2, & i + n j \leq nm + q - h - 1 \\
\gamma_2, & i + n j \in [nm + q - h, nm + q) \\
0, & \text{others}
\end{cases} \quad (4.3)
\]

\[
\tilde{\delta}_{i,j} = \begin{cases} 
i(\delta_1 + \delta_2), & i + n j \leq nm \\
n(m - j)\delta_1 + i\delta_2, & i + n j \in (nm, nm + q] \\
0, & \text{others}
\end{cases} \quad (4.4)
\]

Secondary user feedback in response to the band occupancy

Given the system at state \((i, j)\), where \((i, j) \in S\) and \(j < m\), a newly arrived PU call occupies a band. Let \(A_{i,j}\) denote the total number of sub-bands
4.3. QUEUEING MODEL

that are required by both PU and SU calls when the newly arrived PU has occupied the band. This is given by $A_{i,j} = i + n(j + 1)$, where $(i, j) \in S, j < m$. Because of the protection mechanism for PUs, all SUs in the newly occupied band are dropped from this band. Every dropped SU attempts the intra-handoff to maintain its ongoing call. The success in such attempt depends on the numbers of ongoing PU calls and connected SU calls in the system at state $(i, j)$ as follows:

- If $(i + n j) \leq (n m - n)$, then $A_{i,j} \leq n m$. This means that every dropped SU call can find a new idle sub-band. It is further assumed that a successful intra-handoff can be immediately accomplished by a dropped SU. As a result, the system changes state from $(i, j)$ to $(i, j + 1)$.

- If $(n m - n) < (i + n j) \leq (n m - n + q)$, where $0 < q < n$, we get $n m < A_{i,j} \leq (n m + q)$. In particular, $n m < A_{i,j}$ means that there are not enough idle sub-bands to be allocated to all dropped SU calls. Therefore, several of them have to be queued. Further, $A_{i,j} \leq (n m + q)$ means that there are enough queueing slots for the dropped SU calls, so that no dropped SU call needs to be terminated. Subsequently, the system state changes from $(i, j)$ to $(i, j + 1)$.

- If $(n m - n + q) < (i + n j) < (n m + q)$, we get $A_{i,j} > (n m + q)$. This indicates that the system becomes overloaded not only for allocating the new idle sub-bands to the dropped SU calls, but also for queueing the dropped SU calls. Therefore, several dropped SU calls are forced to be terminated. Let $B_{i,j}$ denote the number of terminated SU calls. This is given by $B_{i,j} = A_{i,j} - (n m + q) = i + n(j + 1 - m) - q$, where $B_{i,j} \in [1,n]$. The number of SU calls remaining in the system is given by $(i - B_{i,j}) = [n(m - j - 1) + q]$. A SU call that remains in the system can be either an ongoing call or a paused ongoing call that is queued.
CHAPTER 4. CASE STUDY I: COGNITIVE RADIO CELLULAR NETWORKS

As a consequence, the system changes the state from \((i, j)\) to \((n(m-j-1)+q, j+1)\).

4.3.2 Steady-State Probability

The system state diagram is shown in Fig 4.4, where \(\theta_{i,j}\) equals one if \(\{j \neq m, n(m-1)+q < (i+nj) \leq (nm+q)\}\) and zero if others. \(\phi_{i,j}\) equals one if \(\{i \neq 0, (i+nj) = (nm+q)\}\) and zero if others.

Let \(\pi_{i,j}\) denote the steady-state probability of state \((i, j)\). If \((i, j) \in S\), the value of \(\pi_{i,j}\) is in the value range \((0, 1.0)\). Otherwise, \(\pi_{i,j}\) is equal to zero. Further, the rate of transition flow into a state \((i, j)\) must be equal to the rate of transition flow out of this state.

For the four particular states \((0, 0)\), \((nm+q, 0)\), \((0, m)\) and \((nm+q, m)\), we have:

\[
\pi_{0,0}(\tilde{\gamma}_{0,0} + \tilde{\lambda}_{0}) = \pi_{1,0} \tilde{\delta}_{1,0} + \pi_{0,1} \tilde{\mu}_{0,1} \tag{4.5}
\]

\[
\pi_{nm+q,0}(\tilde{\delta}_{nm+q,0} + \tilde{\lambda}_{0}) = \pi_{nm+q-1,0} \tilde{\gamma}_{nm+q-1,0} \tag{4.6}
\]

\[
\pi_{0,m}(\tilde{\gamma}_{0,m} + \tilde{\mu}_{m}) = \pi_{0,m-1} \tilde{\delta}_{0,m-1} + \pi_{0,m-1} \tilde{\lambda}_{m-1} \tag{4.7}
\]

\[
\pi_{q,m}(\tilde{\delta}_{q,m} + \tilde{\mu}_{m}) = \pi_{q-1,m} \tilde{\gamma}_{q-1,m} + \pi_{q,m-1} \tilde{\lambda}_{m-1} + \sum_{k=1}^{n} (\pi_{q+k,m-1} \tilde{\lambda}_{m-1}) \tag{4.8}
\]

For the states satisfying \(0 < i \leq (nm-n+q)\) and \(j = 0\), we have:

\[
\pi_{i,0}(\tilde{\gamma}_{i,0} + \tilde{\delta}_{i,0} + \tilde{\lambda}_{0}) = \pi_{i-1,0} \tilde{\gamma}_{i-1,0} + \pi_{i+1,0} \tilde{\delta}_{i+1,0} + \pi_{i,1} \tilde{\mu}_{1} \tag{4.9}
\]

For the states satisfying \((nm-n+q) < i < (nm+q)\) and \(j = 0\), we have:

\[
\pi_{i,j}(\tilde{\gamma}_{i,j} + \tilde{\delta}_{i,j} + \tilde{\lambda}_{0}) = \pi_{i-1,j} \tilde{\gamma}_{i-1,j} + \pi_{i+1,j} \tilde{\delta}_{i+1,j} \tag{4.10}
\]
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State diagram of the modeled system for $0 < g < m, 0 < q < n, 0 < \lambda < g$. 

Figure 4.4.
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For the states satisfying $i = 0$ and $0 < j < m$, we have:

$$
\pi_{0,j}(\tilde{\gamma}_{0,j} + \tilde{\lambda}_j + \tilde{\mu}_j) = \pi_{i,j} \tilde{\delta}_{i,j} + \pi_{0,j-1} \tilde{\lambda}_{j-1} + \pi_{0,j+1} \tilde{\mu}_{j+1}
$$

(4.11)

For the states satisfying $0 < i < q$ and $j = m$, we have:

$$
\pi_{i,m}(\tilde{\gamma}_{i,m} + \tilde{\delta}_{i,m} + \tilde{\mu}_m) = \pi_{r-1,m} \tilde{\gamma}_{r-1,m} + \pi_{r+1,m} \tilde{\delta}_{r+1,m} + \pi_{r,m-1} \tilde{\mu}_{m-1}
$$

(4.12)

Furthermore, for the states satisfying $0 < j < m$ and $0 < i \leq n(m - j - 1) + q$, we have:

$$
\pi_{i,j}(\tilde{\gamma}_{i,j} + \tilde{\delta}_{i,j} + \tilde{\lambda}_j + \tilde{\mu}_j) = \pi_{r-1,j} \tilde{\gamma}_{r-1,j} + \pi_{r+1,j} \tilde{\delta}_{r+1,j} + \pi_{r,j-1} \tilde{\lambda}_{j-1} + \pi_{r,j+1} \tilde{\mu}_{j+1}
$$

(4.13)

For the states satisfying $0 < j < m$ and $n(m - j - 1) + q < i < n(m - j) + q$, we have:

$$
\pi_{i,j}(\tilde{\gamma}_{i,j} + \tilde{\delta}_{i,j} + \tilde{\lambda}_j + \tilde{\mu}_j) = \pi_{r-1,j} \tilde{\gamma}_{r-1,j} + \pi_{r+1,j} \tilde{\delta}_{r+1,j} + \pi_{r,j-1} \tilde{\lambda}_{j-1} + \sum_{k=1}^{n} \pi_{r+k,j-1} \tilde{\lambda}_{j-1}
$$

(4.14)

All steady-state probabilities are summed up in conjunction with the equation $\sum_{(i,j) \in S} [\pi_{i,j}] = 1$. By combining the above equations, a set of linear equations can be constructed. By solving them, the steady-state probabilities of all states can be accordingly computed.

4.3.3 Performance Metrics for SUs

The following performance metrics are considered.

Blocking probability

The newly arrived SU calls consist of both initial and inter-handoff SU calls. According to the SUs inter-handoff scheme, the case of blocking an initial
4.3. QUEUEING MODEL

SU call occurs for \((i + nj) \geq (nm + q - h)\), and the case of blocking an inter-handoff SU call occurs for \((i + nj) = (nm + q)\). The blocking probabilities of initial and inter-handoff SU calls are denoted by \(P_{bi}\) and \(P_{bh}\), respectively:

\[
P_{bi} = \sum_{\forall i,j} \left[ \pi_{i,j} | (i + nj) \geq (nm + q - h) \right] \tag{4.15}
\]

\[
P_{bh} = \sum_{\forall i,j} \left[ \pi_{i,j} | (i + nj) = (nm + q) \right] \tag{4.16}
\]

**Forced-Termination Probability**

As described above, when a newly arrived PU occupies a band, the termination of an ongoing SU call occurs for \((i + nj) > (nm - n + q)\). This means that the system has not enough idle queueing slots to accommodate all dropped SUs that have experienced unsuccessful intra-handoff. Let \(P_{ft}\) denote the forced-termination probability of ongoing SU calls. Similar to the definition in [55], \(P_{ft}\) is defined as:

\[
P_{ft} = \frac{\text{Total forced-termination rate of ongoing SU calls}}{\text{Actual average arrival rate of SU calls into the system}} \tag{4.17}
\]

For the state \((i, j) \in S\) satisfying \((nm - n + q) < (i + nj)\), the forced-termination rate at this state is computed by the product of PUs arrival rate and the number of terminated SU calls. Given that the PU occupies the band with arrival rate \(\bar{\lambda}_j\), the number of terminated SU calls is equal to \(B_{i,j}\). Therefore, at state \((i, j)\) the forced-termination rate is equal to \(B_{i,j} \bar{\lambda}_j\). As a result, the total forced-termination rate of ongoing calls is equal to:

\[
\sum_{\forall i,j} \left[ B_{i,j} \bar{\lambda}_j \pi_{i,j} | (nm - n + q) < (i + nj) \right] \tag{4.18}
\]

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Since the initial and the inter-handoff SU calls are blocked with respective probabilities $P_{bi}$ and $P_{bh}$, the actual average arrival rate of SU calls into the system equals $[\gamma_1(1-P_{bi})+\gamma_2(1-P_{bh})]$. Subsequently, $P_{ft}$ is given by:

$$P_{ft} = \frac{\sum_{(i,j) \in S} [i+n(j+1-m)-q]\tilde{\lambda}_{i,j}\pi_{i,j}}{\gamma_1(1-P_{bi}) + \gamma_2(1-P_{bh})} \quad (4.19)$$

where, $(nm-n+q) < (i+nj) < nm+q$.

Service-Completion Throughput, Departure Throughput, and Average Waiting Time

As presented in section 4.2, the connected SUs calls in the system consist of ongoing and queued calls. Since only the ongoing SU calls use the available sub-bands to transmit data, the service-completion throughput of SU calls is defined as being the average rate of ongoing SU calls completing the transmission service.

Due to the inter-handoff activity, both ongoing and queued SU calls may depart from a source CR cell and move to neighboring CR cells. Hence, the departure rate of SU calls is defined to be the average rate of connected SU calls departing from the system. Let $R_s$ and $R_d$, denote the service-completion and the departure rates of SU calls, respectively. To compute them, the average numbers of ongoing and queued SU calls in the system need to be considered, which are denoted by $N_s$ and $N_q$, respectively. We have $R_s = \delta_s N_s$ and $R_d = \delta_d (N_s + N_q)$.

According to subsection 4.3.1, if $(i+nj) \leq nm$, there are $i$ ongoing SU calls and zero queued SU calls. If $nm < (i+nj) \leq (nm+q)$, the numbers of ongoing and queued SU calls are equal to $n(m-j)$ and $[i-n(m-j)]$.
respectively. Therefore, $N_s$ and $N_q$ are computed with:

$$\begin{align*}
N_s &= \sum_{(i,j) \in S} \left[ i\pi_{i,j} | (i+nj) \leq nm \right] + \\
&\sum_{(i,j) \in S} \left[ n(m-j)\pi_{i,j} | (i+nj) > nm \right] \quad (4.20) \\
N_q &= \sum_{(i,j) \in S} \left[ [i-n(m-j)]\pi_{i,j} | (i+nj) > nm \right] \quad (4.21)
\end{align*}$$

Since each of the arrived SU calls faces four different cases (i.e., being dropped, being force-terminated, departing the system and completing the service), $R_s$ and $R_d$ are constrained by:

$$R_s + R_d = \left[ \gamma_1 (1 - P_{bi}) + \gamma_2 (1 - P_{bh}) \right] (1 - P_{ft}) \quad (4.22)$$

This constraint is validated by numerical results reported in Section 4.4.

Furthermore, it is known that the waiting time of a connected SU call refers to the total time spent by this call in the system. Let $T_w$ denote the average waiting time of a connected SU call, including both the time staying in the queue and the service time. According to Little’s Theorem, $T_w$ is given by:

$$T_w = \frac{N_q + N_s}{\gamma_1 (1 - P_{bi}) + \gamma_2 (1 - P_{bh})} \quad (4.23)$$

**Average Waiting Time**

The waiting time of a connected SU call refers to the total time spent by this call in the system. Let $T_w$ denote the average waiting time of a connected SU call, including both time staying in the queue and service
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time. According to the Little’s Theorem, $T_w$ is computed by:

$$T_w = \frac{N_q + N_s}{\gamma_1 (1 - P_{bh}) + \gamma_2 (1 - P_{bh})}$$

(4.24)

4.3.4 Determination of Inter-Handoff Parameters

So far, it has been assumed that all aforementioned parameters are already known. In reality, when all CR cells are in steady-state, the mean arrival rate of inter-handoff calls depends on other related parameters. In this study, in the case of PUs, $\lambda_2$ depends on three parameters $\mu_1$, $\mu_2$ and $g$. For SUs, $\gamma_2$ depends not only on the PU parameters $\lambda_1$, $\mu_1$, $\mu_2$ and $g$, but also on the SU parameters $\gamma_1$, $\delta_1$, $\delta_2$, $h$ and $q$.

Figure 4.5: When all CR cells are assumed to show identical statistics, the mean arrival rate of inter-handoff calls to a source cell is equal to the departure rate of the ongoing calls to neighboring cells for PUs and SU, respectively.

To determine $\lambda_2$ and $\gamma_2$, a particular scenario is considered (Figure 4.5) that all CR cells show identical statistics [64]. As a result, the mean arrival rate of inter-handoff calls and the departure rate of calls can be assumed
4.3. QUEUEING MODEL

to equal each other for PUs and SUs, respectively. In the following, the departure rate of PU calls is denoted by $R^p_d$ and it is computed in accordance with the representation advanced in [64].

Since PUs exclusively occupy the bands, the birth-death model is used for modelling the PU calls. Let $p_r(k)$ denote the steady-state probability of the $k$ ongoing PU calls in the system. The balance equations are:

$$p_r(0) = \left[ \sum_{k=0}^{m-g-1} \frac{1}{k!} \left( \frac{\lambda_1 + \lambda_2}{\mu_1 + \mu_2} \right)^k \right]^{-1} + \sum_{k=m-g}^{m} \left[ \frac{1}{k!} \cdot \frac{(\lambda_1 + \lambda_2)^{m-g}(\lambda_2)^{k-(m-g)}}{(\mu_1 + \mu_2)^k} \right]$$

(4.25)

$$p_r(k) = \begin{cases} 
  p_r(0) \left( \frac{\lambda_1 + \lambda_2}{\mu_1 + \mu_2} \right)^k, & \text{if } 0 < k \leq m - g \\
  p_r(0) \frac{(\lambda_1 + \lambda_2)^{m-g}(\lambda_2)^{k-(m-g)}}{(\mu_1 + \mu_2)^k}, & \text{if } m - g \leq k \leq m 
\end{cases}$$

(4.26)

$R^p_d$ is computed as:

$$R^p_d = \mu_2 \sum_{k=1}^{m} [kp_r(k)]$$

(4.27)

This equation is constrained by the fixed-point equation $\lambda_2 = R^p_d$. Similarly, for inter-handoff SU calls, we have the constraint $\gamma_2 = R_d$. Finally, determining the values of $\lambda_2$ and $\gamma_2$ follows an iteration method (described by Algorithm 1).

**Algorithm 1:** Determine the value of $\lambda \in \{\lambda_2, \gamma_2\}$.

1: $\lambda \leftarrow$ Setting an initial value
2: Compute departure throughput $R$ \hspace{1cm} $\triangleright$ For PU or SU
3: while $|\lambda - R| \geq \epsilon$ do
4: \hspace{1cm} $\lambda = R$, and compute departure throughput $R$
5: \hspace{1cm} end while \hspace{1cm} $\triangleright$ Parameter value is determined

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4.4 Performance Evaluation

In this section, numerical and simulation results are reported for the performance evaluation of the modelled CR cell system. Simulation experiments have been conducted to demonstrate the validity of the numerical analysis. The simulator is developed in C/C++. In experiments, the simulator is run in a looping manner and each loop indicates 1 ms in time domain.

<table>
<thead>
<tr>
<th>Table 4.4: Parameter Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum</td>
</tr>
<tr>
<td>PUs activity</td>
</tr>
<tr>
<td>SUs activity</td>
</tr>
</tbody>
</table>

To study the effects of PUs activity and inter-handoff priority scheme on SUs transmission performance, the parameters defined in Table 4.4 are considered. These parameters have been selected with reference to [54, 55, 59–61]. For every specific parameter setting, the simulator runs \( t = 10^7s \) simulation time. Twelve simulation statistics are indicated in Table 4.5, together with the corresponding notations and definitions. With these statistics, the performance metrics derived in Section 4.3.3 are computed by:

\[
R_s = z' / t, \quad R_d = z'' / t, \quad N_s = \left[ \sum_{k=1}^{l} v_s(k) \right] / l, \quad N_q = \left[ \sum_{k=1}^{l} v_q(k) \right] / l, \quad P_{bi} = x' / x, \quad P_{bh} = y' / y, \quad P_{ft} = z / (x + y - x' - y'), \quad \text{and} \quad T_w = t_w / (x + y - x' - y').
\]

The numerical results of \( \lambda_2 \) are shown in Table 4.6. The results of \( R_d, N_s, N_q, P_{bi}, P_{bh}, P_{ft}, R_s \) and \( T_w \) are shown in Figures 4.6, 4.7, 4.8, 4.9, 4.10, 4.11, 4.12 and 4.13, respectively. The computed numerical results of \( R_s \) and \( R_d \) satisfy the equation (4.22). In all figures, the marker ‘+’ indicates...
Table 4.5: Simulation Statistics in a Simulation Run

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t )</td>
<td>Simulation time, ( t = 10^7 s ).</td>
</tr>
<tr>
<td>( l )</td>
<td>Number of loopings, ( l = 10^{10} ).</td>
</tr>
<tr>
<td>( x )</td>
<td>Number of arrived initial SU calls.</td>
</tr>
<tr>
<td>( x' )</td>
<td>Number of blocked initial SU calls.</td>
</tr>
<tr>
<td>( y )</td>
<td>Number of arrived inter-handoff SU calls.</td>
</tr>
<tr>
<td>( y' )</td>
<td>Number of blocked inter-handoff SU calls.</td>
</tr>
<tr>
<td>( z )</td>
<td>Number of terminated SU calls.</td>
</tr>
<tr>
<td>( z' )</td>
<td>Number of completed SU calls.</td>
</tr>
<tr>
<td>( z'' )</td>
<td>Number of connected SU calls departing from the cell.</td>
</tr>
<tr>
<td>( v_s(k) )</td>
<td>Number of ongoing SU calls during the ( k^{th} ) loop.</td>
</tr>
<tr>
<td>( v_q(k) )</td>
<td>Number of queued SU calls during the ( k^{th} ) loop.</td>
</tr>
<tr>
<td>( t_w )</td>
<td>Total time of all accepted SU calls staying in the system.</td>
</tr>
</tbody>
</table>

the simulation result. From the tables and figures, it is observed that the simulation results closely match the numerical results. The discussions of results are as follows.

4.4.1 Departure Throughputs of PUs and SUs

For the fixed value of \( g \) (i.e., \( g = 1 \) or \( g = 2 \)), Table 4.6 indicates that \( \lambda_2 \) increases with \( \lambda_1 \). The reason for this is intuitive. The larger the number of initial PU calls in a cell is, the larger the number of departing ongoing PU calls becomes. On the other hand, Figure 4.6 shows that the changing trends of \( R_d \) with \( \lambda_1 \) are not the same for different settings of \( g, q \) and \( h \).
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For instance, if $g = 1$, $q = 2$ and $h = 1$, $R_d$ decreases with $\lambda_1$; if $g = 1$ and $q = 3$ and $h = 1$, $R_d$ increases with $\lambda_1$. To explain this behavior, the average numbers of ongoing and queued SU calls are considered, which are shown in Figures 4.7 and 4.8, respectively.

Table 4.6: Numerical results of PUs inter-handoff arrival rate $\lambda_2$.

<table>
<thead>
<tr>
<th></th>
<th>$\lambda_1 = 0.03s^{-1}$</th>
<th>$\lambda_1 = 0.06s^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g = 1$</td>
<td>$\lambda_2 = 0.0195635$</td>
<td>$\lambda_2 = 0.0193765$</td>
</tr>
<tr>
<td>$g = 2$</td>
<td>$\lambda_2 = 0.0358217$</td>
<td>$\lambda_2 = 0.0337456$</td>
</tr>
<tr>
<td>$g = 1$</td>
<td>$\lambda_2 = 0.0475164$</td>
<td>$\lambda_2 = 0.0424333$</td>
</tr>
<tr>
<td>$g = 2$</td>
<td>$\lambda_2 = 0.0557855$</td>
<td>$\lambda_2 = 0.0479201$</td>
</tr>
</tbody>
</table>

The two figures show that, for a specific setting of $g$, $q$ and $h$, $N_s$ decreases with $\lambda_1$ and $N_q$ increases with $\lambda_1$. This is because the resource availability for SUs is reduced when $\lambda_1$ is increasing, which means that more PUs are requesting for resources. Therefore, more sub-bands become unavailable for SUs, and more connected SU calls need to be queued. Moreover, when the queue length is small, i.e., $q = 2$, the amount of decrease in $N_s$ is larger than the amount of increase in $N_q$. In the opposite case, when the queue length is larger, i.e., $q = 3$ or $q = 4$, the amount of decrease in $N_s$ is smaller than the amount of increase in $N_q$.  

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4.4. PERFORMANCE EVALUATION

4.4.2 SUs Transmission Performance

Same values of $q$ and $h$

As addressed in subsection 4.4.1, if the value of $g$ is fixed, the increase of $\lambda_1$ reduces the resource availability for SUs. The reduction can be observed in Figures 4.9, 4.10 and 4.11 as $P_{bi}$, $P_{bh}$ and $P_{ft}$ increase with $\lambda_1$. Therefore, SUs service-completion throughput $R_s$ decreases with $\lambda_1$, as shown in Figure 4.12. However, for the same $\lambda_1$, if $g$ is increased, the resource availability for SUs is increased. This is because more initial PU calls are blocked and more sub-bands become available. As a result, $P_{bi}$, $P_{bh}$ and $P_{ft}$ decrease with $g$ (see Figures 4.9, 4.10 and 4.11), and thus $R_s$ is increased.

Regarding the metric $T_w$, this is an increasing function of $N_q$, $P_{bi}$, $P_{bh}$ and $P_{ft}$ with regard to equation (4.24). For the same $g$, $N_q$, $P_{bi}$, $P_{bh}$ and $P_{ft}$ increase with $\lambda_1$. This indicates that $T_w$ also increases with $\lambda_1$, matching the results shown in Figure 4.13. Further, for the same $\lambda_1$, the increase of $g$ increases the resource availability for SUs. This means that more SUs are completing the transmission, so that $N_q$ is decreased (Figure 4.8). As a result, $T_w$ decreases with $g$, as shown in Figure 4.13.

Same values of $g$ and $\lambda_1$

For a specific value of $q$, Figures 4.9 and 4.10 show that $P_{bi}$ increases with $h$ and $P_{bh}$ decreases with $h$. This is because when $h$ becomes larger, more inter-handoff SU calls can actually get into the system. Meanwhile, a larger number of initial SU calls are blocked. Further, it is observed in Figure 4.11 that $P_{ft}$ decreases with $h$ because the average number of ongoing SUs $N_s$ is decreased. The decrease of $N_s$ can be observed from Figure 4.7. By comparing Figure 4.9 with Figures 4.10 and 4.11, it is observed that the
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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{departure_throughput_SU_calls_Rd.png}
\caption{Departure throughput of SU calls, $R_d$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{average_number_ongoing_SU_calls_Ns.png}
\caption{Average number of ongoing SU calls, $N_s$.}
\end{figure}
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Figure 4.8: Average number of queued SU calls, $N_q$.

Figure 4.9: Blocking probability of initial SU calls, $P_{bi}$. 
CHAPTER 4. CASE STUDY I: COGNITIVE RADIO CELLULAR NETWORKS

Figure 4.10: Blocking probability of inter-handoff SU calls, $P_{bh}$.

Figure 4.11: Forced-termination probability of SU calls, $P_{ft}$.  

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Figure 4.12: Service-completion throughput of SU calls, $R_s$.

Figure 4.13: Average waiting time of SU calls, $T_w (s)$. 
amount of increase in $P_{bi}$ is larger than the amounts of decrease in $P_{bh}$ and in $P_{ft}$. Hence, both $R_s$ and $T_w$ decrease with $h$, which can be observed in Figures 4.12 and 4.13, respectively.

For a specific value of $h$, Figures 4.9, 4.10 and 4.11 indicate that $P_{bi}$, $P_{bh}$ and $P_{ft}$ decrease with $q$. This is because when the queue length is increased, more SU calls can be accepted by the system. As such, the number of SUs that require the transmission service is increased, and thus $R_s$ is improved, as shown in Figure 4.12. However, the increase of $q$ means that more SU calls are queued. Therefore, SUs average waiting time $T_w$ is increased, as shown in Figure 4.13.

4.5 Fuzzy-Logic Based Performance Optimization

Based on the above presented performance evaluation, it is found that both $R_s$ and $T_w$ decrease with $h$ and increase with $q$. From the mobile user viewpoint, the larger the value of $R_s$ is, the better the transmission performance becomes. In contrast, the transmission performance becomes worse if $T_w$ is increased. The conclusion therefore is that it is important to optimize the SUs transmission performance with respect to both parameters $R_s$ and $T_w$. Usually, the performance optimization for queueing models can be conducted in two different ways:

- Optimization is represented as a function of the mean arrival rate of calls and service rate of the system. The corresponding solution is based on using techniques like convex mathematical programming [39].
- Optimization is referred to as a trade-off among multiple conflicting parameters that have the same measure. For instance, in [64], the
4.5. FUZZY-LOGIC BASED PERFORMANCE OPTIMIZATION

Performance optimization is associated with the minimization of both blocking probability and dropping probability of calls.

However, the case the performance optimization for SU calls is different. The first difference is that the focus is on the effects of PUs activity and the finite queue based inter-handoff priority scheme on the transmission performance of SUs. The second difference is that the two parameters $R_s$ and $T_w$ vary in distinct measures. This creates a difficulty in jointly considering these two parameters. To alleviate this problem, the mathematical tool of fuzzy logic is used. The key capability is to cope with various decision criteria for decision making purposes. The importance of using fuzzy logic in CRNs was, e.g., addressed in [40]. The effectiveness of applying fuzzy logic to ad-hoc based CRNs for channel selection was reported in [58].

Subsequently, the performance optimization is represented in the form of a two-constraint based decision making problem by using fuzzy logic. Further, given the fixed values of $g$ and $\lambda_i$, the focus of decision making is on deciding which values of $q$ and $h$ should be selected for SU calls. In the following, a parameter called Fuzzy Transmission Performance is introduced.

4.5.1 Fuzzy Transmission Performance

**Proposition 1:** Fuzzy Transmission Performance (FTP) is a fuzzy logic based parameter used to represent three different levels of the SUs transmission performance. The three levels are respectively formalized as three fuzzy sets, namely, “high-level”, “medium-level” and “low-level” transmission performance of SUs.

FTP is used to map different types of parameter values to an uniform type, i.e., fuzzy membership degree. Let $X$ denote a parameter of
either $R_s$ or $T_w$, i.e., $X \in \{R_s, T_w\}$. Given the fixed values of $g$ and $\lambda_1$, the value of parameter $X$ depending on $h$ and $q$ is denoted by $X(q,h)$. The notations $\alpha_X$, $\beta_X$ and $\gamma_X$ are used to denote three fuzzy sets “high-level”, “medium-level” and “low-level” under the parameter $X$, respectively. Their membership functions are denoted by $F_{\alpha_X}$, $F_{\beta_X}$, and $F_{\gamma_X}$, respectively. $F_{\alpha_X}[X(q,h)] \in [0.0, 1.0]$, $F_{\beta_X}[X(q,h)] \in [0.0, 1.0]$, $F_{\gamma_X}[X(q,h)] \in [0.0, 1.0]$ are defined as membership degrees of $X(q,h)$ to fuzzy sets $\alpha_X$, $\beta_X$ and $\gamma_X$, respectively. For example, the case of $F_{\alpha_X}[X(q,h)] = 0$ means that $X(q,h)$ is not a member of $\alpha_X$, whereas the case of $F_{\alpha_X}[X(q,h)] = 1$ means that $X(q,h)$ is a full member of $\alpha_X$. In addition, the case of $0 < F_{\alpha_X}[X(q,h)] < 1$ implies that $X(q,h)$ belongs only partially to $\alpha_X$.

By using the same fuzzy comparison mechanism as presented in Section 3.3.3, three values $F_{\alpha_X}[X(q,h)]$, $F_{\beta_X}[X(q,h)]$ and $F_{\gamma_X}[X(q,h)]$ can be integrated into a joint value referred to as the SUs transmission performance. This value is formulated as:

$$\psi_X(q,h|g,\lambda_1) = \omega_\times F_{\alpha_X}[X(q,h)] + \omega_+ F_{\beta_X}[X(q,h)] + \omega_- F_{\gamma_X}[X(q,h)] \quad (4.28)$$

where $\psi_X(t)$ is called the FTP-based effect factor of the parameter $X$ for doing decision making. In the equation, $\omega_\times$, $\omega_+$, and $\omega_-$ denote the weights of how important the “high-level”, “medium-level” and “low-level” transmission performance affect the decision making, respectively. According to the equation 3.10, the values of $\omega_\times$, $\omega_+$, and $\omega_-$ are given by:

$$\{\omega_\times, \omega_+, \omega_-\} \simeq \{0.94, 0.31, 0.19\} \quad (4.29)$$

Based on the formulated value $\psi_X(t)$, a hybrid decision making algorithm is suggested below.
### Table 4.7: Numerical results of SUs service-completion throughput and average waiting time in the system.

<table>
<thead>
<tr>
<th>$g$</th>
<th>$q$</th>
<th>$h$</th>
<th>$(R_s, T_w(s))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>$(0.815555, 0.887299)$</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>$(0.817266, 0.888399)$</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>$(0.816223, 0.887812)$</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>$(0.81473, 0.889140)$</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>$(0.818473, 0.889140)$</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
<td>$(0.817573, 0.886814)$</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>3</td>
<td>$(0.816470, 0.887992)$</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>$(0.818194, 0.885906)$</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>$(0.818891, 0.886353)$</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>$(0.818466, 0.886114)$</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>$(0.819381, 0.886655)$</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
<td>$(0.819015, 0.886440)$</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>3</td>
<td>$(0.818566, 0.886187)$</td>
</tr>
</tbody>
</table>
CHAPTER 4. CASE STUDY I: COGNITIVE RADIO CELLULAR NETWORKS

4.5.2 Hybrid Decision Making

The numerical results of $R_s$ and $T_w$ are reported in Table 4.7.

According to the table, the values of $R_s(q,h)$ and $T_w(q,h)$ are first mapped to fuzzy membership degrees to FTP’s three fuzzy sets, respectively. For the same setting of $(g, \lambda)$, we let $R_s^*, R_s, T_w^*$ and $T_w$ denote the four values $\argmax\{R_s(q,h)\}$, $\argmin\{R_s(q,h)\}$, $\argmax\{T_w(q,h)\}$ and $\argmin\{T_w(q,h)\}$, respectively. Further, we let three pairs of values $\{R_s^*, T_w\}$, $\{(R_s^* + R_s)/2, (T_w^* + T_w)/2\}$ and $\{R_s, T_w^*\}$ indicate that, under the three pairs, the SUs transmission performance is exactly equivalent to high-level, medium-level and low-level, respectively. That means $F_{R_s, \alpha}(R_s) = F_{R_s, \beta}(R_s) = 1$ and $F_{T_w, \alpha}(T_w) = F_{T_w, \beta}(T_w) = 1$.

Given that the SUs transmission performance increases with $R_s(q,h)$ and decreases with $T_w(q,h)$, the constraints for the corresponding fuzzy membership degrees are obtained as:

- For the same $T_w(q,h)$, when $R_s(q,h)$ is increasing, we have: i) $F_{R_s, \alpha}[R_s(q,h)]$ should increase, ii) $F_{R_s, \beta}[R_s(q,h)]$ should increase for $R_s(q,h) < (R_s^* + R_s)/2$ and decrease for $R_s(q,h) > (R_s^* + R_s)/2$, and iii) $F_{R_s, \gamma}[R_s(q,h)]$ should decrease.

- For the same $R_s(q,h)$, when $T_w(q,h)$ is increasing, we have: i) $F_{T_w, \alpha}[T_w(q,h)]$ should decrease, ii) $F_{T_w, \beta}[T_w(q,h)]$ should increase for $T_w(q,h) < (T_w^* + T_w)/2$ and decrease for $T_w(q,h) > (T_w^* + T_w)/2$, and iii) $F_{T_w, \gamma}[T_w(q,h)]$ should increase.

Hence, the membership functions of FTP under $R_s$ and $T_w$ are formalized as simple linear functions (illustrated in Figures 4.14 and 4.15):
4.5. FUZZY-LOGIC BASED PERFORMANCE OPTIMIZATION

\[
F_{R_s, \alpha}[R_s(q,h)] = \begin{cases} 
\frac{R_s(q,h) - R_s}{R_s^* - R_s}, & R_s \leq R_s(q,h) \leq R_s^* \\
\frac{2R_s(q,h) - 2R_s}{R_s^* - R_s}, & R_s \leq R_s(q,h) \leq (R_s^* + R_s)/2 \\
\frac{2R_s^* - 2R_s(q,h)}{R_s^* - R_s}, & (R_s^* + R_s)/2 \leq R_s(q,h) \leq R_s^* 
\end{cases} \tag{4.30}
\]

\[
F_{R_s, \beta}[R_s(q,h)] = \begin{cases} 
\frac{R_s^* - R_s(q,h)}{R_s^* - R_s}, & R_s \leq R_s(q,h) \leq R_s^* \\
\frac{2R_s(q,h) - 2R_s}{R_s^* - R_s}, & R_s \leq R_s(q,h) \leq (R_s^* + R_s)/2 \\
\frac{2R_s^* - 2R_s(q,h)}{R_s^* - R_s}, & (R_s^* + R_s)/2 \leq R_s(q,h) \leq R_s^* 
\end{cases} \tag{4.31}
\]

\[
F_{T_w, \alpha}[T_w(q,h)] = \begin{cases} 
\frac{T_w^* - T_w(q,h)}{T_w^* - T_w}, & T_w \leq T_w(q,h) \leq T_w^* \\
\frac{2T_w(q,h) - 2T_w}{T_w^* - T_w}, & T_w \leq T_w(q,h) \leq (T_w^* + T_w)/2 \\
\frac{2T_w^* - 2T_w(q,h)}{T_w^* - T_w}, & (T_w^* + T_w)/2 \leq T_w(q,h) \leq T_w^* 
\end{cases} \tag{4.32}
\]

\[
F_{T_w, \beta}[T_w(q,h)] = \begin{cases} 
\frac{T_w^* - T_w(q,h)}{T_w^* - T_w}, & T_w \leq T_w(q,h) \leq T_w^* \\
\frac{2T_w(q,h) - 2T_w}{T_w^* - T_w}, & T_w \leq T_w(q,h) \leq (T_w^* + T_w)/2 \\
\frac{2T_w^* - 2T_w(q,h)}{T_w^* - T_w}, & (T_w^* + T_w)/2 \leq T_w(q,h) \leq T_w^* 
\end{cases} \tag{4.33}
\]

\[
F_{T_w, \gamma}[T_w(q,h)] = \begin{cases} 
\frac{T_w^* - T_w(q,h)}{T_w^* - T_w}, & T_w \leq T_w(q,h) \leq T_w^* \\
\frac{2T_w(q,h) - 2T_w}{T_w^* - T_w}, & T_w \leq T_w(q,h) \leq (T_w^* + T_w)/2 \\
\frac{2T_w^* - 2T_w(q,h)}{T_w^* - T_w}, & (T_w^* + T_w)/2 \leq T_w(q,h) \leq T_w^* 
\end{cases} \tag{4.34}
\]

Moreover, we let \( \psi_{R_s}(q,h|g,\lambda_i) \) and \( \psi_{T_w}(q,h|g,\lambda_i) \), respectively denote the FTP-based effect factors of \( R_s \) and \( T_w \) under the specific setting of \( q, h, g \) and \( \lambda_i \). They can be computed according to equation (4.28).

Although, the values of \( \psi_{R_s}(q,h|g,\lambda_i) \) and \( \psi_{T_w}(q,h|g,\lambda_i) \) have the same type with respect to fuzzy membership degree of FTP, their respective weights for decision making still need to be configured. In other words, the performance optimization of SU calls can be pre-regulated with reference to the SUs different requirements on the two parameters \( R_s \) and \( T_w \). Therefore, a variable \( p_r \in [0.0, 1.0] \) is introduced, in which the decision maker configures \( \psi_{R_s}(q,h|g,\lambda_i) \) with weight \( p_r \) and \( \psi_{T_w}(q,h|g,\lambda_i) \) with weight \( (1 - p_r) \). The
CHAPTER 4. CASE STUDY I: COGNITIVE RADIO CELLULAR NETWORKS

Figure 4.14: Membership functions of FTP under $R_s$.

Figure 4.15: Membership functions of FTP under $T_w$.
transmission performance of SUs under $R_s$ and $T_w$ is finally formulated as:

$$
\theta(q,h|p_r,g,\lambda_1) = p_r \psi_{s}(q,h|g,\lambda_1) + (1 - p_r) \psi_{w}(q,h|g,\lambda_1)
$$

Consequently, for the particular values of $p_r$, $g$ and $\lambda_1$, the optimal transmission performance of SUs is associated with the largest value of $\theta(q,h|p_r,g,\lambda_1)$, which determines the best selected $(q,h)$ parameters.

### 4.5.3 Decision Making Results

To evaluate the effectiveness of the suggested algorithms for the performance optimization for SU calls, five decision making scenarios are considered with regard to $p_r$ equal to 0.0, 0.3, 0.5, 0.7 and 1.0, respectively. The best selected $(q,h)$ parameters for different settings of $(p_r,g,\lambda_1)$ are presented in Table 4.8. In the table, it is observed that, for each $p_r \in \{0.0, 0.3, 0.7, 1.0\}$, the best selected $(q,h)$ parameters are the same for all different settings of $(g,\lambda_1)$. This is because the values of $q$ and $h$ are in the work constrained by $q \in \{2,3,4\}, h \in \{1,2,3\}$ and $h < q$. If the number of licensed bands and the queue length become larger, the variety of selection results for $(q,h)$ may be increased. The selection results are discussed bellow.

For the $p_r = 1.0$ scenario, the decision maker only takes into account $R_s$. The best selected $(q,h)$ parameters are $(4,1)$ for all different settings of $(g,\lambda_1)$. If $T_w$ is only considered by the decision maker, i.e., $p_r = 0.0$, then $(2,1)$ are best. These selection results match the evaluation results shown in Figures 4.12 and 4.13. Moreover, for the $p_r = 0.3$ scenario, $R_s$ is considered with lower importance than $T_w$, and $(2,1)$ are the best selected $(q,h)$ parameters. For the $p_r = 0.7$ scenario, $R_s$ is considered with higher
importance than \( T_w \), and \((3, 1)\) becomes best. For the \( p_r = 0.5 \) scenario, both \( R_s \) and \( T_w \) are considered to be equally important for performance optimization. In this case, the best selected \((q, h)\) parameters rely on the two parameters \( \lambda_i \) and \( g \). That is, \((4, 3)\) are best for \( g = 1, \lambda_i \in \{0.03, 0.06\} \). For \( g = 2, \lambda_i \in \{0.03, 0.06, 0.09, 0.12\} \), \((2, 1)\) are best for \( g = 1, \lambda_i \in \{0.09, 0.12\} \). These selection results show the adaptability and flexibility of the suggested algorithm to the PUs activity and SUs performance optimization requirements in CR cellular networks.

### 4.6 Summary

The OSA based Cognitive Radio Cellular Networks (CRCNs) have been studied. Specifically, the inter- and intra-handoff activities of users have been presented and modelled. The first activity is connected to the handover procedure and it is regarding both PUs and SUs. While, the second activity is only related to SUs when they switch the frequency bands for data transmission within the same CR cell. The importance of giving pri-
4.6. SUMMARY

Priority to the inter-handoff calls was addressed as well. To provide such priority, the band reservation and queueing-slot reservation based schemes were suggested for inter-handoff PUs and SUs, respectively.

To investigate the SUs transmission performance in the considered CR-CNs, a Continuous Time Markov Chains (CTMC) based queueing model was used. The corresponding numerical analysis was validated as a feasible approach by simulation experiment. For performance evaluation, six metrics were derived: blocking probability of initial SU calls, blocking probability of inter-handoff SU calls, forced-termination probability of SU calls, SUs service-completion, average rate of SU calls departing the cell, and average time spent by SU calls in the CR cell. The results indicated that the parameters service-completion throughput and average waiting time increase with the queue length and decrease with the number of reserved queueing slots for inter-handoff SU calls. To provide a trade-off between these two parameters, a fuzzy logic based hybrid decision making algorithm was suggested to optimize the SUs transmission performance. The decision making results indicated the feasibility of this algorithm.
CHAPTER 4. CASE STUDY I: COGNITIVE RADIO CELLULAR NETWORKS
CHAPTER 5

CASE STUDY II: COGNITIVE RADIO AD-HOC NETWORK

This chapter describes the OSA based data transmission between two SUs, which operates in a single-hop ad-hoc manner. A queueing buffer based priority scheme is suggested for the SU transmitter to concurrently transmit different types of packets. The transmission performance of SUs is studied under the joint consideration of the suggested priority scheme and imperfect spectrum sensing. The Markov chains based numerical analysis is validated by simulation experiments. The results show that the suggested priority scheme is able to improve the transmission performance of SUs, together with significant decreased average transmission delay and minor decreased total transmission throughput.

5.1 Introduction

In Cognitive Radio Ad-Hoc Networks (CRAHNs), a SU may transmit different types of packets to a receiver like, e.g, another SU. By a packet, it
is meant the portion of the data that is transmitted during a short time period. An example of this short time period is referred to as a single slot in time-slotted transmission model. Further, each packet type may be generated from a particular higher layer application. Multiple applications may have various performance requirements for the packet transmission. For instance, real-time traffic (e.g., voice streaming) may need the guarantee of low transmission delay compared to the non-real-time traffic. Therefore, different types of packets should be given different priorities when they perform medium access of the available channels during the transmission process.

In this chapter, the focus is on the one-hop based packet transmission from a SU transmitter to a SU receiver by sharing a licensed channel with PUs. The transmitted packets may be of multiple types, which are assigned different transmission priorities. Based on this, a queueing buffer priority scheme is suggested for packet transmission at SU transmitter side, and also taking into consideration the imperfect spectrum sensing. A two-stage parallel server (i.e., $M/H_2/1$) based queuing model is developed to study the SU’s transmission performance.

## 5.2 System Model

As shown in Figure 5.1, an one-hop based CRAHN system is considered. In the system, there exists a single channel and two SUs. The single channel is denoted as $c$ and it is licensed to PUs. The two SUs are denoted as $s_e$ and $s_d$. They are allowed to opportunistically access the channel $c$ when it is not used by PUs.

The PU activity in channel $c$ is assumed to use a time-slotted basis. The length of every slot identically equals $\delta$ in time domain. In every slot, the
5.2. SYSTEM MODEL

PU is either present or absent in channel $c$ during the whole slot duration. The channel occupancy by the PU is assumed to follow a two-state busy-free Markov process. The state busy refers to the event that the channel $c$ is occupied by the PU for one or more consecutive slots. Similarly, state free refers to the event that there is no PU in channel $c$ for one or more consecutive slots. The time periods of the two states busy and free are integer times of $\delta$. They are assumed to be exponentially distributed with mean values $1/\alpha$ and $1/\beta$, respectively.

Two SUs $s_s$ and $s_d$ are assumed to be able to perceive the radio signals from each other. It is further assumed that they take roles as radio transmitter and receiver, respectively. When the channel $c$ is free (i.e., not used by PUs), the SU $s_s$ transmits packets to SU $s_d$. The activity of two SUs is assumed to be synchronized with PUs. Meaning, packet transmission of SU $s_s$ operates in a time-slotted basis, which has an uniform slot length $\delta$ same with PUs. Each SU slot consists of two phases: spectrum sensing and packet transmission. During the first phase, SU $s_s$ performs the spectrum sensing on channel $c$. If channel $c$ is sensed to be free, SU $s_s$ transmits a packet during the second phase. A successful transmission can be acknowledged by SU $s_d$ at the end of the slot.
5.2.1 Imperfect Spectrum Sensing

During every SU slot, the sensing result is considered to be imperfect. The imperfection may be due to factors like sensing-duration limitation and hardware sensitivity [15]. As shown in Figure 5.2, two different types of errors may occur in sensing results: 1) a free channel is sensed to be busy (so-called overlook), and 2) a busy channel is sensed to be free (so-called misidentification). Overlook errors lead to the overlooking of transmission opportunity when the channel $c$ is free, i.e., being available for the use of SUs. When misidentification error occurs, SU may select a busy channel.

![Figure 5.2: Two categories of sensing errors: overlook and misidentification.](image)

Clearly, a successful transmission occurs only during the time period when the channel $c$ is free. Meaning, if SU $s_x$ transmits a packet under the misidentification error, the packet transmission collides with PUs. Thus, SU $s_x$ experiences unsuccessful transmission by missing acknowledgment message from SU $s_d$. Subsequently, only the overlook error is considered in the following study. To simplify the analysis, the durations of both spectrum sensing and receiving acknowledgment message are assumed to
be zero. Further, the occurrence probability of an overlook error is denoted by $\varepsilon$, where $\varepsilon \in (0,1.0)$.

5.2.2 Transmission Prioritization

The packets transmitted by SU $s_i$ are assumed to be categorized into $M$ different types. Let $T_m$ denote the $m^{th}$ type of packets. The transmission priority of type $T_m$ packets is higher than of the type $T_{m+1}$ packets, where $m = 1, 2, ..., M - 1$. Furthermore, the arrivals of these $M$ categories of packets are assumed to independently follow Poisson processes with mean rates $\lambda_1$, $\lambda_2$, ..., $\lambda_M$, for type $T_1$, $T_2$, .., $T_M$, respectively.

As a hardware limitation, SU $s_i$ is assumed to be equipped with a finite buffer. The goal is to queue the newly arrived packets (of different types) when SU $s_i$ is transmitting a packet. The buffer length is denoted as $L$, indicating the maximum number of idle queueing slots when the buffer is empty. Each queueing place can only be used by one packet at a time.

![The finite buffer](image)

**Figure 5.3:** Different numbers, expressed by the set $\{h_m | m = 1, 2, ..., M\}$, of queueing slots are reserved for different categories of SU packets. The element values of this set are constrained by $(h_m | m \neq M) \in (0,L)$, $h_M = 0$ and $0 < \sum_{m=1}^{M-1} h_m < L$, where $L$ is the buffer size.
CHAPTER 5. CASE STUDY II: COGNITIVE RADIO AD-HOC NETWORK

Based on the finite buffer assumption, the priority scheme for $M$ types of packets is depicted in Figure 5.3, together with descriptions as follows:

- Compared with the type $T_{m+1}$ packets, a fixed number, $h_m$, of queueing slots are reserved for the type $T_m$ packets. If $h_m > 0$, the type $T_m$ packets are given higher priority over the type $T_{m+1}$ packets, where $m < M$. Because the type $T_M$ packets have the lowest priority, we set $h_M = 0$. Subsequently, we obtain a set of reserved queueing slots $h_1, h_2, ..., h_{M-1}$, for types $T_1, T_2, ..., T_{M-1}$, respectively.

- When a type $T_1$ packet arrives and one or more queueing slots are idle, the $T_1$ packet is accepted. Otherwise, the $T_1$ packet packet is blocked. When a type $T_m$ packet arrives where $m > 1$, it is accepted if at least $(1 + \sum_{i=1}^{m-1} h_i)$ queueing slots are idle. Otherwise, the type $T_m$ packet is blocked. To avoid that the type $T_m$ packets are blocked altogether, the value of $\sum_{i=1}^{m-1} h_i$ must be less than $L$, where $m > 1$.

5.3 Queueing Analysis

According to the above modelled system, the Markov Chains based queueing model is built up to study the transmission performance of SUs. This queueing model jointly takes into consideration the imperfect spectrum sensing and priority requirement for different types of SU packets.

5.3.1 Spectrum Access under Imperfect Sensing

We consider a particular time period of $n$ consecutive slots, during which channel $c$ is free for SU $s_x$ to use. Let $t$ denote this time period, and it equals $n\delta$. In each of these $n$ slots, SU $s_x$ may not transmit a particular packet.
(either type $T_1$, $T_2$, ..., or $T_M$) with probability $\varepsilon$ due to overlook error. In
other words, the probability of a successful transmission in a slot is equal to
$(1 - \varepsilon)$. Let $p_r(k;n,\varepsilon)$ denote the probability of $k$ successful transmissions
within time period $t$, where $0 \leq k \leq n$. Its value can be computed with
respect to the probability mass function (pmf) of the Binomial process.

$$p_r(k;n,\varepsilon) = \binom{n}{k} e^{n-k}(1-\varepsilon)^k$$  \hspace{1cm} (5.1)

Note that the binomial pmf can be approximated by using the pmf of
Poisson process [64]:

$$p_r(k;n,\varepsilon) \approx e^{-n(1-\varepsilon)} \left(\frac{n(1-\varepsilon)}{k!}\right)^k = e^{-\gamma} \left(\frac{\gamma}{k!}\right)^k$$  \hspace{1cm} (5.2)

where $\gamma = n(1-\varepsilon)$, and $\gamma$ denotes the mean rate of successful transmissions
within time interval $(0,t]$. The value of $\gamma$ is given by:

$$\gamma = \frac{1-\varepsilon}{\delta}$$  \hspace{1cm} (5.3)

Naturally, the successful transmission only takes place when the channel
c_r is free. Whereby, there is no transmission service when channel c_r is busy.
Similar to [66], the packet transmission at SU s_s side can be modelled as
an Interrupted Poisson Process (IPP), where its infinitesimal generator $Q$
and rate matrix $U$ are given by:

$$Q = \begin{bmatrix} -\alpha & \alpha \\ \beta & -\beta \end{bmatrix} \quad U = \begin{bmatrix} \gamma & 0 \\ 0 & 0 \end{bmatrix}$$  \hspace{1cm} (5.4)

Because an IPP is equivalent to a hyper-exponential process [63], the corre-
spanding probability density function (pdf) of service time is given by:

$$f(t) = \theta \mu_a e^{-\mu_at} + (1 - \theta) \mu_b e^{-\mu_b t}$$  \hspace{1cm} (5.5)
CHAPTER 5. CASE STUDY II: COGNITIVE RADIO AD-HOC NETWORK

where:

\[
\begin{align*}
\mu_a &= \frac{\gamma + \alpha + \beta + [(\gamma + \alpha + \beta)^2 - 4\gamma\beta]^{\frac{1}{2}}}{2} \\
\mu_b &= \frac{\gamma + \alpha + \beta - [(\gamma + \alpha + \beta)^2 - 4\gamma\beta]^{\frac{1}{2}}}{2} \\
\theta &= \frac{\gamma - \mu_b}{\mu_a - \mu_b}
\end{align*}
\]  \hfill (5.6)

5.3.2 Queueing Model

As shown in Figure 5.4, the pdf given by equation (5.5) can be expressed by a two-stage parallel server based queueing system [68].

![Figure 5.4: A two-stage parallel server based queueing model.](image)

In the figure, the large oval represents the server facility, where a particular packet at SU $s_s$ side approaches from the left. Transmitting this particular packet to SU $s_d$ is proceeded to service stage $a$ with probability $\theta$ or to service stage $b$ with probability $(1 - \theta)$. Transmission spends the exponentially distributed service time with mean values $1/\mu_a$ and $1/\mu_b$ for stages $a$ and $b$, respectively. After that service time, a successful packet transmission is accomplished and only then a new packet transmission is allowed into the service facility.

Let a set of three integers $(j_0, j_1, j_2)$ denote a system state that $j_0$ packets are in the buffer of SU $s_s$, and $j_1$ and $j_2$ packets are served by stages $a$ and $b$,
5.3. QUEUEING ANALYSIS

respectively. Given the buffer length equal to $L$, the value of $j_0$ is in the set \{0,1,...,L\}. Since only one of two service stages is active for transmission at a time, the values of $j_1$ and $j_2$ are constrained by $0 \leq (j_1 + j_2) \leq 1$. Therefore, the system state space is given by $S = \{(j_0, j_1, j_2) | j_0 \in \{0,1,...,L\}; j_1, j_2, (j_1 + j_2) \in \{0,1\}\}$. Considering a system state $(j_0, j_1, j_2) \in S$, the state transitions are as follows.

A new packet arrives at SU $s_s$

- For $j_0 = j_1 = j_2 = 0$, the server facility has no packet for transmission, and there is no queued packet in the buffer. Hence, the newly arrived packet is accepted for all $M$ types and it is proceeded to service stages $a$ and $b$ with rates $(\theta \sum_{m=1}^{M} \lambda_m)$ and $((1 - \theta)(\sum_{m=1}^{M} \lambda_m))$, respectively.

- When $0 \leq j_0 < L$ and $j_1 + j_2 = 1$, there is a packet being in transmission service, so that the newly arrived packet is accepted in accordance with the priority scheme. For $0 \leq j_0 < (L - \sum_{m=1}^{M-1} h_m)$, the new packet is accepted for $M$ types with acceptance rate $\sum_{m=1}^{M} \lambda_m$. For $(L - \sum_{i=1}^{m+1} h_i) \leq j_0 < (L - \sum_{i=1}^{m} h_i)$, the new packet is accepted only for types $T_1, T_2,..., T_m$ and $T_{m+1}$ with acceptance rate $\sum_{i=1}^{m+1} \lambda_i$. For $(L - h_1) \leq j_0 < L$, only type $T_1$ packets can be accepted with acceptance rate $\lambda_1$.

A packet is transmitted to SU $s_d$

- For $j_0 = 0$ and $(j_1 + j_2) = 1$, there exists one packet being in transmission service and there is no packet queued in the buffer. Hence, the service rate is equal to $\mu_a$ and $\mu_b$ for stages $a$ and $b$, respectively.

- For $j_0 \neq 0, j_1 = 1$ and $j_2 = 0$, a packet transmission is in stage $a$ with
CHAPTER 5. CASE STUDY II: COGNITIVE RADIO AD-HOC NETWORK

service rate $\mu_a$. When this transmission is finished, a queued packet is proceeded to service stages $a$ and $b$ with probabilities $\theta$ and $(1 - \theta)$, respectively. Meanwhile, the system changes state from $(j_0, 1, 0)$ to $(j_0 - 1, 1, 0)$ and to $(j_0 - 1, 0, 1)$ with transition rates $\theta \mu_a$ and $(1 - \theta) \mu_a$, respectively.

- For $j_0 \neq 0$, $j_1 = 0$ and $j_2 = 1$, a packet transmission is in stage $b$ with service rate $\mu_b$. Similar to the above case, after the packet is transmitted, the system changes state from $(j_0, 0, 1)$ to $(j_0 - 1, 0, 1)$ and to $(j_0 - 1, 1, 0)$ with transition rates $(1 - \theta) \mu_b$ and $\theta \mu_b$, respectively.

Based on the above analysis, the state transition diagram is illustrated in Figure 5.5. Let $\pi_{j_0,j_1,j_2}$ denote the steady-state probability of state $(j_0, j_1, j_2)$. The following steady-state balance equations can be obtained from the diagram.

For the three particular states $(0, 0, 0)$, $(L, 1, 0)$ and $(L, 0, 1)$, we have:

$$\pi_{0,0,0} \sum_{m=1}^{M} \lambda_m = \pi_{0,1,0} \mu_a + \pi_{0,0,1} \mu_b \quad (5.7)$$
$$\pi_{L,1,0} \mu_a = \pi_{L-1,1,0} \lambda_1 \quad (5.8)$$
$$\pi_{L,0,1} \mu_b = \pi_{L-1,0,1} \lambda_1 \quad (5.9)$$

For another two particular states $(0, 1, 0)$ and $(0, 0, 1)$, we have:

$$\pi_{0,1,0} \left( \sum_{m=1}^{M} \lambda_m + \mu_a \right) = \theta (\pi_{0,0,0} \sum_{m=1}^{M} \lambda_m + \mu_a \pi_{1,1,0} + \mu_b \pi_{1,0,1}) \quad (5.10)$$
$$\pi_{0,0,1} \left( \sum_{m=1}^{M} \lambda_m + \mu_b \right) = (1 - \theta) (\pi_{0,0,0} \sum_{m=1}^{M} \lambda_m + \mu_a \pi_{1,1,0} + \mu_b \pi_{1,0,1}) \quad (5.11)$$

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Figure 5.5: State diagram of the modelled system.
CHAPTER 5. CASE STUDY II: COGNITIVE RADIO AD-HOC NETWORK

For other states \((j_0, j_1, j_2) \in S\) satisfying \(0 < j_0 < L\), if \((L - h_1) < j_0 < L\), we have the equations:

\[
\begin{align*}
\pi_{j_0,1,1}(\lambda_1 + \mu_a) &= \pi_{j_0-1,1,1} \lambda_1 + \theta (\pi_{j_0+1,1,0} \mu_a + \pi_{j_0+1,0,1} \mu_b) \quad (5.12) \\
\pi_{j_0,0,1}(\lambda_1 + \mu_b) &= \pi_{j_0-1,0,1} \lambda_1 + (1 - \theta) (\pi_{j_0+1,1,0} \mu_a + \pi_{j_0+1,0,1} \mu_b) \quad (5.13)
\end{align*}
\]

Further, if \(\psi_m(L - \sum_{i=1}^{M-m+1} h_i) < j_0 \leq (L - \sum_{i=1}^{M-m} h_i)\), we have the equations:

\[
\begin{align*}
\pi_{j_0,1,0} \left( \sum_{i=1}^{M-m} \lambda_i + \xi_m \lambda_{M-m+1} + \mu_a \right) &= \pi_{j_0-1,1,1} \sum_{i=1}^{M-m+1} \lambda_i + \theta (\pi_{j_0+1,1,0} \mu_a + \pi_{j_0+1,0,1} \mu_b) \quad (5.14) \\
\pi_{j_0,0,1} \left( \sum_{i=1}^{M-m} \lambda_i + \xi_m \lambda_{M-m+1} + \mu_b \right) &= \pi_{j_0-1,0,1} \sum_{i=1}^{M-m+1} \lambda_i + (1 - \theta) (\pi_{j_0+1,1,0} \mu_a + \pi_{j_0+1,0,1} \mu_b) \quad (5.15)
\end{align*}
\]

where \(1 \leq m < M\), \(\psi_m\) equals zero if \(m = 1\) and one otherwise. \(\xi_m\) equals zero if the value of \(j_0\) is in the set \(\{(L - \sum_{i=1}^{M-m} h_i) | 1 \leq m < M\}\) and one otherwise.

By summing up all steady-state probabilities in conjunction with normalization constraint, we have:

\[
\sum_{(j_0, j_1, j_2) \in S} \pi_{j_0, j_1, j_2} = 1 \quad (5.16)
\]

The equations (5.7-5.16) help in constructing a set of linear equations. By solving them, all steady-state probabilities can be computed.
5.3.3 Performance Metrics

To study the packet transmission performance at SU $s_x$ side, the following performance metrics are used.

**Blocking Probability**

The newly arrived packets to SU $s_x$ consist of $M$ types. For a state $(j_0, j_1, j_2) \in S$, blocking of the type $T_1$ packets occurs for $j_0 = L$. Blocking of the type $T_m$ packets, where $1 < m \leq M$, occurs for $j_0 \geq (L - \sum_{i=1}^{m-1} h_i)$. Let $P_{bl,m}$ denote the blocking probability of the type $T_m$ packets, and it is given by:

$$[P_{bl,m}|m = 1] = \sum_{\forall j_0, j_1, j_2} \pi_{j_0, j_1, j_2} | j_0 = L] (5.17)$$

$$[P_{bl,m}|m = 2, \ldots, M] = \sum_{\forall j_0, j_1, j_2} \pi_{j_0, j_1, j_2} | j_0 \geq (L - \sum_{i=1}^{m-1} h_i) (5.18)$$

Given these blocking probabilities, the actual average arrival rate of packets to SU $s_x$, denoted by $\lambda_{eff}$, is formulated as:

$$\lambda_{eff} = \sum_{m=1}^{M} \lambda_m (1 - P_{bl,m}) (5.19)$$

**Transmission Throughput**

This is defined as the average rate of packets completing the transmission from SU $s_x$ to SU $s_d$. Let $R$ denote the transmission throughput for all types of SU packets. For every particular system state $(j_0, j_1, j_2) \in S$ for $j_0 \neq 0$, since there is only a single packet in transmission service, $R$ is given by:

$$R = \sum_{j_0=0}^{M} (\mu_a \pi_{j_0, 1, 0} + \mu_b \pi_{j_0, 0, 1}) (5.20)$$
Further, let $R_m$ denote the transmission throughput of the type $m$ packets. It is given by:

$$R_m = R \frac{\lambda_m (1 - P_{bl,m})}{\lambda_{eff}}$$  \hspace{1cm} (5.21)

where $m = 1, 2, ..., M$.

**Average Transmission Delay**

The transmission delay of a packet is given by the total time spent by the particular packet for the transmission from SU $s_s$ to SU $s_d$. Let $D$ denote the average delay time of a packet, including both time for queueing in the buffer and for transmission. To compute it, one needs to consider the average number of packets in the system, which is denoted by $N$ and it is given by:

$$N = \sum_{(j_0, j_1, j_2) \in S} \left[ (j_0 + j_1 + j_2) \pi_{j_0, j_1, j_2} \right]$$  \hspace{1cm} (5.22)

According to Little’s Theorem, $D$ is computed by:

$$D = \frac{N}{\lambda_{eff}}$$  \hspace{1cm} (5.23)

**5.4 Performance Evaluation**

In this section, numeric and simulation results are reported for performance evaluation of the modelled system. The evaluation focuses on the effectiveness of the suggested priority scheme for transmitting different types of packets in the presence of imperfect sensing.
5.4. PERFORMANCE EVALUATION

5.4.1 Parameter Settings

Without loss of generality, two different types of SU packets are considered, e.g., type $T_1$ and $T_2$. The type $T_1$ packets have higher priority than the type $T_2$. According to the CRNs standard IEEE 802.22 [9], the slot length $\delta$ is set equal to $10^{-2}$s. To make an adequate approximation using equation (5.2), the overlook error probability is set $\varepsilon = 0.93$, the arrival rates of type $T_1$ and $T_1$ packets $\lambda_1 = 5.0$ and $\lambda_2 \in \{2.5, 3.0\}$. Other parameter settings are reported in Table 5.1 [57]. For future work, other relevant set of parameters will be considered.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>The mean time period of channel $c$ being in busy state</td>
<td>$1/\alpha = 1/0.05$</td>
</tr>
<tr>
<td>The mean time period of channel $c$ being in free state</td>
<td>$1/\beta = 1/0.06$</td>
</tr>
<tr>
<td>The length of the buffer at SU $s_i$ side for queueing packets</td>
<td>$L = 32$</td>
</tr>
<tr>
<td>The reserved queueing slots for type $T_1$ packets</td>
<td>$h_1 \in {2, 7, 12, 17}$</td>
</tr>
<tr>
<td>The reserved queueing slots for type $T_2$ packets</td>
<td>$h_2 = 0$</td>
</tr>
</tbody>
</table>

5.4.2 Simulation Experiment

The simulation experiment is conducted to demonstrate the validity of the numerical analysis. The simulator is developed in C++. For every specific parameter setting, the simulator runs in looping manner within $\tau = 10^8$s simulation time, and each looping indicates a slot length $\delta = 10^{-2}s$ in the time domain. Seven simulation statistics with notations and definitions are
Table 5.2: Simulation Statistics in a Simulation Run

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>The number of arrived types $T_1$ SU packets.</td>
</tr>
<tr>
<td>$x_2$</td>
<td>The number of arrived types $T_2$ SU packets.</td>
</tr>
<tr>
<td>$y_1$</td>
<td>The number of blocked types $T_1$ SU packets.</td>
</tr>
<tr>
<td>$y_2$</td>
<td>The number of blocked types $T_2$ SU packets.</td>
</tr>
<tr>
<td>$z_1$</td>
<td>The number of transmitted types $T_1$ SU packets.</td>
</tr>
<tr>
<td>$z_2$</td>
<td>The number of transmitted types $T_2$ SU packets.</td>
</tr>
<tr>
<td>$w$</td>
<td>The number of loopings costed by all transmitted SU packets.</td>
</tr>
</tbody>
</table>

shown in Table 5.2. With these statistics, the performance metrics derived in Section 5.3.3 are computed as follows:

\[
P_{bl,1} = \frac{y_1}{x_1} \quad \quad \quad (5.24)
\]
\[
P_{bl,2} = \frac{y_2}{x_2} \quad \quad \quad (5.25)
\]
\[
D = \frac{w\delta}{(z_1 + z_2)} \quad \quad \quad (5.26)
\]
\[
R = \frac{(z_1 + z_2)}{\tau} \quad \quad \quad (5.27)
\]
\[
R_1 = \frac{z_1R}{(z_1 + z_2)} \quad \quad \quad (5.28)
\]
\[
R_2 = \frac{z_2R}{(z_1 + z_2)} \quad \quad \quad (5.29)
\]

5.4.3 Results and Discussions

The results of six performance metrics $P_{bl,1}/P_{bl,2}$, $D$, $R_1/R_2$ and $R$ are shown in Figs. 5.7(a), 5.7(b), 5.6(a) and 5.6(b), respectively. In each figure, the marker ‘+’ indicates the simulation results. From these figures, it is
5.4. PERFORMANCE EVALUATION

Figure 5.6: Numerical and simulation results of $R$ and $D$ versus the number of reserved queueing slots for type $T_1$ SU packets.

(a) $R$ versus $h_1$

(b) $D$ versus $h_1$
Figure 5.7: Numerical and simulation results of $P_{bl,1}$, $P_{bl,2}$, $R_1$ and $R_2$ versus the number of reserved queueing slots for type $T_1$ SU packets.
observed that the simulation results closely match the numerical results. Detailed discussions are as follows.

**For the same setting of \( \{\lambda_1, \lambda_2\} \)**

In Figure 5.7(a), it is observed that \( P_{bl,1} \) decreases with \( h_1 \), while \( P_{bl,2} \) increases with \( h_1 \). Figure 5.7(b) indicates that \( R_1 \) increases with \( h_1 \), while \( R_2 \) decreases with \( h_1 \). The reason for these is because when \( h_1 \) is increasing, the priority given to the type \( T_1 \) SU packets over the type \( T_2 \) becomes higher. As a result, the numbers of blocked SU packets are decreased and increased for types \( T_1 \) and \( T_2 \), respectively. Subsequently, the number of the transmitted type \( T_1 \) SU packets becomes larger, but the one for type \( T_2 \) becomes smaller.

Figs. 5.6(a) and 5.6(b) show that both \( R \) and \( D \) decrease with \( h_1 \). Further, the percentage decrease in \( D \) is much larger than the one in \( R \). Taking for example the case of \( \lambda_2 = 2.5 \), the value of \( R \) under \( h_1 = 17 \) is only about 0.6% smaller than the one under \( h_1 = 2 \). Whereas, the value of \( D \) under \( h_1 = 17 \) is about 18.5% smaller than the one under \( h_1 = 2 \).

These results indicate the effectiveness of the suggested priority scheme. Meaning, it can improve the transmission throughput of the particularly prioritized SU packets, and it can also reduce the average transmission delay for an arbitrary SU packet. The price is only a small decrease in the total transmission throughput of all SU packets.

**For the same value of \( h_1 \)**

Figure 5.7(a) shows that, under the same setting of \( \{\lambda_1, \lambda_2\} \), \( P_{bl,1} \) is smaller than \( P_{bl,2} \). This is because of the higher priority (i.e., \( h_1 > 0 \) and \( h_0 = 0 \)) that
is given to the type $T_1$ SU packets over the type $T_2$. Thus, the transmission throughput of the type $T_1$ SU packets is larger than the one of the type $T_2$, as shown in Figure 5.7(b).

Figure 5.7(a) also shows that both $P_{bl,1}$ and $P_{bl,2}$ increase with $\lambda_2$. This is because of the larger arrival rate of the type $T_2$ SU packets, which enhances the competition for transmission among all newly arrived SU packets at SU transmitter side. Since the mean arrival rate of the type $T_1$ SU packets does not change, i.e., $\lambda_1 = 5.0$, the increase in $P_{bl,1}$ leads to the decrease in $R_1$, as shown in Figure 5.7(b). However, when $\lambda_2$ is increasing, more type $T_2$ SU packets may compete for transmission and $R_2$ is increased. Further, because the total arrival rate (on average) of SU packets becomes larger, their total transmission throughput, i.e., $R$, is increased, as shown in Figure 5.6(a). Accordingly, the average transmission delay of SU packets, i.e., $D$, is also increased, as shown in Figure 5.6(b).

By comparing Figures 5.6(a) and 5.6(b), the second effectiveness of the suggested priority scheme can be observed. That is, when both $R$ and $D$ increase with $\lambda_2$, increasing $h_1$ can enhance the increase in $R$ and reduces the increase in $D$. For instance, when $\lambda_2$ is increased from 2.5 to 3.0, the percentage increase in $R$ under $h_1 = 17$ is about 197.2% larger than the one under $h_1 = 2$. Meanwhile, the percentage increase in $D$ under $h_1 = 17$ is about 52.1% smaller than the one under $h_1 = 2$.

5.5 Summary

The opportunistic spectrum access with imperfect spectrum sensing in one-hop based CR ad-hoc networks has been studied. A buffer reservation based priority scheme has been suggested to give priorities to different types of SU packets according to their QoS requirements. A two-stage parallel server
based queueing model $M/H_2/1$ was used to investigate the SU transmission performance. Three performance metrics were derived: blocking probabilities of different types of SU packets, average transmission delay of an arbitrary packet, and transmission throughput of SU packets. Performance evaluation shows that the suggested priority scheme can decrease the average transmission delay of SU packets only at the expense of small decrease in transmission throughput. Moreover, when mean arrival rate of SU packets is increased, the suggested priority scheme can reduce the increase of average transmission delay. The analytical results were validated by simulation results.
Chapter 6

Case Study III: Cognitive Radio Mesh Network

In Cognitive Radio Mesh Networks (CRMNs), the operation of transmitting packets from a source SU to a Gateway Router (GR) typically operates over multiple Mesh Routers (MRs). While, these packets may be blocked at a particular MR, with the consequence of the packet retransmission from the source SU to the particular MR. Therefore, the QoS performance of the whole system may degrade due to a large amount of packet retransmissions. To solve this problem, a queueing buffer based priority scheme is suggested for MRs. The goal is to accept the relayed SU packets with higher priority than the locally generated SU packets. Based on this scheme, the transmission performance of SUs in CRMNs is studied under the consideration of the imperfect spectrum sensing. The performance evaluation results show that the suggested priority scheme is able to significantly decrease the average end-to-end (e2e) transmission delay, together with minor decrease in the total e2e transmission throughput.
CHAPTER 6. CASE STUDY III: COGNITIVE RADIO MESH NETWORK

6.1 Introduction

Many studies done on CRMNs have focused on the critical research task of finding an available e2e routing path between a source SU and a GR. This task has two important components: i) selecting a set of suitable MRs to create the routing path, and ii) identifying the available channels for packet transmission between two neighboring MRs.

For instance, in [36] the authors suggested a distributed routing scheme for SUs in CRMNs. The goal is to avoid the e2e re-routing procedure due to the exposed or hidden router problem. In [34], the authors suggested a power-estimation based algorithmic framework to formulate the task of channel allocation in CRMNs. In [35], the authors studied the QoS performance of CRMNs by comparing with classic wireless mesh networks. They also suggested a general model for investigating the resource sharing in CRMNs, including both channel and MRs sharing. Further, in [37] the authors reported on the high complexity of the joint problem of finding the best routing path and selecting the available channels for optimizing the transmission throughput in CRMNs. Therefore, they suggested a heuristic algorithm to solve this joint problem. Similarly, in [38] the authors also studied the problem of joint design of routing and channel allocation algorithms for CRMNs. The difference is that their research objective is to minimize the aggregate e2e transmission delay of the whole CRMN system. To achieve this, they developed a distributed solution, which is based on the Lagrangian dual problem. However, these studies did not consider the priority scheduling at the MR side, which may have significant effect on the transmission performance of SUs in CRMNs.

Given an e2e routing path in CRMNs, a particular MR along this path may concurrently receive two different categories of SU packets. The first
category of SU packets are relayed from the neighboring MRs of this particular MR, the so-called relayed packets. Clearly, a relayed SU packet is originally generated from a source SU, which is located within the radio range of another MR. The second category of SU packets are originally generated from the source SUs, which are located within the radio range of the particular MR, the so-called local packets. Either relayed or local packets may be blocked by the particular MR due to its hardware limitation. Compared with blocking a local packet, blocking a relayed packet may interrupt the packet transmission from a source SU to its destination, thus creating the packet retransmission from the source SU to the particular MR. As a result, the QoS performance (e.g., e2e delay, throughput) along the given e2e routing path may degrade. Subsequently, to alleviate such degradation, the particular MR needs to give transmission priority to the relayed packets over the local ones.

In this chapter, a realistic CRMN is considered in the presence of imperfect spectrum sensing. A queueing buffer based priority scheme is suggested for the MRs along the e2e routing path. A two-stage parallel serve based queuing model is developed to study the e2e transmission performance of SUs. Three performance metrics are derived for conducting the performance evaluation. The are the average e2e transmission delay, the individual e2e transmission throughput of each MR and the total e2e transmission throughput of the whole system.

\section{System Model}

As shown in Figure 6.1, a CRMN is considered coexisting with an infrastructure based primary network. In the primary network, a Primary Base Station (PBS) provides wireless access to PUs through a set of licensed
CHAPTER 6. CASE STUDY III: COGNITIVE RADIO MESH NETWORK

channels, which is denoted as $\mathbb{C}$. The CRMN is assumed to be located within the radio range of PBS. It includes a GR and a set of MRs, which is denoted as $\mathbb{R}$.

![Diagram of a CR mesh network coexisting with an infrastructure based primary network.]

**Figure 6.1:** A CR mesh network coexists with an infrastructure based primary network.

6.2.1 Network Model

In the considered CRMN system, the GR can be like a secondary base station or a support node [30] [13]. It is connected to the Internet using the wired cable and provides the Internet access to SUs.

For a particular MR in the set $\mathbb{R}$, it is assumed to use two different channels allocated from the channel set $\mathbb{C}$. The first channel is used to receive packets from the SUs located within the radio range of the particular MR, the so-called Allocated Channel for Local (AC-L). While, the second one is used to relay packets from/to the neighboring MRs of the particular MR, the so-called Allocated Channel for Relay (AC-R). Accordingly, the channel allocation to all MRs belonging to set $\mathbb{R}$ can be done by using sig-
nalling protocols like, e.g., information exchange among neighboring MRs. Further, with these signalling protocols, the e2e routing path over the multiple MRs and the GR is assumed to be prescribed when the whole CRMN is built up. Since there may exist multiple different e2e routing paths for SUs, the set of these paths are denoted as $\mathbb{P}$.

It is also assumed that the transmission interference and the hidden problem among MRs can be avoided based on the above mentioned signalling protocols. The focus is laid instead on a particular e2e routing path $\mathbb{P}^* \in \mathbb{P}$, which consists of $K$ MRs, as shown in Figure 6.2. These MRs are labeled by $R_1, R_2, ..., R_K$, respectively. Let $\mathbb{R}^*$ and $\mathbb{C}^*$ denote the sets of these $K$ MRs and their used channels, respectively. They are the subsets of $\mathbb{R}$ and $\mathbb{C}$, i.e., $\mathbb{R}^* \subseteq \mathbb{R}$ and $\mathbb{C}^* \subseteq \mathbb{C}$. For a particular MR $R_k \in \mathbb{R}^*$ where $k = 1, 2, ..., K$, its AC-L and AC-R channels are denoted by $C_{L,k}$ and $C_{R,k}$.

Moreover, the geographical location and packet transmission of each MR $R_k \in \mathbb{R}^*$ are assumed to be constrained as below:

- MR $R_1$ has the farthest hop away from the GR, MR $R_K$ is only one hop away from the GR.

- The radio range of MR $R_1$ is partially overlapped with MR $R_2$. The radio range of MR $R_k$ is partially overlapped with both MR $R_{k-1}$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.2.png}
\caption{Uplink transmission along a particular e2e routing path.}
\end{figure}
and MR $R_{k+1}$, where $k = 2, 3, ..., K - 1$. The radio range of MR $R_K$ is partially overlapped with the GR.

- MR $R_k$ uses the channel $C_{R,k}$ to transmit the SU packets to MR $R_{k+1}$ for $0 \leq k < K$, or to the GR for $k = K$.

- For the SU packets originally transmitted\(^1\) from MR $R_k$, other MRs $\{R_k | k < k' \leq K\}$ are responsible for providing relay service, the so-called relay MRs.

\section*{6.2.2 PU Model}

For each channel in set $\mathbb{C}^*$, the transmission activity of PUs in this particular channel is assumed to use a synchronous time-slotted basis. The length of every slot identically equals $\delta$ in the time domain. In every slot, PUs are either present or absent in the channel during the whole slot duration. The channel occupancy by PUs is assumed to follow a two-state busy-free Markov process. State \textit{busy} means the event that a PU is occupying a channel for one or more consecutive slots. Similarly, state \textit{free} means the event that there is no PU in the channel for one or more consecutive slots. The time periods of the two states \textit{busy} and \textit{free} are integer times of $\delta$. They are assumed to be exponentially distributed with mean values $1/\alpha$ and $1/\beta$, respectively.

\section*{6.2.3 SU and MR Models}

By considering the previously described e2e routing path $P^*$, the uplink transmission is defined as the packet transmission from the SU side to the

\(^1\)These SU packets are originally generated by the SUs which are located within the radio range of MR $R_k$.  

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GR. The packet transmission at the MR side is described below.

Every MR in the set $\mathbb{R}^*$ can perform a long-term spectrum sensing on its two allocated channels $C_{L,k}$ and $C_{R,k}$. By long-term, it is meant that the sensing time is long enough (e.g., over multiple PU slots), so that the MR can realize the transmission activity of PUs. Further, if a particular SU is located within the radio range of a MR, it can register the request for channel access through this MR. The registration can be done by performing the above mentioned signalling protocols over the AC-L channel provided by the MR. After that, the particular SU can obtain the information about the transmission activity of PUs. As a result, the transmission activities of SUs and MRs can also operate in a time-slotted basis, which has an uniform slot length $\delta$ same with PUs.

![Figure 6.3: Transmission activity of SU or MR operates in time-slotted manner, with the slot length $\delta$.](image)

As shown in Figure 6.3, each SU or MR slot consists of two phases: spectrum sensing and packet transmission. Simply put, a particular MR $R_k \in \mathbb{R}^*$ and its registered SUs are considered. During the spectrum sensing phase of a slot, MR $R_k$ and these SUs perform a short-term spectrum sensing on channels $C_{R,k}$ and $C_{L,k}$, respectively:

- For MR $R_k$, if the channel $C_{R,k}$ is sensed to be free, this particular MR transmits a packet to the next router, which is one hop closer to the GR. If $k < K$, the next router is MR $R_{k+1}$. If $k = K$, the next
router is the GR. The packet transmission is carried out during the second phase, and a successful transmission can be acknowledged by the next router at the end of the slot.

- For SUs, if the channel $C_{L,k}$ is sensed to be free, they are allowed to transmit packets to MR $R_k$ during the second phase. Their packet transmissions are assumed to follow a CSMA/CA-like protocol model, so that the collision among them can be alleviated\(^2\). Further, the successful transmission of a particular SU is acknowledged by MR $R_k$ at the end of the slot.

However, due to sensing-duration limitation, the short-term spectrum sensing may lead to imperfect sensing results in terms of overlook error and misidentification error. Overlook means that a free channel is sensed to be busy, while misidentification means that a busy channel is sensed to be free. Only the overlook error is considered in the system model. This is because that, for either a MR or a SU, a successful transmission occurs only during the time period when its used channel is free\(^3\).

### 6.2.4 Priority Scheduling

It is assumed that the arrivals of the SU packets at MR $R_k \in \mathbb{R}^*$ independently follow the Poisson processes with mean rates $\lambda_k$ and $\gamma_k$ for relayed and for local packets, respectively. As hardware limitation, the MR $R_k$ is assumed to be equipped with a finite buffer. The goal is to queue the

\(^2\)It is assumed that in each slot, only a single SU can successfully transmit a packet to the MR.

\(^3\)If a transmitter (either a MR or a SU) transmits a packet under the misidentification error, the packet transmission collides with PUs. Thus, this transmitter experiences unsuccessful transmission by missing acknowledgment message from the receiver.
newly arrived packets (either relayed packets or local packets) when MR $R_k$ is transmitting a packet. The buffer length is denoted as $l_k$. It equals to the maximum number of idle queueing slots for saving SU packets, when the entire buffer is empty. Each queueing slot can only save a single SU packet at a time.

Further, $h_k$ out of $l_k$ queueing slots are reserved for the relayed packets. If $h_k > 0$, the relayed packets are given higher priority over the local packets. When a relayed packet arrives and one or more queueing slots are idle, the relayed packet is accepted. Otherwise, the relayed packet is blocked. When a local packet arrives, it is accepted if at least $(h_k + 1)$ queueing slots are idle. Otherwise, the local packet is blocked. To avoid that the local packets are blocked altogether, $h_k$ is less than $l_k$. Particularly, since MR $R_1$ only receives the local packet, this gives rise to two constraints $\lambda_1 = 0$ and $h_1 = 0$.

### 6.2.5 Retransmission Scheme

A particular SU is considered to be located within the radio range of MR $R_k \in \mathbb{R}^*$. This particular SU generates the packets and transmits them to MR $R_k$. Naturally, these SU packets may be blocked at the MRs $R_{k'}$ satisfying $R_{k'} \in \mathbb{R}^*$ and $k' \geq k$.

When the event of blocking a SU packet occurs at MR $R_{k'}$, it is assumed that this event can be informed to that particular SU by using collaborative communication among the MRs\footnote{Such collaborative communication can be done through a Common Control Channel (CCC) shared by both MRs and SUs.}. As a result, the blocked SU packet needs to be retransmitted from that particular SU to its destination, the so-called retransmitted packet.

Depending on the specific value of $k'$, MR $R_{k'}$ has different ways to deal
with the retransmitted packets from the particular SU.

- For the case of $k' = k$, MR $R_k'$ treats these retransmitted SU packets as local SU packets.

- For the case of $k' > k$, MR $R_k'$ treats these retransmitted SU packets as relay SU packets.

Moreover, for all SUs located within the radio range of MR $R_k$, their average packet retransmission rate is denoted by $\vartheta_k$. The arrivals of these SU packets at MR $R_k$ side are assumed to follow the Poisson process.

### 6.3 Queueing Analysis

For simplicity purposes, it is assumed that the packet transmission between SUs and MRs via the AC-L channels are based on the situation of perfect spectrum sensing (i.e., there are no sensing errors). The focus of the analysis is laid on the prioritized packet transmission among MRs via the AC-R channels in the presence of imperfect spectrum sensing.

#### 6.3.1 Spectrum Access under Imperfect Sensing

For a particular MR $R_k \in \mathbb{R}^*$, we consider the time period of $m$ consecutive slots, during which the AC-R channel $C_{R,k}$ of MR $R_k$ is free to use. In other words, the PUs are absent in channel $C_{R,k}$ during this time period.

Let $t$ denote the above time, which is equal to $m\delta$. Further, in each of the $m$ slots, MR $R_k$ may not transmit a packet (either a relayed packet or a local packet) with probability $\varepsilon_k$ due to the overlook error, the so-called
overlook probability. This also indicates that the probability of a successful
transmission in a slot is equal to \((1 - \varepsilon_k)\).

Let \(p_r^{(k)}(n;m,(1 - \varepsilon_k))\) denote the probability of \(n\) successful trans-
missions within time period \(t\) at the MR \(R_k\) side, where \(0 \leq n \leq m\). Similar to
the approximation method used in subsection 5.3.1, one can formulate the
equation below:

\[
p_r^{(k)}(n;m,(1 - \varepsilon_k)) \simeq e^{-\eta_t}(\eta_t)^n/n!
\]

where \(\eta_t = m(1 - \varepsilon_k)\), and the denotation \(\eta_t\) denotes the mean rate of
successful transmissions within the time interval \((0,t]\). In other words, the
value of \(1/\eta_t\) can be considered as the mean service time for transmitting a
packet from MR \(R_k\) to MR \(R_{k+1}\). Given \(t = m\delta\), the value of \(\eta_t\) is computed
as:

\[
\eta_t = \frac{m(1 - \varepsilon_k)}{t} = \frac{1 - \varepsilon_k}{\delta}
\]

Clearly, the successful transmission of a SU packet from MR \(R_k\) to MR \(R_{k+1}\) only takes place when channel \(C_{R,k}\) is free, while there is no transmis-
sion service available for MR \(R_k\) when \(C_{R,k}\) is busy (i.e., PUs being present
in \(C_{R,k}\)). Subsequently, similar to equations (5.4) and (5.5), the packet
transmission at MR \(R_k\) side can be modeled as an IPP. The corresponding
probability density function of service time is given by:

\[
f(t) = \theta_k \mu_{a,k} e^{-\mu_{a,k}t} + (1 - \theta_k) \mu_{b,k} e^{-\mu_{b,k}t}
\]

where:

\[
\begin{align*}
\theta_k &= \frac{\eta_k - \mu_{b,k}}{\mu_{a,k} - \mu_{b,k}} \\
\mu_{a,k} &= \frac{\eta_k + \alpha + \beta + [(\eta_k + \alpha + \beta)^2 - 4\eta_k\beta]^{1/2}}{2} \\
\mu_{b,k} &= \frac{\eta_k + \alpha + \beta - [(\eta_k + \alpha + \beta)^2 - 4\eta_k\beta]^{1/2}}{2}
\end{align*}
\]
For simplicity purposes, it is assumed that the overlook probability $\varepsilon_k$ at each MR has the same value $\varepsilon$, i.e., $\varepsilon = \varepsilon_k$. Therefore, we have $\eta = \eta_k$, $\theta = \theta_k$, $\mu_a = \mu_{a,k}$ and $\mu_b = \mu_{b,k}$. The equation (6.3) can then be further modelled by a two-stage parallel server based queueing system, as shown in Figure 6.4.

In the figure, the large oval represents the server facility, where a particular packet at MR $R_k$ side approaches from the left. Transmitting this particular packet to MR $R_k$ is proceeded to service stage 1 with probability $\theta$ or to service stage 2 with probability $(1 - \theta)$. Transmission spends the exponentially distributed service time with mean values $1/\mu_a$ and $1/\mu_b$ for stage 1 and stage 2, respectively. After the particular service time, a successful packet transmission is accomplished and only then a new packet transmission is allowed into the service facility.

According to subsection 6.2.2, since the PU activity is assumed to be the same in every channel in the set $C^*$, the two-stage parallel server based queueing system is suitable for every MR in the set $R^*$. 

Figure 6.4: A two-stage parallel server.
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6.3.2 Queueing Model

Clearly, the packet transmission of each MR in the set $\mathbb{R}^*$ is independent from each other. Therefore, a queueing model is built up for a particular MR $R_k$.

Let a set of three integers $(j_{k,0}, j_{k,1}, j_{k,2})$ denote a system state that $j_{k,0}$ packets are in the queuing buffer of MR $R_k$, and $j_{k,1}$ and $j_{k,2}$ packets are served by the stages $a$ and $b$, respectively. Given the buffer length is equal to $l_k$, the value of $j_{k,0}$ is in the set $\{0, 1, \ldots, l_k\}$. Since only one of two service stages can be activated for transmission at a time, the values of $j_{k,1}$ and $j_{k,2}$ are constrained by $0 \leq (j_{k,1} + j_{k,2}) \leq 1$. Therefore, the system state space of MR $R_k$ is given by $S_k = \{(j_{k,0}, j_{k,1}, j_{k,2})| j_{k,0} \in \{0, 1, \ldots, l_k\}; j_{k,1}, j_{k,2}, (j_{k,1} + j_{k,2}) \in \{0, 1\}\}$. Considering a system state $(j_{k,0}, j_{k,1}, j_{k,2}) \in S_k$, the state transitions are described as follows.

A new packet arrives at MR $R_k$

- Given that $h_k$ out of $l_k$ queueing slots are reserved for relay packets, for $0 \leq j_{k,0} < (l_k - h_k)$, the packet is accepted for either relayed or for local packet. The acceptance rate equals $(\lambda_k + \gamma_k)$. For $(l_k - h_k) \leq j_{k,0} \leq l_k$, only a newly relayed packet is accepted according to the priority scheme. The acceptance rate equals $\lambda_k$.

- For $j_{k,0} = j_{k,1} = j_{k,2} = 0$, the server facility has no packet in transmission service, so that the newly accepted packets are proceeded to service stages 1 and 2 with rates $\theta(\lambda_k + \gamma_k)$ and $((1 - \theta)(\lambda_k + \gamma_k))$, respectively.
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A packet is transmitted to MR $R_k$

- For $j_{k,0} = 0$ and $(j_{k,1} + j_{k,2}) = 1$, there exists one packet in transmission service and there is no queued packet in the buffer. Hence, the service rate is equal to $\mu_a$ and $\mu_b$ for stage 1 and stage 2, respectively.

- For $j_{k,0} \neq 0$, $j_{k,1} = 1$ and $j_{k,2} = 0$, a packet transmission is in stage 1 with service rate $\mu_a$. When this transmission is finished, a queued packet is proceeded to service stages 1 and 2 with probabilities $\theta$ and $(1 - \theta)$. Meanwhile, the system state changes from $(j_{k,0},1,0)$ to $(j_{k,0} - 1,1,0)$ and to $(j_{k,0} - 1,0,1)$ with transition rates $\theta \mu_a$ and $(1 - \theta)\mu_a$, respectively.

- For $j_{k,0} \neq 0$, $j_{k,1} = 0$ and $j_{k,2} = 1$, a packet transmission is in stage 2 with service rate $\mu_b$. Similar to the above case, after the packet is transmitted, the system state changes from $(j_{k,0},0,1)$ to $(j_{k,0} - 1,0,1)$ and to $(j_{k,0} - 1,1,0)$ with transition rates $(1 - \theta)\mu_b$ and $\theta \mu_b$, respectively.

![State diagram of the modelled system.](image)

**Figure 6.5:** State diagram of the modelled system.

Based on the above analysis, the state transition diagram is presented in Figure 6.5. Let $\pi_{j_{k,0},j_{k,1},j_{k,2}}^{(k)}$ denote the steady-state probability of the MR $R_k$
being in state \((j_k,0,j_k,1,j_k,2)\). The following steady-state balance equations can be obtained from the diagram. For the MR \(R_k\) being in three particular states \((0,0,0)\), \((l_k,1,0)\) and \((l_k,0,1)\), we have:

\[
\begin{align*}
\pi_{0,1,0}^{(k)}(\lambda_k + \gamma_k) &= \theta(\mu_a \pi_{1,1,0}^{(k)} + \mu_b \pi_{1,0,1}^{(k)}) \\
\pi_{k,1,0}^{(k)} \mu_a &= \lambda_k \pi_{k-1,1,0}^{(k)} \\
\pi_{k,0,1}^{(k)} \mu_b &= \lambda_k \pi_{k-1,0,1}^{(k)}
\end{align*}
\]

(6.5) (6.6) (6.7)

For the MR \(R_k\) being in two particular states \((0,1,0)\) and \((0,0,1)\), we have equations (6.8) and (6.9). For the MR \(R_k\) being in other states of \(0 < j_k,0 < l_k\), we have equations (6.10) and (6.11) where \(\xi\) equals one if \(j_k,0 < (l_k - h_k)\) and zero otherwise.

\[
\begin{align*}
(\lambda_k + \gamma_k + \vartheta_k + \mu_a) \pi_{0,1,0}^{(k)} &= \theta \left[(\lambda_k + \gamma_k + \vartheta_k) \pi_{0,0,0}^{(k)} + \mu_a \pi_{1,1,0}^{(k)} + \mu_2 \pi_{1,0,1}^{(k)}\right] \\
(\lambda_k + \gamma_k + \vartheta_k + \mu_b) \pi_{0,0,1}^{(k)} &= (1 - \theta) \left[(\lambda_k + \gamma_k + \vartheta_k) \pi_{0,0,0}^{(k)} + \mu_a \pi_{1,1,0}^{(k)} + \mu_2 \pi_{1,0,1}^{(k)}\right] \\
[\lambda_k + \xi(\gamma_k + \vartheta_k)] \pi_{j_k,0,1,0}^{(k)} &= [\lambda_k + \xi(\gamma_k + \vartheta_k)] \pi_{j_k,0,1,0}^{(k)} + \theta(\mu_a \pi_{j_k,0,1,0}^{(k)} + \mu_2 \pi_{j_k,0,1,0}^{(k)}) \\
[\lambda_k + \xi(\gamma_k + \vartheta_k)] \pi_{j_k,0,0,1}^{(k)} &= [\lambda_k + \xi(\gamma_k + \vartheta_k)] \pi_{j_k,0,0,1}^{(k)} + (1 - \theta)(\mu_1 \pi_{j_k,0,1,0}^{(k)} + \mu_2 \pi_{j_k,0,1,0}^{(k)})
\end{align*}
\]

(6.8) (6.9) (6.10) (6.11)

By summing up all steady-state probabilities in conjunction with normalization constraint, the following is obtained:

\[
\sum_{\forall j_k,0,j_k,1,j_k,2 \in \mathbb{S}_k} \pi_{j_k,0,j_k,1,j_k,2}^{(k)} = 1
\]

(6.12)
6.3.3 Computation of Steady-State Probabilities

Based on the above equations (6.5-6.12), a set of linear equations can be constructed. By solving them, all steady-state probabilities of MR $R_k$ can be expressed in terms of parameters $\lambda_k, \varphi_k, l_k, h_k, \mu_a, \mu_b$ and $\theta$.

Clearly, the values of $l_k$ and $h_k$ are related to the priority configuration at the MR $R_k$ side, and the values of $\mu_a, \mu_b$ and $\theta$ are given by equation (6.4). Further, the value of $\gamma_k$ and $\vartheta_k$ is connected with the SUs activity at the MR $R_k$. Moreover, due to the event of blocking the SU packets at the MR $R_{k-1}$, the average rate of relayed packets from the MR $R_{k-1}$ to $R_k$, i.e., $\lambda_k$, depends on several parameters: $\lambda_{k-1}, \gamma_{k-1}, \vartheta_{k-1}$, and also the blocking probabilities of local, retransmitted and relayed packets at the MR $R_{k-1}$. Based on this, the computation of steady-state probabilities is presented below.

According to subsection 6.3.2, the event of blocking either a local or a retransmitted SU packet occurs for $(l_k - h_k) \leq j_{k,0} < l_k$. While, the event of blocking a relayed SU packet occurs for $j_{k,0} = l_k$. Let $P_{bl,l}^{(k)}$ denote the blocking probability of both the local and the retransmitted SU packets, and let $P_{bl,r}^{(k)}$ denote the blocking probability of the relayed SU packets. We then obtain:

$$P_{bl,l}^{(k)} = \sum_{(j_{k,0},j_{k,1},j_{k,2}) \in S_k} \prod_{j_{k,0},j_{k,1},j_{k,2}} \mathbb{P}_{bl,l}^{(k)}$$

$$P_{bl,r}^{(k)} = \sum_{(j_{k,0},j_{k,1},j_{k,2}) \in S_k} \prod_{j_{k,0},j_{k,1},j_{k,2}} \mathbb{P}_{bl,r}^{(k)}$$

Based on these two blocking probabilities, let $\lambda_k^*$ denote the actual average rate of SU packets arriving at the MR $R_k$. $\lambda_k^*$ is computed by:

$$\lambda_k^* = \lambda_k \left(1 - P_{bl,r}^{(k)}\right) + (\gamma_k + \vartheta_k) \left(1 - P_{bl,l}^{(k)}\right)$$
Naturally, these arrived packets are the packets that will be transmitted from MR $R_k$ to MR $R_{k+1}$. In other words, the value of $\lambda_k^*$ is equal to the average arrival rate of the relayed packets at the MR $R_{k+1}$, i.e., $\lambda_{k+1}$. Hence, a serial of equations can be formulated as follows:

\begin{align*}
\lambda_k & = \lambda_{k-1}^* \\
\lambda_{k-1} & = \lambda_{k-2}^* \\
... & = ... \\
\lambda_2 & = \lambda_1^* 
\end{align*}  \hspace{1cm} (6.16)

Given the constraint $\lambda_1 = 0$ (see subsection 6.2.4), the equation (6.18) is equivalent to:

$$
\lambda_2 = (\gamma_1 + \vartheta_1) \left( 1 - P_{bl,l}^{(l)} \right) 
$$  \hspace{1cm} (6.19)

By substituting this serial of equations into the set of linear equations (6.8-6.12), all steady-state probabilities of each MR $R_k \in \mathbb{R}^*$ can be eventually computed.

### 6.3.4 Performance Metrics

To explore the SU’s uplink transmission performance along the e2e routing path $P^* \in \mathbb{P}$, the three performance metrics are studied. They are the average e2e transmission delay, the individual transmission throughput for every MR and the total transmission throughput for the whole system.

#### Average E2E Transmission Delay

The e2e transmission delay of a packet means the total time spent by the packet for transmission from the source SU to the GR. Its value equals
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The sum of the waiting time of this particular packet at each arrived MR. Let $D_k$ denote the average waiting time experienced by an arbitrary packet at MR $R_k \in \mathbb{R}^*$, including both time for queueing in the buffer and for transmission. To compute $D_k$, the average number of packets in MR $R_k$ needs to be considered, which is denoted by $N_k$ and it is computed by:

$$N_k = \sum_{(j_{k,0}, j_{k,1}, j_{k,2}) \in S_k} \left[ (j_{k,0} + j_{k,1} + j_{k,2}) \pi_{j_{k,0}, j_{k,1}, j_{k,2}}^{(k)} \right]$$  \hspace{1cm} (6.20)

According to Little’s Theorem, $D_k$ is computed by:

$$D_k = \frac{N_k}{\lambda_k^*}$$  \hspace{1cm} (6.21)

Subsequently, the average e2e transmission delay is given by:

$$\bar{D} = \sum_{k=1}^{K} D_k$$  \hspace{1cm} (6.22)

Individual E2E Transmission Throughput

The individual e2e transmission throughput is associated with each MR along the e2e routing path. For a particular MR, this metric is defined as the average rate of the packets provided that the SUs located within this particular MR successfully transmitted their packets to the destination GR.

Let $T_k$ denote the individual transmission throughput for the MR $R_k \in \mathbb{R}^*$. As described in subsections 6.2.1 and 6.2.5, the SU packets originally transmitted from MR $R_k$ may be blocked as local packets by MR $R_k$ with probability $P_{bl,l}^{(k)}$. They may also be blocked as relayed packets by other MRs $R_{k'} > k \in \mathbb{R}^*$ with probability $P_{bl,l}^{(k')}$. Therefore, given that the SU packets arrive at MR $R_k$ with rate $(\gamma_k + \theta_k)$, $T_k$ is computed by:
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\[ T_k = (\gamma_k + \vartheta_k) \left( 1 - P^{(k)}_{bl,l} \right) \prod_{k' = k+1}^{K} \left( 1 - P^{(k')}_{bl,r} \right) \] (6.23)

Total E2E Transmission Throughput

The total transmission throughput is connected with the transmission capacity along the whole e2e routing path. This metric is defined as the average rate of the SU packets successfully transmitted from the SUs to the GR. Let \( T \) denote the total transmission throughput. \( T \) is equal to the sum of the individual e2e transmission throughputs of all MR along the e2e routing path:

\[ T = \sum_{k=1}^{K} T_k \] (6.24)

6.3.5 Determination of Retransmission Rate

So far, the retransmission rate of SU packets at a particular MR \( R_k \in \mathbb{R}^* \), i.e., \( \vartheta_k \), is assumed to be priorly known. But in reality, it relies on the blocking probability of local and retransmitted SU packets at the MR \( R_k \), and the blocking probability of relayed packets at any other MR \( R_{k'} \in \mathbb{R}^* \) satisfying \( k' > k \).

Specifically, the value of \( \vartheta_k \) should equal the rate of those SU packets, which are originally transmitted form MR \( R_k \), and not completing the transmission to the destination GR. Therefore:

\[ \vartheta_k = \gamma_k \left[ 1 - \left( 1 - P^{(k)}_{bl,l} \right) \prod_{k' = k+1}^{K} \left( 1 - P^{(k')}_{bl,r} \right) \right] \] (6.25)

With regard to the equations (6.13 - 6.25), changing the value of \( \vartheta_k \)
also changes the individual e2e transmission throughput at the at MR $R_k$ side, i.e., $T_k$. Such that, the rate of the relayed SU packets arriving at the MR $R_{k+1}$ side is also changed, together with the changes in its blocking probabilities of the local and relayed SU packets, i.e., $P^{(k+1)}_{bl,l}$ and $P^{(k+1)}_{bl,r}$. By considering these changes, the determination of retransmission rate of SU packets at each MR $R_k \in \mathbb{R}^*$ follows an iteration method described by Algorithm 2.

**Algorithm 2: Determine the values of $\vartheta_1$, $\vartheta_2$,..,$\vartheta_K$**

1: $\text{LoopTag} \leftarrow \text{TRUE}$ \hspace{1cm} ▷ Initial tag for following loops.
2: while $k = 1 : K$ do
3: \hspace{1cm} $\vartheta_k \leftarrow 0$ \hspace{1cm} ▷ Initial retransmission rates.
4: end while
5: while $\text{LoopTag} = \text{TRUE}$ do
6: \hspace{1cm} $\text{TempNo} \leftarrow 0$ \hspace{1cm} ▷ Number of determined $\vartheta_k \in \{\vartheta_k | k = 1,2,...,K\}$.
7: \hspace{1cm} while $k = 1 : K$ do
8: \hspace{2cm} Compute $T_k$
9: \hspace{2cm} if $[\vartheta_k - (\gamma_k - T_k)] \geq \epsilon$ then \hspace{1cm} ▷ $\epsilon = 10^{-2}$
10: \hspace{3cm} $\vartheta_k \leftarrow \vartheta_k - \epsilon / 2$
11: \hspace{2cm} else if $[\vartheta_k - (\gamma_k - T_k)] \leq -\epsilon$ then
12: \hspace{3cm} $\vartheta_k \leftarrow \vartheta_k + \epsilon / 2$
13: \hspace{2cm} else
14: \hspace{3cm} $\text{TempNo} = \text{TempNo} + 1$ \hspace{1cm} ▷ $\vartheta_k$ is temporarily determined.
15: \hspace{2cm} end if
16: end while
17: if $\text{TempNo} = K$ then
18: \hspace{1cm} $\text{LoopTag} \leftarrow \text{FALSE}$
19: end if
20: end while \hspace{1cm} ▷ If all of $\vartheta_1$, $\vartheta_2$,..,$\vartheta_K$ are determined, the program then stops.

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6.4 Performance Evaluation

In this section, numeric results for the performance evaluation of the modelled system are presented. The evaluation is focused on the effectiveness of the suggested priority scheme for e2e uplink transmission from the source SUs to the GR in the presence of imperfect sensing.

6.4.1 Parameter Settings

Without loss of generality, a particular e2e routing path consisting of five MRs is considered. Similar to the parameter settings presented in section 5.4.2, other parameters are configured as follows. The slot length $\delta$ is configured to equal $10^{-2}s$. The overlook error probability is configured as $\varepsilon = 0.93$. The parameter related to the PUs activity and the local SU packets are configured as: $\alpha = 0.05$, $\beta = 0.06$ and $\gamma_k = 3.0$, where $k = 1, 2, 3, 4$.

Regarding the priority scheduling, the buffer length of each MR $R_k$ is configured to equal a constant value 32, i.e., $l_1 = l_2 = l_3 = l_4 = 32$. Further, the number of queueing slots reserved by each MR is configured to equal an integer variable $h$. The value of $h$ is in the set $\{5, 7, 12, 17\}$. For future work, other relevant set of parameters will be considered.

6.4.2 Results and Discussions

Figures 6.6(a), 6.6(b), 6.7(a) and 6.7(b) show the results of the retransmission rate of each MR, i.e., $\{\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4\}$, the individual e2e transmission throughput of each MR, i.e., $\{T_1, T_2, T_3, T_4\}$, the average e2e transmission delay $\overline{D}$ and the total transmission throughput of the whole system $T$, respectively.
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Figure 6.6: Numerical results of $\vartheta_k$ and $T_k$ versus the number of reserved queueing slots for relayed SU packets.
Figure 6.7: Numerical results of $\bar{D}$ and $T$ versus the number of reserved queueing slots for relayed SU packets.
Figures 6.6(a) and 6.6(b) show that, when the number of reserved queueing slots for relayed SU packets is increasing, different MRs may have different trends of change in either the retransmission rate or the individual e2e transmission throughput:

- For MR $R_1$, $\vartheta_1$ decreases with $h$, while $T_1$ increases with $h$.
- For MR $R_2$, $\vartheta_2$ first decreases with $h$ and then increases with $h$. $T_2$ first increases with $h$ and then decreases with $h$.
- For MR $R_3$, $\vartheta_3$ increases with $h$, and $T_3$ decreases with $h$
- For MR $R_4$, $\vartheta_4$ increases with $h$, and $T_4$ decreases with $h$

By considering a particular MR, the explanation of these results is as follows.

- Usually, farther the particular MR is located from the GR, more relay MRs are needed for constituting an e2e routing path from this particular MR to the GR. As a result, the SU packets originally transmitted from this particular MR demand more relay services before reaching GR, and thus there is a bigger probability of being blocked.

- By applying the suggested priority scheduling scheme in each relay MR, the SU packets originally transmitted from the particular MR are given higher priority for transmission, so that the possibility of blocking these packets at each relay MR side is decreased. Therefore, the retransmission rate of SU packets at the particular MR may decrease, and the individual e2e transmission throughput may increase.

- In contrast to the above case, closer the particular MR is located from the GR, more relayed SU packets this particular MR needs to deal
with. The consequence is that more local SU packets originally transmitted from this particular MR are blocked due to lower transmission priority than the relayed SU packets. Subsequently, the retransmission rate of these local SU packets may be increased, such that their e2e transmission throughput may be decreased.

Figure 6.7(b) shows that the total e2e transmission throughput along the whole e2e routing path, i.e., $T$, decreases with $h$. This is because, for each MR, the transmission priority is given to the relayed SU packets over the local SU packets. Further, higher this transmission priority is, more local SU packets are likely to be blocked. As a result, the system’s capacity of accepting the local SU packets (including the retransmitted ones) is decreased. Subsequently, $T$ is decreased.

Although, the suggested priority scheme leads to the decrease in $T$ when $h$ is increasing. However, this has a big advantage in that the average e2e transmission delay, i.e., $\bar{D}$, decreases with $h$, as shown in Figure 6.7(a). Moreover, by comparing Figures 6.7(b) and 6.7(a), one can observe the significant effectiveness of the suggested priority scheme. That is, increasing $h$ actually gives rise to minor decrease in $T$ and significant decrease in $\bar{D}$. For instance, when $h$ is increased from 10 to 30, the percentage decrease in $T$ under $h = 30$ is about 8% smaller than the one under $h = 10$. Meanwhile, the percentage increase in $\bar{D}$ under $h = 30$ is about 25% smaller than the one under $h = 10$.

6.5 Summary

By considering the realistic factor of imperfect spectrum sensing, the end-to-end (e2e) opportunistic transmission in multiple-hop based Cognitive
CHAPTER 6. CASE STUDY III: COGNITIVE RADIO MESH NETWORK

Radio Mesh Networks (CRMNs) has been studied. For every particular mesh router in CRMNs, a buffer reservation based priority scheme has been suggested to give higher priority to the relayed unlicensed user packets over the locally generated ones. The goal is to alleviate the retransmission of the relayed packets, which are originally generated far away from the particular mesh router. To investigate the e2e uplink transmission performance of SUs, a two-stage parallel server based queueing model $M/H_2/1$ was developed for each mesh router. The performance evaluation shows that the suggested priority scheme can significantly decrease the e2e transmission delay of SUs, together with a minor decrease in the e2e transmission throughput of SUs.
In CRNs, the SUs need to learn from environmental changes. This is a process that can be done in a cooperative or non-cooperative manner. Due to the competition for channel utilization among SUs, the non-cooperative approach may lead to overcrowding in the available channels. This chapter is about a fuzzy logic based decision making algorithm for competition-based channel selection. The underlying decision criterion integrates both the statistics of channel occupancy by PUs and the competition level of SUs. By using such an algorithm, the SU competitors can achieve an efficient sharing of the available channels. Simulation results are reported to demonstrate the performance and effectiveness of the suggested algorithm.

7.1 Introduction

In CRNs, the data transmission of SUs may be interrupted due to channel occupancy by PUs. To alleviate the interruption from PUs, the SUs need to
learn from the statistical information about channel availability, and thus select the most available channels to use. An existing solution along with this line is given by the idle-time-based statistics \([52,58]\). For a single channel, being idle indicates the PU absence and the idle time indicates how long this absence is. In \([52]\), the authors consider that longer an available channel remains idle in the near future, higher the channel availability becomes. Further, by predicting the idle time, the most available channel is attributed to the characteristic of having the longest remaining idle time.

The problem however is regarding the competition among SUs in accessing available channels. This problem is addressed by a fact that, if the channel availability is spatial invariant in a CRN, the idle time statistics can be shared by all SUs within this CRN. When multiple SUs simultaneously want to use the available channels, the selection criterion based on the longest remaining idle time may lead to the same channels. In particular, the SUs that can perceive (by receiving radio signals) each other are likely to compete for the channel utilization over a single channel \([20]\).

In this chapter, the adopted solution is based on a joint consideration of the statistics of idle time of spectrum and also the characteristics of the competition among SUs for accessing the available channels. By using this solution, the SUs first learn from the statistical properties of PUs activities. At the same time, the SUs learn from own behaviour with the help of a Two-Step Information-Exchange (TSIE) mechanism in an ad-hoc environment. Based on this, and also on using a fuzzy logic based decision making algorithm, the SUs take decisions in accessing the spectrum. The goal is to provide channel selection with leverage for long remaining time of PUs being absent and low level SU competition. The reported performance results indicate the feasibility of this approach.
7.2 System Model

A CRN system with $N$ licensed channels marked with indexes $1, 2, ..., N$ is considered. The PU’s activity in these channels is assumed to be done in a synchronous time-slotted basis. Each PU’s slot has an uniform length $\delta$ in time domain. In the system, there are $M$ SUs having the labels $s_1, s_2, ..., s_M$. We define $S$ as the set of $M$ SUs, i.e., $S = \{s_1, s_2, ..., s_M\}$. These SUs are ready to transmit data to other SU receivers in a single-hop ad-hoc manner.

A central coordinator is assumed to be used in the system. The coordinator can be, e.g., a secondary base station or a support node [13, 30]. Similar to [30], the collaborative spectrum sensing is done on both coordinator and SU sides, and thus the probabilities of missed detection and false alarm can be decreased. It is assumed that the sensing results are perfect. The central coordinator is also responsible for collecting information about PU’s slot, and thus periodically performs sensing with duration $\delta$ corresponding to PU’s activity. Both PU’s slot information and sensing results are broadcasted by the coordinator to SUs via a common control channel [4, 13]. Moreover, the coordinator helps every SU transmitter/receiver pair in establishing a reliable communication. In [8], the authors suggest a Partially Observed Markov Decision Process (POMDP) based method to achieve the channel synchronization for a SU transmitter/receiver pair. However, due to the dynamic nature of PU’s and SU’s activities, the design of precise and reliable channel synchronization is very challenging in ad-hoc CR networks.

It is assumed that SUs use a time-slotted transmission scheme to opportunistically access the available channels. By receiving broadcast messages from the central controller, the SUs can be synchronized with the PUs. To differentiate the PU’s signal from the SU’s signal, the SUs usually keep si-
lence at the same time while doing sensing [30]. Further, the SU configures its transmission slot length as $\delta$. More specifically, a SU’s slot consists of three phases [31], as shown in Figure 7.1.

![Phase I | Phase II | Phase III](image)

**SU slot**

**Figure 7.1:** SU’s slot: sensing and receiving broadcast, information exchange and data transmission are accomplished in the phases I, II and III, respectively.

In the figure, the sensing and receiving broadcast are done in the first phase. The second and third phases are used by SUs to cooperatively exchange information and to transmit data, respectively. The information exchange among SUs can be done by using either the CCC or cooperative mechanisms like signaling protocol [32]. For data transmission, in [29] the authors suggest to divide the third phase into multiple identical sub-slots. Further, by using a modified CSMA/CA protocol, several SU competitors for the same channel can use different sub-slots to transmit data with low-level collision.

It is assumed that the above mentioned functions (i.e., perfect spectrum sensing, coordinator’s broadcasting, information exchange, sub-slot and CSMA/CA based transmission) are applicable in the modelled system. These functions are not deeply studied in this chapter. The focus is laid instead on the joint consideration of idle time statistics and SUs’ competition problem.
7.3. IDLE TIME STATISTICS

7.3 Idle Time Statistics

Unlike [52], it is assumed that SUs do not have a priori knowledge about distribution parameters regarding idle time like the PU arrival and departure rates. Thus, the learning of idle time statistics requires a short-term historical information about the PU channel occupancy.

7.3.1 PU Channel Occupancy

Given the current time $t$, the PU’s activity may have a change at the time points $\{t - H\delta, t - (H - 1)\delta, ...\}$. The time interval $[t - H\delta, t]$ is identically divided into $H$ time slots, within each of which PUs are either present or absent. Let $h$ denote the slot $[t - (H - h)\delta, t - (H - h - 1)\delta]$, where $h = 0, 1, ..., H - 1$. The random variable $v^n_h$ denotes the sensing result of detecting the PU’s activity in channel $n \in \{1, 2, ..., N\}$ in slot $h$. $v^n_h$ is specified as:

$$v^n_h = \begin{cases} 
1 & \text{PU presence} \\
0 & \text{PU absence} 
\end{cases}$$

(7.1)

This gives a binary sequence indicating the PU channel occupancy. An example of this sequence is presented in Figure 7.2.

At time $t$, if channel $n$ is sensed to be idle, we have $v^n_H = 0$. This means that the channel $n$ will be idle in the whole interval $[t, t + \delta]$ and it may remain idle in one or more consecutive slots after the time point $(t + \delta)$. As such, the capability of looking ahead the future trends of all channels is desirable for SUs. One needs therefore to know in advance the remaining idle time on every channel.
7.3.2 Remaining Idle Time

To achieve the above mentioned task, the average idle time and ongoing PU absence on a channel $n$ (available at time $t$) during the past interval $H\delta$ are computed.

To compute the average idle time, one needs to know the occurrence times of two events, namely, the event “$v_{nh}^n = 0$” and the event “PU being absent”. It is observed in Figure 7.2 that the occurrence time of the first event is given by:

\[
\sum_{h=0}^{H-1} (1 - v_{nh}^n)
\]  

(7.2)

The occurrence time of the second event is computed with:

\[
\left\lfloor \frac{1}{2} \sum_{h=0}^{H-1} \Lambda(n,h) \right\rfloor + 1
\]  

(7.3)

where $\Lambda(n,h)$ means a change of PU activity and equals 1 if $v_{nh}^n \neq v_{nh+1}^n$, otherwise 0. The average idle time on channel $n$ in interval $[t - H\delta, t]$ is
therefore obtained as:

\[ E_{idle}^n(t) = \frac{1}{2} \sum_{h=0}^{H-1} \Lambda(n,h) + 1 \]

\[ \sum_{h=0}^{H-1} (1 - v_h^n) \] (7.4)

Let \( x^n(t) \) denote the time period of the ongoing PU absence on channel \( n \) until the time point \( t \). For instance, in Figure 7.2, the last four slots before time \( t \) are associated with an ongoing PU absence. To compute \( x^n(t) \), we find out the slot in which the latest event \( v_h^n = 1 \) takes place. Let \( h' \) denote this slot:

\[ h' = \max \{ h | v_h^n = 1 : h = 0,1,...,H-1 \} \] (7.5)

The value of \( x^n(t) \) is then computed by:

\[ x^n(t) = (H - h') \delta. \] (7.6)

Actually, \( E_{idle}^n(t) \) provides an insight into how long the duration of a PU absence is expected to be. In contrast to the remaining idle time, the larger \( x^n(t) \) is, the lower the availability of channel \( n \) becomes. In Section 7.5, the estimation of fuzzy-logic based channel availability with respect to parameters \( E_{idle}^n(t) \) and \( x^n(t) \) is presented.

### 7.4 Competition Among Secondary Users

For the simplicity purpose, it is assumed that when the SUs do single-hop ad-hoc transmission, they have the same transmission range \( D \). Let \( d_{ij}(t) \) denote, at time \( t \), the distance between two different SUs, \( s_i, s_j \in S \). Let
CHAPTER 7. CASE STUDY IV: FUZZY LOGIC BASED SOLUTION

ξ_{ij}(t) denote a relation of whether or not s_i can perceive s_j:

$$
\xi_{ij}(t) = \begin{cases} 
1 & (can), \\
0 & (cannot), 
\end{cases} \quad d_{ij}(t) \leq D \\
\end{cases} \quad (7.7)
$$

where $\xi_{ij}(t) = \xi_{ji}(t)$.

When $\xi_{ij}(t) = 1$, s_i is said to be a neighbor of s_j. If both s_i and s_j switch to the same available channel for data transmission, they become SU competitors against each other.

### 7.4.1 Competition Problem

To address the competition problem, a measure called sub-slot utilization is introduced. Consider a slot $h$, in which the transmission phase is identically divided into $L$ sub-slots, each denoted by $1,2,...,L$. Given a channel $n \in \{1,2,...,N\}$ available in slot $h$, a SU $s_m \in S$ attempts to access channel $n$ and to transmit data within the particular sub-slots. Clearly, when $s_m$ activity follows a CSMA/CA-like protocol model, its transmission may only take place in a subset of $L$ sub-slots. Let $l_n^m(h)$ denote the number of used sub-slots in slot $h$, i.e., $0 \leq l_n^m(h) \leq L$. The sub-slot utilization of $s_m$ on channel $n$ in slot $h$ can be therefore defined, which is denoted by $u_n^m(h)$. This is the ratio between the number of used sub-slots and the number of total sub-slots, i.e.:

$$
u_n^m(h) = \frac{l_n^m(h)}{L} \quad (7.8)
$$

The reliable communication between SU transmitter and receiver is therefore constrained by the sub-slot utilization threshold, denoted by $U$. In other words, if $u_n^m(h)$ is less than $U$ (due to other SU competitors), $s_m$ may terminate the transmission since the QoS performance may not be satisfied by the receiver any more.
7.4. COMPETITION AMONG SECONDARY USERS

Figure 7.3: Example of five SUs competing for the use of the same channel.

A competition example is illustrated in Figure 7.3. In the figure, five SU transmitters, denoted by \( s_a, s_b, s_c, s_d, s_e \) \( \in S \), want to use the same available channel \( n \) within slot \( h \). Assume a particular threshold \( U = 25\% \). For \( s_a, s_b, s_c, s_d \), each of them can perceive other two SU transmitters, so that the number of competitors for them is three. Thus, the largest sub-slot utilization allowed for each of them to hold is 75\%. However, for \( s_e \) the number of competitors is five, since \( s_e \) can perceive four other SU transmitters. As a result, all of \( s_a, s_b, s_c, s_d \) could successfully use channel \( n \) in slot \( h \), but \( s_e \) could not do reliable transmission on channel \( n \) in slot \( h \) because of not enough sub-slots available to use.

As another example, assume that the channel \( n \) was also available in slot \( (h-1) \) and SUs \( s_b, s_c, s_d \) and \( s_e \) have been using it. It is also assumed that the SU \( s_a \) newly starts using channel \( n \) in slot \( h \). In this case, \( s_b, s_c, s_d \) and \( s_e \) are called ongoing SUs on channel \( n \), and \( s_e \) is called new SU on channel \( n \). Further, if each of the five SUs has the same sub-slot utilization
threshold $U = 25\%$, the new $s_a$ will interrupt the ongoing transmission of $s_e$ in slot $h$.

### 7.4.2 Two-Step Information Exchange

To solve the above described competition problem, a simple method called Two-Step Information Exchange (TSIE) is suggested for SUs. TSIE is accomplished by SUs during the second phase of every SU’s slot. The process of doing TSIE is shown in Figure 7.4.

![Two-Step Information Exchange diagram](image)

**Figure 7.4:** Two-Step Information Exchange method for SU transmitters.

The first step is performed by ongoing SUs among themselves via accessed channels. The information is about which available channels the ongoing SUs are using. Let $n_m(t)$ denote an available channel used by an ongoing SU $s_m \in S$ at time $t$. If no channel is used by $s_m$ at time $t$, then
7.4. COMPETITION AMONG SECONDARY USERS

\( n_m(t) \) equals zero. By exchanging information with neighboring ongoing SUs via channel \( n_m(t) \), \( s_m \) can obtain the number, denoted by \( \psi^n(t) \), of SU competitors on channel \( n_m(t) \). This is given by:

\[
\psi^n_m(t) = \sum_{i=1}^{M} [\xi_{mi}(t)|n_i(t) = n_m(t)].
\] (7.9)

The second step is initiated by new SUs and it is conducted between new and ongoing SUs. The information is about the competitor number perceived by different ongoing SUs. Consider that a newly arrived SU \( s_m' \in S \) wants to use channel \( n \) in slot \( h \). By communicating with a neighboring ongoing SU \( s_m \), the SU \( s_m' \) can get information of \( \psi^n_m(t) \) from \( s_m \). Similarly, after communicating with all neighboring ongoing SUs, \( s_m' \) can learn the largest number, denoted by \( y^n(t) \), of SU competitions on channel \( n \) as being:

\[
y^n_m'(t) = \max \{ \psi^n_i(t)|n_i(t) = n, \xi_{m'i}(t) = 1, i = 1, 2, \ldots, M \}
\] (7.10)

where \( y^n_m(t) \) is called competition level for \( s_m' \) to access the channel \( n \) at time \( t \). If \((y^n_m(t) + 1)U\) is not larger than one, then SU \( s_m' \) can use the channel \( n \). Otherwise \( s_m' \) has to look for other available channels in order to protect the ongoing SUs using channel \( n \). Let \( T_{com} \) denote the maximum of SU competitors accommodated by the same channel. This is given by:

\[
T_{com} = \left\lfloor \frac{1}{U} \right\rfloor
\] (7.11)

Clearly, for new SUs, the competition level on a channel indicates how heavily the channel is used by ongoing SUs. The larger the competition level on a channel is, the lower the channel availability becomes.
7.5 Channel Selection

So far, two pairs of parameters \((x^n, E_{idle}^n)\) and \((y^m_m, T_{com})\) have been formulated. It is clear that these parameters vary in distinct metrics and measures. This gives rise to a two-constraint based decision problem of finding the most available channel for SUs.

7.5.1 Fuzzy Channel Availability

To solve the above mentioned problem, the parameter Fuzzy Channel Availability (FCA) is used, which was introduced in Subsection 3.3.2. The use of FCA is to map two different types of parameter values \(x^n(t)\) and \(y^m_m(t)\) to an uniform type, i.e., fuzzy membership degree.

Let \(\sigma\) denote a parameter of either \(x^n\) or \(y^m_m\), i.e., \(\sigma \in \{x^n, y^m_m\}\). The notations \(\alpha_\sigma\), \(\beta_\sigma\) and \(\gamma_\sigma\) are used to denote FCA’s three fuzzy sets “high-level”, “medium-level” and “low-level” under parameter \(\sigma\). Their membership functions are denoted by \(g_\sigma^{\alpha}\), \(g_\sigma^\beta\), and \(g_\sigma^\gamma\), respectively. \(g_\sigma^{\alpha}(\sigma(t)), g_\sigma^\beta(\sigma(t)), g_\sigma^\gamma(\sigma(t))\) \(\in [0.0, 1.0]\) are defined as membership degrees of \(\sigma(t)\) to fuzzy sets \(\alpha_\sigma\), \(\beta_\sigma\), and \(\gamma_\sigma\), respectively. The three membership degrees form a vector:

\[
V_\sigma(t) = \left( g_\sigma^{\alpha}(\sigma(t)), g_\sigma^\beta(\sigma(t)), g_\sigma^\gamma(\sigma(t)) \right)
\]  

(7.12)

We call \(V_\sigma(t)\) the FCA-based characterization of parameter \(\sigma\) at time \(t\).

By using the same fuzzy comparison mechanism as presented in Section 3.3.3, one can compound three coordinates into a joint value as follows:

\[
\xi_\sigma(t) = g_\sigma^{\alpha}(\sigma(t)) \omega_\alpha + g_\sigma^\beta(\sigma(t)) \omega_\beta + g_\sigma^\gamma(\sigma(t)) \omega_\gamma
\]  

(7.13)

where \(\xi_\sigma(t)\) is called the FCA-based decision factor of parameter \(\sigma\) at time \(t\) for channel selection. In the equation, \(\omega_\alpha\), \(\omega_\beta\), and \(\omega_\gamma\) denote the weights
7.5. CHANNEL SELECTION

of how important the “high-level”, “medium-level” and “low-level” channel availabilities affect the decision making, respectively. According to equation 3.10 given in Subsection 3.3.3, the values of \( \omega_x \), \( \omega_+ \), and \( \omega_- \) are given by:

\[
\{ \omega_x, \omega_+, \omega_- \} \simeq \{0.94, 0.31, 0.19\} \tag{7.14}
\]

7.5.2 Hybrid Decision Making

Considering a channel \( n \) available at time \( t \), the idle time statistics, i.e., the parameter pair \( (x^n, E^n_{idle}) \), are mapped as fuzzy membership degree of \( x^n \) to \( g^\alpha_{x^n} \), \( g^\beta_{x^n} \) and \( g^\gamma_{x^n} \), respectively. As an example, the values 0, \( E^n_{idle} \) and \( 2E^n_{idle} \) are chosen to indicate that, under the three values, the availability of channel \( n \) is exactly equivalent to high-level, medium-level and low-level:

\[
\begin{align*}
g^\alpha_{x^n}(0) &= 1.0 \\
g^\beta_{x^n}(E^n_{idle}) &= 1.0 \\
g^\gamma_{x^n}(2E^n_{idle}) &= 1.0
\end{align*}
\tag{7.15}
\]

As described in subsection 7.3.2, since the availability of channel \( n \) is assumed to decrease with \( x^n(t) \), this implies that:

- When \( x^n(t) \) is increasing, the channel availability is far away from the high level and becomes closer to the low level.
- When \( x^n(t) \) is increasing and it is smaller than \( E^n_{idle} \), the channel availability becomes closer to the medium level.
- When \( x^n(t) \) is increasing and it is larger than \( E^n_{idle} \), the channel availability is far away from the medium level.

The consequence is that:
• $g^\alpha_{x^n}(x^n(t))$ should not increase with $x^n(t)$.

• $g^\beta_{x^n}(x^n(t))$ should not decrease before $x^n(t)$ reaching $E^n_{idle}$ and not increase after $x^n(t)$ exceeding $E^n_{idle}$.

• $g^\gamma_{x^n}(x^n(t))$ should not decrease with $x^n(t)$.

Subsequently, the membership functions of FCA under $x^n$ are formalized as simple linear functions:

$$ g^\alpha_{x^n}(x^n(t)) = \begin{cases} 1 - \frac{x^n(t)}{E^n_{idle}}, & 0 \leq x^n(t) < E^n_{idle} \\ 0, & \text{others} \end{cases} \quad (7.16) $$

$$ g^\beta_{x^n}(x^n(t)) = \begin{cases} \frac{x^n(t)}{E^n_{idle}}, & 0 \leq x^n(t) < E^n_{idle} \\ 2 - \frac{x^n(t)}{E^n_{idle}}, & E^n_{idle} \leq x^n(t) < 2E^n_{idle} \\ 0, & \text{others} \end{cases} \quad (7.17) $$

$$ g^\gamma_{x^n}(x^n(t)) = \begin{cases} \frac{x^n(t)}{E^n_{idle}} - 1, & E^n_{idle} \leq x^n(t) < 2E^n_{idle} \\ 0, & \text{others} \end{cases} \quad (7.18) $$

For the parameter pair $(y^n_{m}, T_{com})$, it is known that larger $y^n_{m}(t)$ is, lower the availability of channel $n$ for SU $s_m$ becomes. Therefore, similar membership functions are adopted with regard to equations (7.20), (7.21) and (7.22). The difference is that we set:

$$ \begin{align*}
 g^\alpha_{y^n_{m}}(0) &= 1.0 \\
 g^\beta_{y^n_{m}}(T_{com}/2) &= 1.0 \\
 g^\gamma_{y^n_{m}}(T_{com}) &= 1.0
\end{align*} \quad (7.19) $$
The membership functions of FCA under $y^n_m(t)$ are given by:

$$g_{ym}^\alpha(y^n_m(t)) = \begin{cases} 1 - \frac{y^n_m(t)}{T_{com}/2}, & 0 \leq y^n_m(t) < T_{com}/2 \\ 0, & \text{others} \end{cases} \quad (7.20)$$

$$g_{ym}^\beta(y^n_m(t)) = \begin{cases} \frac{y^n_m(t)}{T_{com}/2}, & 0 \leq y^n_m(t) < T_{com}/2 \\ 2 - \frac{y^n_m(t)}{T_{com}/2}, & T_{com}/2 \leq y^n_m(t) < T_{com} \\ 0, & \text{others} \end{cases} \quad (7.21)$$

$$g_{ym}^\gamma(y^n_m(t)) = \begin{cases} \frac{y^n_m(t)}{T_{com}/2} - 1, & T_{com}/2 \leq y^n_m(t) < T_{com} \\ 0, & \text{others} \end{cases} \quad (7.22)$$

Figure 7.5 shows the membership functions under parameters $x^n$ and $y^n_m$. According to equation (3.11), one can compute the FCA-based decision factors of $x^n$ and $y^n_m$ at time $t$, denoted by $\xi_{x^n}(t)$ and $\xi_{y^n_m}(t)$, respectively.

![Diagram](image1.png)

**Figure 7.5:** Membership functions of $x^n(t)$ and $y^n_m(t)$ to FCA.

Although, the values of $\xi_{x^n}(t)$ and $\xi_{y^n_m}(t)$ have the same type with respect to FCA, their respective weights for decision making still need to be
configured. Therefore, a variable $p_r \in [0.0, 1.0]$ is introduced, in which the
decision maker configures $\xi_{x^n}(t)$ with weight $(1 - p_r)$ and $\xi_{y^m}(t)$ with weight $p_r$. For a given SU $s_m$, the numerical channel availability of channel $n$ at
time $t$ is finally given by $\theta_{m}^{n}(t) = (1 - p_r)\xi_{x^n}(t) + p_r\xi_{y^m}(t)$. In this equation, $p_r$ is called hybrid coefficient of integrating both $\xi_{x^n}(t)$ and $\xi_{y^m}(t)$ when
doing decision making. For instance, at $p_r = 0$, the pure idle time based selection is performed. By computing the numerical channel availabilities of the channels of interest, the most available channel in this particular case
is determined by the largest value of $\theta_{m}^{n}(t)$.

7.6 Performance Evaluation

In this section the simulation results for performance evaluation of the suggested hybrid decision making algorithm are reported. A CRN environment was simulated (in C++ language and using GNU Scientific Library [53]), where 100 SU transmitters are uniformly distributed over a $500m \times 500m$ district. The time periods of “PU presence” and “PU absence” are exponentially distributed with mean values $T_{p1}$ and $T_{p2}$, respectively. Every SU holds a time period $T_{s1}$ before performing an access. The expected time period of a SU transmission is equal to a constant value $T_{s2}$. Once an ongoing SU transmission is interrupted by PU’s channel occupancy, the SU will restart the transmission after a time interval equal to $T_{s1}$ plus the remaining duration of $T_{s2}$. The simulation parameter settings are presented in Table 7.1.
### 7.6. PERFORMANCE EVALUATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensing setting</td>
<td>$\delta = 10\text{ms}; H = 20000$</td>
</tr>
<tr>
<td>Radio setting</td>
<td>$D = 200\text{m}; T_{com} = 6$</td>
</tr>
<tr>
<td>Number of channels</td>
<td>$N = 10, 15$</td>
</tr>
<tr>
<td>Number of SUs</td>
<td>$M = 100$</td>
</tr>
<tr>
<td>SU activity</td>
<td>$T_{s1}$, Uniform in $[1.0\text{s}, 10.0\text{s}]$; $T_{s2} = 1.0\text{s}$</td>
</tr>
<tr>
<td>PU activity</td>
<td>$T_{p1}, T_{p2}$, Uniform in $[1.0\text{s}, 10.0\text{s}]$; Idle time is between $2.0\text{s}$ and $20.0\text{s}$</td>
</tr>
</tbody>
</table>

#### 7.6.1 Simulation Scenarios and Performance Metrics

To compare the performance of the hybrid spectrum decision with other solutions, three different channel selection algorithms are considered: random based selection, pure idle time based selection and fuzzy logic based hybrid decision making based selection. Since the value range of hybrid coefficient is $[0.0, 1.0]$, four typical values $p_r = 0.1$, $p_r = 0.2$, $p_r = 0.4$ and $p_r = 0.8$ are used to study how well the hybrid coefficient affects. In other words, six different simulation scenarios are considered, which are denoted by random, idle time, $pr - 0.1$, $pr - 0.2$, $pr - 0.4$ and $pr - 0.8$. Further, the TSIE method is used in all six scenarios. For each simulation scenario, the simulator runs in looping manner, and each loop indicates $10\text{ms}$. Furthermore, each scenario is run $40$ times, and the simulation time of each run is $10000\text{s}$.

Three metrics are used for performance evaluation, namely, the average dropping probability, the average blocking probability and the average
success probability. They are denoted by $P_d$, $P_b$ and $P_s$, respectively. Considering the $i^{th}$ simulation run of a scenario, assume that the $m^{th}$ SU performed $\alpha_{i,m}$ times of attempting channel access, while the SU got $\beta_{i,m}$ times of drops and $\gamma_{i,m}$ times of blocks. For 40 runs, this means:

$$
P_d = \frac{1}{40} \sum_{i=1}^{40} \left[ \frac{1}{M} \cdot \sum_{m=1}^{M} \beta_{i,m} \right]
$$
$$
P_b = \frac{1}{40} \sum_{i=1}^{40} \left[ \frac{1}{M} \cdot \sum_{m=1}^{M} \gamma_{i,m} \right] \tag{7.23}
$$
$$
P_s = 1.0 - P_d - P_b
$$

7.6.2 Results and Discussion

The simulation results regarding the SUs’ average dropping and blocking probabilities are shown in Figures 7.6 and 7.7, respectively. The 95% confidence interval is shown as well. The SUs’ average success probability is shown in Figure 7.8.

As observed in Figure 7.6, for the fixed channel number $N$ (10 or 15), the pure idle time scenario leads to the smallest dropping probability $P_d$, while $P_d$ in the random scenario is largest. The reason for this is that in pure idle time scenario the SUs have learned in advance the channel availability based on idle time statistics. Thus, SUs may have more concentration on good channels, and the possibility of being dropped due to PUs is reduced. Since in hybrid scenarios the SUs use statistical information in part, the corresponding values of $P_d$ under fixed $N$ are between the values used in random and pure idle time scenarios.

In Figure 7.7, it is observed that, under fixed $N$, the pure idle time scenario stands out as showing the worst performance in the form of largest blocking probability $P_b$. This is because the limited channel capacity may
have the consequence that parts of SUs access the best channels, whereas other SUs are left with the worse channels. Figure 7.7 further shows that, for the same scenario, $P_b$ under $N = 15$ is smaller than the one under $N = 10$. This is because of the larger number of channels provided for SUs under $N = 15$ than under $N = 10$. However, the possibility of SUs being dropped may increase with $N$ (i.e., from 10 to 15). Hence, for the same scenario, $P_d$ under $N = 15$ is larger than the one under $N = 10$, as shown in Figure 7.6.

To investigate the overall performance of different channel selection algorithms, the SU’s average success probability $P_s$ is studied. In Figure 7.8, it is observed that: i) under $N = 15$, the value of $P_s$ in pure idle time scenario is smaller than the ones in hybrid scenarios, and ii) under $N = 10$, $P_s$ in pure idle time scenario is smallest. This means that: i) by learning only from idle time statistics, SUs are good at looking for the best channels, yet
ii) this may increase the number of SUs with the starvation of the available channels. By using the hybrid decision making, every SU can learn how heavily the interested channels are used by other SUs (on average). Thus, SUs are able to do a trade-off between the long remaining idle time and the low SU competition level when doing channel selection. In Figure 7.8, the gain from trade-off is such as, under $N = 15$, $P_s$ in $pr\cdot0.2$ scenario is about 6.6% and 4.2% larger than the ones in random and pure idle time scenarios, respectively.

### 7.7 Summary

In this chapter, a SU competition-based channel selection algorithm for cognitive radio networks has been developed. The idle time statistics based on
information about PU channel occupancy have been derived. An information-exchange based method has been suggested for SUs to learn the SU competition level on available channels. From fuzzy logic point of view, the idle time statistics and SUs’ competition level have been integrated into a hybrid decision criterion. The channel selection has been optimized by the decision that the largest value referred to the hybrid decision criterion indicates the most available channel. Under suitable hybrid coefficient, simulation results have demonstrated that the overall performance of the developed algorithm outperforms both random and pure idle time based channel selection algorithms.
The main objective of the PhD thesis is to advance a new software framework for the study and practical implementation of prioritized spectrum access in heterogeneous Cognitive Radio Networks (CRNs). Accordingly, the main challenges are regarding the representation of heterogeneous aspects of CRNs, the development of priority scheduling schemes, the numerical performance evaluation and the experimental validation.

8.1 Summary of the Thesis

For the purpose of our study, the basic CR transmission model and four typical network topologies were investigated to highlight the heterogeneous aspects of CRNs. Connected with this, a particular focus was laid on the competition problem of SUs in heterogenous CRNs.

The need of priority scheduling for the practical implementation of heterogeneous CRNs was addressed. The solution approaches to alleviating
the competition problem of SUs was also investigated. Based on these, a new software framework PRioritized Opportunistic spectrum Access System (PROAS) was introduced. In PROAS, both the priority scheduling and the intelligent spectrum decision strategy are integrated together. The goal is to efficiently manage the data transmission of SUs in heterogenous CRNs with respect to their specific QoS requirements.

The next step was to provide several particular case studies to show the effectiveness of the suggested solutions in PROAS. These cases studies are associated with the CR cellular networks, the single-hop based ad-hoc CRNs and the CR mesh networks. The suggested solutions include the Markov chains based queueing models, the queueing buffer based priority schemes, the fuzzy logic based hybrid decision making algorithms and the discrete-event based simulations.

Consequently, the primary focus of this thesis was to make PROAS flexible in adapting to the heterogeneous aspects of CRNs. Such thus, PROAS can be useful for different research and development purposes like, e.g., simulation based study of CRNs, network setting up, testbed evaluation, algorithm development.

8.2 Concluding Remarks

A new software framework PROAS was advanced for alleviating the competition problem of SUs in heterogeneous CRNs. PROAS is designed and developed at the MAC and network layers, and it uses a specific middleware to integrate priority scheduling, fuzzy logic control, a set of network topologies, a set of queueing models and experimental simulation together. Based on these, in PROAS the heterogeneity aspects of CRNs were represented from scientific point of view. A fuzzy logic based spectrum decision
strategy was also developed, which can jointly take into account various characteristic parameters of spectrum channels.

Furthermore, the emphasis of the PhD thesis was laid on four case studies by using PROS. The first case study was regarding the handover procedure in CR cellular networks. The intra- and inter-handoff activities of SUs were defined and a queueing buffer based priority scheme was suggested for inter-handoff SU calls.

The second case study was regarding the single-hop based data transmission between two neighboring SUs, which consists of different types of traffics. The idea was to give transmission priority to the real-time based traffic over the non-real-time based traffic, so that the QoS performance of the whole system was improved in terms of significant delay decrease and minor throughput decrease.

The third case study was about the improvement of end-to-end (e2e) transmission performance in CR mesh networks. A queueing buffer based priority scheme was suggested for mesh routers, so that they can give the transmission priority to the relayed SU traffics over the locally generated SU traffics.

Similar to the second case study, the fourth case study was also regarding the ad-hoc based CRNs. The difference is that multiple pairs of SU transmitters/receivers were considered in the system model. The fuzzy logic control was used to implement a hybrid spectrum decision strategy that jointly considers the historical statistics of PUs transmission activity and the channel utilization by SUs. The goal was that these SUs fairly share the most available channels during a long time period.
8.3 Future Work

There are a number of important research tasks that need to be considered in the future. As the future work, several topics of particular interest are as follows.

To investigate the algorithms associated with artificial intelligence and computational intelligence like, e.g., ant colony optimization, game theory, genetic algorithm, machine learning, to fill up the functionality of PROAS. Also to implement a visual simulator based on PROAS, which can be conveniently used by the PROAS users.

To develop the e2e routing algorithms for the data transmission of SUs in multiple-hop based CR ad-hoc networks. To analyze the e2e transmission performance of SU in such CRNs. To investigate the system performance of CR cellular networks under the case of multiple types of SU traffics.

To develop real-world experiments by using Universal Software Radio Peripheral (USRP) based CR devices. To apply the PROAS to such experiments, and evaluate the effectiveness of the suggested solutions in real-world environment. To expand the set of parameters for other scenarios as well.
Appendix A

Complete publication list


APPENDIX A. COMPLETE PUBLICATION LIST


Conference on Next Generation Internet (NGI), Karlskrona, Sweden, June 2012.


Ultra Modern Telecommunications and Control Systems (ICUMT), Moscow, Russia, October 2010.


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ABSTRACT

Today, the radio spectrum is rarely fully utilized. This problem is valid in more domains, e.g., time, frequency and geographical location. To provide an efficient utilization of the radio spectrum, the Cognitive Radio Networks (CRNs) have been advanced. The key idea is to open up the licensed spectrum to unlicensed users, thus allowing them to use the so-called spectrum opportunities as long as they do not harmfully interfere with licensed users. An important focus is laid on the limitation of previously reported research efforts, which is due to the limited consideration of the problem of competition among unlicensed users for spectrum access in heterogeneous CRNs.

A software framework is introduced, which is called PRioritized Opportunistic spectrum Access System (PROAS). In PROAS, the heterogeneity aspects of CRNs are specifically expressed in terms of cross-layer design and various wireless technologies. By considering factors like ease of implementation and efficiency of control, PROAS provides priority scheduling based solutions to alleviate the competition problem of unlicensed users in heterogeneous CRNs. The advanced solutions include theoretical models, numerical analysis and experimental simulations for performance evaluation. By using PROAS, three particular CRN models are studied, which are based on ad-hoc, mesh-network and cellular-network technologies. The reported results show that PROAS has the ability to bridge the gap between research results and the practical implementation of CRNs.