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Optimization of Spectrum Management in Cognitive Radio Networks

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in fulfillment of the requirement for the degree of
Doctor of Philosophy

2013

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research done by me and has not been submitted for a higher degree to any other University or Institute.

....	....
Date	Zhang Wenjie

To Dad and Mom,
for their encouragements and love.

Abstract

The rapid growth of wireless services has resulted in the increasing demand on spectrum. However, a recent study has shown that most of the allocated frequency bands are significantly under-utilized. Cognitive radio has been proposed as a potential technology to mitigate the spectrum scarcity by allowing the secondary users (SUs) to opportunistically utilize the licensed spectrum without causing interference to the primary users (PUs). Spectrum sensing is required to be performed first before accessing the channels. If more than one channels are detected, the SUs need to decide which channels are suitable for data transmission. As soon as the return of the PU is detected, the SU is required to vacate the channel, and find another opportunity to resume its unfinished transmission. These are the so called spectrum management problem in cognitive radio networks (CRNs). In this dissertation, the author widely exploits the spectrum sensing, spectrum sharing and spectrum handoff in the network design to improve the system performance. It is shown that the spectrum, if well managed, is able to enhance the network performance, increase the achievable throughput, reduce the cooperation overhead as well as provide sufficient protection to PUs. According to the specific challenges of spectrum management in the cognitive radio networks, different models and solutions are provided.

In this work, the author studies the optimization of spectrum management in CRNs. The first problem addressed is spectrum sharing among the SUs and PUs. The author proposes a cluster-based adaptive multi-spectrum sensing and access strategy, in which the SUs seeking to access the channel can select a set of channels to sense and access with adaptive sensing time. Specifically, the spectrum sensing and access problem is formulated into an optimization problem, which maximizes the utility of the SUs and

ensures sufficient protection of the PUs and the transmitting SUs (The SUs who have already gained access to the channel and are transmitting.) from unacceptable interference. Moreover the author explicitly calculates the expected number of channels that are detected to be idle, or being occupied by the PUs, or being occupied by the transmitting SUs. Spectrum sharing with the primary and transmitting SUs is accomplished by adapting the transmission power to keep the interference to an acceptable level. In addition, simulation is conducted to demonstrate the effectiveness of the proposed sensing and access strategy as well as its advantage over conventional sensing and access methods in terms of improving the achievable throughput and keeping the sensing overhead low.

MAC sensing-transmission protocols have been widely investigated for the SUs to efficiently utilize and share the spectrum licensed by the PU. One important issue associated with MAC protocols design is how the SUs determine when and which channel they should sense and access without causing harmful interference to the PU. The author's second contribution focuses on jointly considering the MAC-layer spectrum sensing and channel access. Normal Spectrum Sensing (NSS) is required to be carried out at the beginning of each frame to determine whether the channel is idle. On detecting the available transmission opportunity, the SUs employ CSMA for channel contention. The novelty is that, Fast Spectrum Sensing (FSS) is inserted after channel contention to promptly detect the return of the PUs. This is unlike most other MAC protocols which do not incorporate FSS. Having FSS, the PU can benefit from more protection. A concrete protocol design is provided, and the throughput-collision tradeoff, utility-collision tradeoff problems are formulated to evaluate its performance.

Finally, the author studies sequential sensing based spectrum handoff in multiple users scenario. Spectrum handoff occurs when the PUs appear in the licensed spectrum temporarily occupied by the SUs. Efficient spectrum handoff aims to help the

SUs to vacate the spectrum rapidly and to resume unfinished transmission on newly selected available channels. However, a spectrum handoff policy that comprehensively considers spectrum sensing, target channel selection as well as spectrum estimation has yet to be developed. Thus, in this work, the author presents a sequential sensing based spectrum handoff policy for multiple users in CRNs. The author first selects the appropriate candidate channels for each SU, then their associated optimal sensing order together with the best target handoff channel is determined through sequential sensing using Dynamic Programming (DP). Note that many spectrum handoffs will occur during one SU transmission and the objective is to minimize the total number of spectrum handoff. The sequential sensing based spectrum handoff policy is evaluated through a comprehensive simulation study. The results reveal significant improvements in the system performance by reducing the number of spectrum handoff over conventional approaches. Moreover, the proposed DP method can significantly lower the computational complexity compared to exhaustive search and common DP.

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Last but not least, the author would like to thank his parents and sisters for the endless love, meticulous care and everlasting support that they have shown upon me all these years. The author's family has been the greatest source of strength and inspiration. The author owes all his achievements to them. This thesis is dedicated to them. Thank you so much for always being there for me.

Contents

List of Figures

List of Abbreviations

ABBREVIATIONS	**FULL EXPRESSIONS**
PU	Primary User
SU	Secondary User
FC	Fusion Center
CRN	Cognitive Radio Network
CR	Cognitive Radio
CSS	Cooperative Spectrum Sensing
NSS	Normal Spectrum Sensing
FSS	Fast Spectrum Sensing
DP	Dynamic Programming
CH	Cluster Head
OSA	Opportunistic Spectrum Access
MAC	Medium Access Control
CSMA	Carrier Sense Multiple Access
ASA	Adaptive Spectrum Assessment
SSS	Sequential Spectrum Sensing
SS	Spectrum Sharing
AF	Amplify-and-Forward
SNR	Signal to Noise Ratio
TX	Transmitter
RX	Receiver
VSH	Voluntary Spectrum Handoff
DCF	Distributed Coordination Function
PRP	Preemptive Resume Priority
POMDP	Partially Observable Markov Decision Process
CSCG	Circular Symmetric Complex Gaussian
SCD	Spectral Correlation Density
SCF	Spectral Coherence Function
PHY	Physical Layer
IEEE	Institute of Electrical and Electronics Engineers
WLAN	Wireless Local Area Network
QoS	Quality of Service
DIFS	Distributed Coordination Function Interframe Space
SIFS	Short Interframe Space
ACK	Acknowledgement

Chapter 1

Introduction

1.1 Background and Research Objective

Spectrum resource demand has greatly increased in the last two decades due to emerging deployment of new wireless services in both the licensed and unlicensed frequency spectrum. The frequency allocation chart in United States indicates that most of the spectrum bands have been exclusively allocated to specific users as shown in Figure 1.1 [5]. However, in actual fact, recent measurements of the spectrum usage pattern have revealed that most of the assigned spectrum experiences low utilization, and it varies in time, geographical locations and frequency. This motivates the concept of spectrum reuse that allows the licensed/allocated spectrum to be used when the spectrum is temporally not being utilized.

To improve efficient use of allocated spectrum, the concept of cognitive radio has been introduced. The term, *cognitive radio*, can formally be defined as follows [6]:

"*Cognitive Radio is a radio for wireless communications in which either a network or a wireless node changes its transmission or reception parameters based on the inter-*

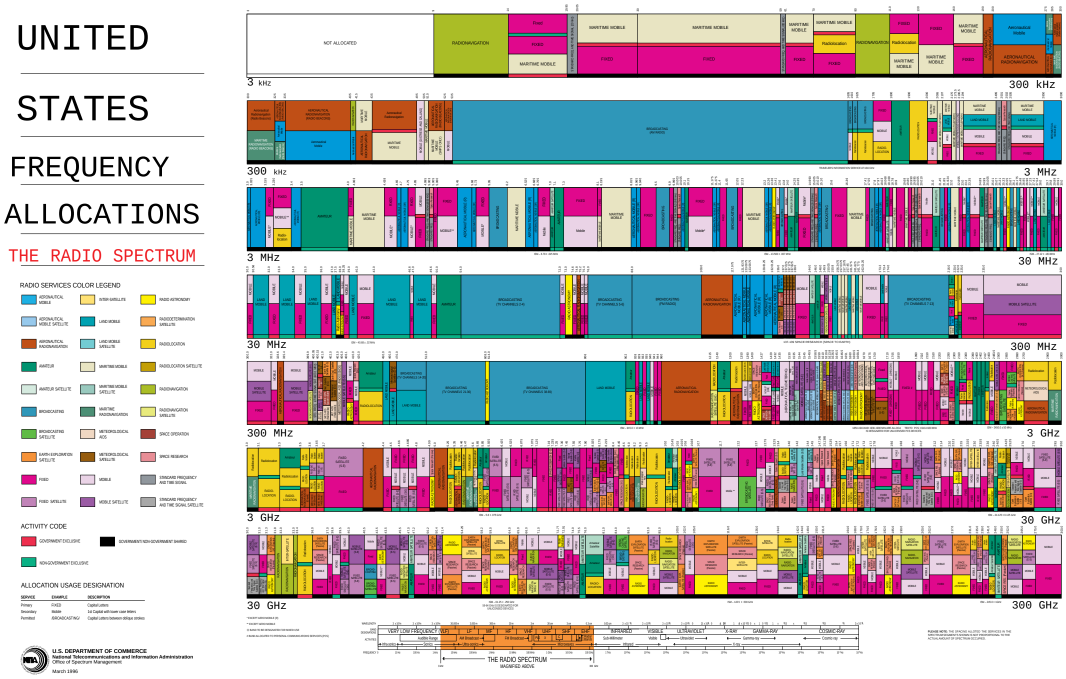

Figure 1.1: U.S. Frequency Allocation Chart.[1]

action with the environment to communicate efficiently without interfering with licensed users."

This changing of parameters is based on the active monitoring of the radio environment such as radio frequency spectrum, user behavior and network state. The idea of cognitive radio is first proposed by Joseph Mitola [7] as a promising solution for the dynamic usage of the spectrum. Cognitive radio networks (CRNs) consist of two types of users - licensed and unlicensed. The former has absolute priority to occupy and utilize the assigned spectrum whenever they wish and are not aware of the unlicensed users' behavior. On the other hand, the unlicensed users are opportunistically allowed to use the spectrum when it is not occupied by the licensed users. When the reappearance of the licensed user is detected, the unlicensed user is required to vacate

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[1] http://www.extremetech.com/wp-content/uploads/2013/01/us-spectrum-allocation-chart.jpg

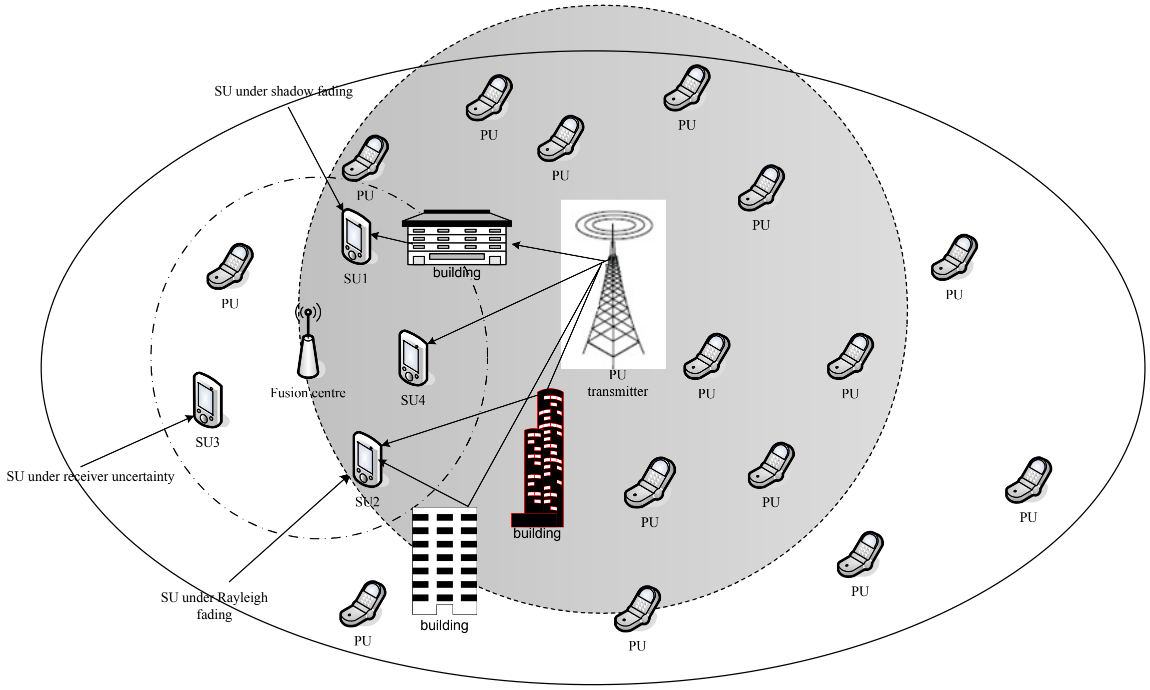

Figure 1.2: One example of the cognitive radio system architecture.

the spectrum or immediately change its transmit power so as not to degrade the transmission of the licensed users. The author adopts the conventional terminology within the cognitive radio (CR) community: licensed users are the primary users (PUs) and unlicensed users are the secondary users (SUs) or the cognitive radios. CRN provides efficient utilization of the radio spectrum and highly reliable communication to users whenever and wherever needed by allowing a SU to utilize a licensed band when PU is absent. One of the cognitive radio system architecture is shown in Figure 1.2.

One major characteristics of CR is the cognitive capability which enables the CR to sense the information from the radio environment in order to find out the unused radio spectrum at a specific time or location. Then the SUs can adjust its operating parameters so as to use the spectrum efficiently without any interference to the PUs. Thus, CR has to perform some tasks which is referred to as cognitive cycle which consists of four major parts: spectrum sensing, spectrum sharing, spectrum decision,

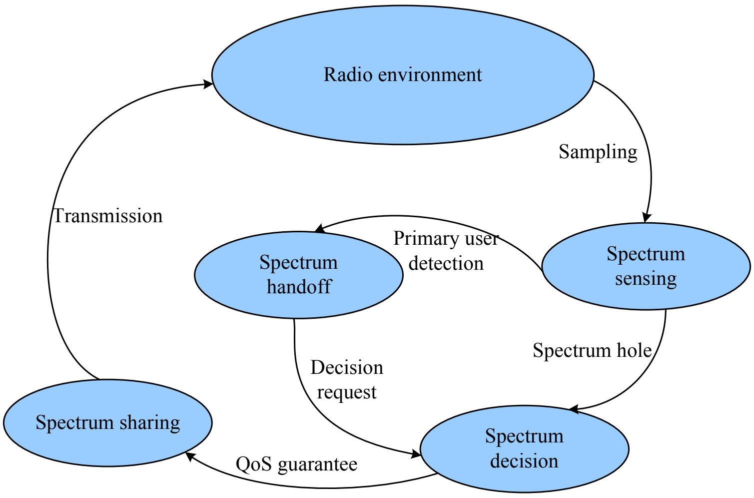

Figure 1.3: The relationships of the four spectrum management functions in CRNs: spectrum sensing, spectrum decision, spectrum sharing, and spectrum handoff.

and spectrum handoff [8][9]. The relationships of these four spectrum management techniques are shown in Figure 1.3. The following section describes the techniques which have been proposed to address these problems.

For a CRN with multiple PU channels, in order to improve system performance while keeping the protection of PUs to a high level, there are many basic tradeoffs which need to be tackled. With this dissertation, the author aims to address some of the major issues as follows:

1. The SUs can sense more than one channels and decide which channels are suitable for data transmission. On one hand, by increasing the number of sensed channels, the more transmission opportunities can be discovered, and the SUs can achieve higher throughput; on the other hand, the overhead incurred in the spectrum sensing increases when the number of selected sensed channels becomes larger. Thus it is an important issue to balance between the desire to improve the achievable throughput and the need to keep the sensing overhead low. Thus, how to determine the optimal number of sensed channels in order to balance the

tradeoff between these two aspects is investigated to improve the cognitive radio system effectiveness in Chapter 3.

2. In particular, the detection quality generally increases with the sensing period since more data samples can be collected, but in the meantime, due to the hardware limitation, each SU may be equipped with only a single radio interface and therefore can only perform either spectrum sensing or transmission at any one time [10] [11] [12]. Thus the longer the sensing time, the less is the time left for data transmission which in turn reduces the achievable throughput for SUs. Therefore, there exists a tradeoff between detection quality and achievable throughput. Moreover, for a fixed sensing period, increasing the sensing period allows the SU to have more time for data transmission. However, the longer the sensing period, the more chance that the PU will return to the channel, thus increasing the collision probability with the PU, which will further reduce the achievable throughput for both the SU and the PU. Thus there is a tradeoff problem between collision and achievable throughput for the SUs. These two tradeoffs will be further discussed in Chapter 4 for a more complicated scenario.

3. The more SUs participating in spectrum sensing, the higher is the sensing accuracy of that channel, the more spectrum opportunity can be discovered, but the cooperative sensing overhead will be higher as well due to the large amount of message exchange. That is why finding the optimal cooperative SUs is an important issue. Moreover, in the case that more than one channels are sensed, the optimal sensing sequence needs to be determined in order to discover the transmission opportunity as soon as possible. If more than one idle channels are detection, there is a need to determine the best one the SU should switch to in order to resume its unfinished transmission. These problems will be analyzed in Chapter 5.

The research methodology adopted is as follows. First, the author identifies a set of problems and challenges for spectrum sensing, spectrum sharing and spectrum handoff in CRNs, then proposes suitable mathematical models and algorithms to address these problems to optimize the system performance in terms of either minimizing overhead or maximizing the achievable throughput for SUs. Subsequently, the author performs comprehensive literature survey for each of the problems outlined and highlights the unique features of the proposed methods. The protocol design and theoretical analysis for the established problems are then proposed and described in detail, followed by performance evaluation using extensive simulations. In this dissertation, the author mainly focuses on spectrum sensing which is discussed in detail in the following chapters, while spectrum sharing and spectrum handoff are also discussed.

1.2 Motivation and Scope

The idea behind CRN is to enhance the utilization of the idle frequency bands while keeping the interference to PUs at an acceptable level. Hence CRN aims to detect the idle spectrum bands and allocate them to the SUs. Although the CRN has produced great expectation since its first appearance, optimization of spectrum management is still an open research field, such as 1) How many SUs should participate in spectrum sensing? 2) How many channels should SUs sense and utilize? 3) How long should the SUs spend on spectrum sensing? 4) How to choose the best target channel when the spectrum handoff is required? All these problems will be investigated in this dissertation.

1.2.1 Cluster-Based Adaptive Sensing and Access

The overhead associated with all elements of cooperative spectrum sensing is called cooperation overhead. The issues which dominate the cooperation overhead may include (i) sensing time and reporting delay, (ii) channel impairments, (iii) energy efficiency, (iv) number of SUs in cooperation sensing, (v) number of sensed channels. Moreover, other factors such as mobility of PUs and SUs, reliability and the security, and wideband sensing will also affect the cooperative sensing overhead [13]. Thus, the author is motivated to explore the idea of cooperation in spectrum sensing and provide an insight on how cooperative sensing can be effectively leveraged to achieve optimal cooperative performance (e.g., achievable throughput for SUs) without being compromised by the cooperation overhead incurred. To achieve this, the following problems need to be addressed if cooperative spectrum sensing is adopted.

How to choose the cooperation parameters, such as the number of sensed channels and the sensing time? The number of sensed channels plays a key role in determining the performance of cooperative sensing because it balances the tradeoff between the need for increasing the chance of successful discovery of opportunities and the desire to reduce the cooperative sensing overhead. On one hand, the smaller the number of sensed channels, the idle channels that can be discovered is less, utilized and shared by the SUs, thus the lower the achievable throughput. On the other hand, increasing the number of sensed channels will improve the spectrum utilization but will incur a high overhead. Moreover, the sensing time is proportional to the number of samples taken by the signal detector. It is generally speaking, the longer the sensing time, the better the detection accuracy. However, due to hardware limitation, SUs are required to cease their transmission while performing spectrum sensing, thus the longer the time devoted to spectrum sensing, the less is the time left for data transmissions, which in turn reduces the achievable throughput for SUs. This is known as the sensing-throughput tradeoff problem, which has been widely studied in [14] [15]. By far, most of the existing work on CSS using energy detection focus on the case that all the SUs in the system select identical time and energy detection threshold for spectrum sensing. Moreover, the underlying assumptions are that both the average SNR and the noise power are identical at the different SUs [15]. These assumptions are not always reasonable, due to the following facts [16]: 1) SUs are in different proximities from the PU; 2) The noise power is not identical in reality. The irrationality of these assumptions will become more severe when the secondary network suffers from fading environment or mobility. Thus due to the heterogeneous characteristics of SUs, it may be more effective if adaptive sensing time is considered. Furthermore, the work in [17] has shown that by allowing the SUs to assign non-identical sensing time, the excessive sensing overhead can be significantly reduced. Motivated from that, it is a challenge to address the cooperative overhead issues with the number of sensed channels and the adaptive sensing time.

How can SUs cooperate in spectrum sensing? In cooperative sensing, all the SUs perform the local spectrum sensing independently, then they report the sensing results to the Fusion Center (FC) where the final decision is made. After that the FC will disseminate the result to all the SUs. The message exchange between the FC and the SUs incurs reporting delay which contributes to the cooperative sensing overhead. Thus the advantages of CSS are at the cost of incurring overhead due to the transmission of the decision results, resulting in more power consumption and additional transmission delay. To alleviate this problem, grouping the SUs into clusters [18] [19] [20] [21] [22] or coalitions [23] for cooperative sensing is an effective approach to reduce the cooperation sensing overhead. The problem is how to group the SUs into clusters in order to reduce the cooperative overhead.

Spectrum sharing has attracted a lot of attention in cognitive radio recently, as an effective method of alleviating the spectrum scarcity problem, by allowing SUs to coexist with PUs under the condition of protecting the latter from harmful interference. However, sensing and access strategy which allows other SUs to coexist with both the PU and the currently transmitting SUs while being subjected to some interference power constraints is still an open issue. To achieve this, spectrum sensing performed by cognitive radio cannot be restricted to simply measure the received energy in some channels of interest but must include detection and signal classification. In Chapter 3, the author proposes a two-stage sensing method based on energy detection and cyclostationary detection. For a given channel, energy detection is performed in the first stage to detect whether the channel is occupied or not, then a secondary stage analysis is done using cyclostationary detection to differentiate whether the channel is occupied by PU or transmitting SU. To implement spectrum sharing while not causing harmful interference to the PU and the transmitting SU, adaptive transmission power is required [24]. The term 'transmitting SUs' will be used hereinafter to refer to SUs who have already gained access to the channel and are transmitting. This is to differentiate them from other SUs who are sensing the channels for transmission opportunities.

1.2.2 MAC Spectrum Sensing Protocol Design

One design goal of Medium Access Control (MAC) protocol for CRN is to minimize the impact of the SUs on the PUs. To accomplish the goal, IEEE 802.22 standard considers various types of periodic spectrum sensing: 1) Normal Spectrum Sensing (NSS) with longer sensing time to identify the available transmission opportunity on a channel. e.g. *Channel Available Check Time* [25] [26]; 2) Fast Spectrum Sensing (FSS) to detect the return of the PU on the channel with short sensing time. Therefore, in Chapter 4, the author proposes a MAC sensing-transmission protocol in which the SU operates on a frame-by-frame basis. Unlike [27] [28] [29] [30], the operating frame is divided into four phases: Normal Spectrum Sensing Phase, Channel Contention Phase, Fast Spectrum Sensing Phase and Data Transmission Phase. NSS is carried out at the beginning of each frame to determine whether the channel is idle. On detecting the available transmission opportunity, the SUs employ CSMA for channel contention. As soon as the SU wins the channel, FSS is performed to promptly detect the return of the PUs. If no PU is active, the SU can start to transmit its own data. The MAC sensing and transmission protocol jointly consider NSS and FSS with the purpose of providing more protection to PU.

Traditional Opportunistic Spectrum Access-MAC (OSA-MAC) carries out channel contention before spectrum sensing which may result in wasting system resource due to contention for unavailable channel. The proposed MAC protocol overcomes this shortcoming by providing up-to-date sensing information. On the other hand, in [27] [28] [29] [30], spectrum sensing is performed at the beginning of each frame to detect the presence of the PU followed by channel contention. However, the efficiency of this kind of MAC protocols suffers due to the random arrival of PUs, which in turn can make the channel become unavailable at any time and cause severe interference to the PUs. To address this problem, it is necessary to insert FSS after channel contention to quickly detect the return of PU. Thus, in the proposed MAC spectrum sensing protocol, FSS is triggered whenever the SU wins the channel, such that the collision probability with the PUs can be reduced. In this work, the author does not assume perfect spectrum sensing; both the detection probability and collision probability are used as important metrics to guarantee the Quality of Service (QoS) of the PU. The author considers the mis-detection that will cause collision at the beginning of a transmission as part of the collision probability which makes the model more correct. Moreover, since FSS proposed in this work is a 'continuous' sensing strategy (i.e. SUs keep sensing the channel until the channel is detected as idle), more transmission opportunity can be made available to the SUs. As shown in Chapter 4, the protocol is a more general case, and it encompasses the MAC protocols in [27] and [28] as a particular case.

The main objective to design the MAC sensing-transmission policy in CRN is either to minimize the error rate or to maximize the achievable throughput for the SUs [14] [31] [32]. In comparison, in addition to maximizing the normalized achievable throughput for the SUs, the author will further introduce a utility function to reward the SUs in the case of a successful transmission and penalize it when collision with the PU occurs. The novelty is that, unlike most other MAC protocols which do not incorporate FSS, in this work, the author inserts FSS after channel contention to promptly detect the return of the PUs. A concrete protocol design is provided in this work, the target is to develop a MAC sensing-transmission protocol that can benefit the SU most and meanwhile provide more protection to the PU. Furthermore, performance comparisons are conducted between the protocol without FSS as well as Spectrum Access Policy (SAP) in [4].

1.2.3 Sequential Sensing Based Spectrum Handoff

CRN allows the low-priority SUs to temporarily utilize the unused licensed channels of the high-priority PUs, thereby significantly improving the overall spectrum efficiency. However, the SUs are required to vacate the occupied channel when PU is detected. In order to return the occupied channel to the PU, the spectrum handoff procedures are initiated to discover a suitable target channel to resume the unfinished transmission. Compared with other major functionalities: spectrum sensing, spectrum decision and spectrum sharing, spectrum handoff is less well explored in the research community. Basically, according to the decision timing for selecting target channels, spectrum handoff mechanisms can be generally categorized into two kinds: [33] 1)

Proactive spectrum handoff, which decides the target channels for future spectrum handoff before data connection is established; 2) Reactive spectrum handoff, in which the target channel is searched in an on-demand manner. For the reactive spectrum handoff, spectrum sensing is performed to help the SUs find an idle channel to resume their unfinished transmission, resulting in extended data delivery time. Compared to the reactive spectrum handoff, the proactive spectrum handoff may be able to reduce handoff delay because the time consumed in spectrum sensing is not required, but in the meantime, it is necessary to resolve the issue of channel obsolescence because the preselected target channel may no longer be available when the spectrum handoff is requested. One fundamental issue for spectrum handoff modeling in CRN is to determine the optimal target channel quickly and reliably. In order to mitigate the demerits of these two handoff mechanisms while utilizing the individual merits, it is better to combine the two methods. To implement this, the author proposes a spectrum handoff mechanism which can reliably determine an idle target channel through sequential spectrum sensing. This mechanism can help to resolve the obsolete channel issue in proactive spectrum sensing handoff where the preselected channel may no longer be available. On the other hand, the spectrum sensing handoff is triggered when the residual idle time (which is defined as the duration from the time instant that the channel is detected to be idle and able to be utilized by the SU until the time instant that the interrupting event occurs and a spectrum handoff is required) of the current utilized channel reaches a threshold. By doing so, spectrum sensing and spectrum analysis can be overlapped with the ongoing transmission. Consequently, the high handoff delay in reactive spectrum handoff can be solved.

In multi-channel cognitive radio system, one task is to determine which channel should be observed at a given time so as to quickly detect the spectral opportunities. Hence, another challenge for spectrum handoff is to determine optimal sensing sequence such that the SU in the network can resume its unfinished communication with minimum delay. Most prior work on sensing order issue [34]-[35] only considers single user or two-user scenario. For single user case, it is shown that if the SU resumes its unfinished transmission on the channel with the highest idle probability, the spectrum switching delay can be significantly reduced. However, if multiple SUs perform spectrum sensing at the same time, switching channel according to the descending order of channel idle probability may no longer be optimal, since these selections will cause collisions among SUs. The optimal sensing sequence problem is still open for multiple SUs case. One has to account for the fact that finding the optimal sensing order as well as the best target channel has huge computational complexity. To address this problem, instead of performing sequential sensing over all the channels in the network, it is necessary to select candidate channels for each SU, which analyzes the tradeoff among the three key characteristics: 1) keep the probability of detecting at least one idle channel high; 2) reduce the sensing overhead and computational complexity as much as possible; 3) avoid collision with other SUs. Therefore, each SU only scans its associated candidate channels every time when the spectrum handoff is triggered. It can be expected that the computational complexity is significantly reduced while the system performance is maintained. The main objective of this work is to propose a sequential sensing based spectrum handoff scheme to determine the optimal sensing order as well as the best target channel for SUs when spectrum handoff is required in a multiple-user cognitive network.

1.3 Major Contributions

As part of the research work, the author addresses the problems identified in Section 1.2 as crucial to study spectrum management in CRN. The approaches adopted by the author includes both analysis and design of models and protocols which optimize the system performance. The major contributions of this dissertation are given as follows:

1.3.1 Cluster-Based Adaptive Sensing and Access

The author investigates the design of the cluster-based adaptive sensing and access strategy for a CRN. The overall objective is to jointly design the sensing and access strategy to maximize the utility of the SUs so as to balance the twin requirements of keeping the sensing overhead minimal and achieving maximum throughput for SUs. The sensing strategy specifies the number of channels that should be sensed. The access strategy determines the expected number of channels that can be utilized and shared by the SUs under the interference power constraints to the PU and the currently transmitting SUs. In summary, the main contributions of this work are as follows:

1. The author proposes a cluster-based sensing and access scheme, in which synchronization and cooperation only happen among the SUs who belong to the same cluster and no FC is needed. By doing so, an adaptive sensing time scheme is used by each cluster, which allows different clusters to choose non-identical sensing time based on their channel gains and traffic loads. With adaptive sensing time strategy and no information exchange between the CH and the FC, the sensing overhead will be significantly reduced.

2. The proposed scheme allows the SUs to sense and access multiple channels. Moreover, the author explicitly calculates the expected number of channels that are idle, being occupied by the PUs and being occupied by the transmitting SUs. Spectrum sharing with the PU and transmitting SUs is employed by adapting the transmission power to avoid causing harmful interference. As a result, the achievable throughput for the SUs can be improved.

3. The author derives an utility function which represents the tradeoff between the requirement to increase the achievable throughput and the desire to reduce the sensing overhead. In particular, the author formulates the design of spectrum sensing and access into an optimization problem. The optimal number of channels that ought to be sensed is obtained numerically, such that the utility can be maximized. Simulation results illustrate that the proposed strategy outperforms Adaptive Spectrum Assessment (ASA) [2] and Sequential Spectrum Sensing (SSS) [3].

1.3.2 MAC Spectrum Sensing Protocol Design

One important issue associated with MAC protocol design is how the SUs determine when and which channel they should sense and access without causing harmful interference to the PU. The author jointly considers the MAC-layer spectrum sensing and channel access. In addition to maximizing the normalized achievable throughput for the SUs, the author further introduces a utility function to reward the SU in the case of a successful transmission and penalize it when collision with the PU occurs. The main objective is to develop a MAC sensing transmission protocol that can benefit the SU most and meanwhile provide more protection to the PU. The primary contributions for this work are summarized as follows:

1. In [36] [37], perfect spectrum sensing is assumed, thus collision only happens due to the return of the PU before the SU completes its transmission. In this work, mis-detection is counted as one part of collision probability. Owing to imperfect spectrum sensing, SU may falsely declare the busy channel as idle, and transmit its packet, resulting in collision at the beginning of the transmission.

2. The author considers two kinds of spectrum sensing: NSS and FSS in the MAC

sensing-transmission protocol design. NSS is performed before channel contention to provide up-to-date sensing information. FSS is carried out after channel contention to very quickly detect the return of the PU so as to avoid severe interference. Theoretical analysis illustrates that the MAC sensing-transmission protocol with FSS outperforms other schemes without FSS in terms of both the utility of the SU and PU protection.

3. To evaluate the performance of the proposed MAC protocol with FSS, the author formulates a normalized throughput-collision tradeoff problem subject to sufficient protection for the PU. Furthermore, a utility function that effectively balances the SU transmission and PU protection is introduced. The author attempts to determine the optimal frame duration such that the utility of the SU is maximized with minimal QoS degradation of the PU. Quantitative methods have been developed to obtain the optimal value for the frame duration.

1.3.3 Sequential Sensing Based Spectrum Handoff

Spectrum handoff occurs when the PUs appear in the licensed spectrum temporarily occupied by the SUs and aims to help the SUs to vacate the spectrum rapidly and resume its transmission on a newly selected available channel. However, a spectrum handoff policy that comprehensively considers spectrum sensing, target channel selection as well as spectrum estimation has yet to be developed. In Chapter 5, the author presents a sequential sensing based spectrum handoff policy for multiple-user CRN. The contributions and significance of this work are listed as follows:

1. Instead of only considering single user or two users in a network, the author considers multiple SUs contending the spectrum for handoff. For the case of single user, it is shown that sensing the channels according to the descending order of

primary-free probability is optimal. However, when multiple users are investigated, some factors e.g., activities of PUs and contention among SUs, will together affect the optimal sensing order. The author proposes a sequential sensing based spectrum handoff for multiple-user CRN. By overlapping the spectrum sensing and spectrum analysis with the ongoing transmission, the high handoff delay can be reduced, while the optimal sensing order as well as a reliable target channel with maximal residual idle time can be found.

2. Although Dynamic Programming (DP) search can be used to find the optimal sensing order as well as the best target channel for each SU, it incurs huge complexity. The author determines the candidate channels for sequential sensing, which exploits the tradeoff between the spectrum opportunity, sensing overhead and computational complexity. It is shown that the system performance is maintained while the computational complexity is significantly reduced.

3. To evaluate the proposed sequential sensing based spectrum handoff strategy, a comparison with conventional sequential sensing SSS [3] is conducted. Simulation results show that the proposed strategy outperforms SSS due to the optimal target handoff channel being selected, which results in a reduction in the number of spectrum handoff.

1.4 Dissertation Organization

The rest of the dissertation is organized as follows:

Chapter 2 presents a comprehensive literature survey of each of the problems discussed in Section 1.2, including spectrum sensing, spectrum sharing and spectrum handoff, where the strengths and limitations of the existing literature are discussed from the perspective of improving the system performance in terms of increasing the achievable throughput and reducing the cooperation overhead.

Chapter 3 explores the design of a cluster-based adaptive multi-spectrum sensing and access strategy, in which the SUs can select a set of channels to sense and access with an adaptive sensing time. The proposed scheme is shown to address the high cooperative sensing overhead and improve the achievable throughput for SUs.

Chapter 4 studies the design of a MAC sensing and transmission protocol that inserts FSS after the channel contention phase. The purpose of inserting FSS into the MAC protocol is to overcome the high collision problem, since the PU packet may arrive and utilize the channel without sensing and contention due to its higher priority. The protocol design of MAC sensing and transmission, including sensing period and the primary busy period, is described.

A sequential sensing based spectrum handoff policy for multiple users CRN is provided in Chapter 5. The focus of this chapter is to select a set of candidate sensed channels while keeping the sensing overhead and computational complexity low and maintaining the idle probability high. The optimal sensing order as well as the best target handoff channel for SUs when spectrum handoff is required in a multiple-user cognitive network is determined using DP. Simulation results are obtained using MATLAB.

Chapter 6 concludes the thesis and the author also discusses the directions of the future research.

Chapter 2

Literature Review

The rapid growth of wireless services has resulted in the increasing demand for spectrum. However, a recent study by Federal Communications Commission (FCC) has shown that most of the allocated frequency bands in US are significantly under-utilized. The current utilization of a licensed spectrum resource varies from 15% to 85% [6] [38]. Moreover, measurement conducted by the Office of Communications in UK shows that there are significant portions of the spectrum being left in vacancy [39]. Similarly, spectrum occupancy measurement taken in [40] indicates that the utilization of spectrum in Washington D.C is less than 35% of the radio spectrum below 3GHz, while in New York the occupancy is only 13.1%. All these reports indicate that the spectrum scarcity is largely due to the inefficient fixed spectrum allocation policy rather than the physical shortage of spectrum. Cognitive radio is therefore proposed as a potential technology to mitigate the spectrum scarcity by allowing the CR/SU to opportunistically access the licensed spectrum unoccupied by the PU [7] [41] [42] [43]. With the underutilization of valuable spectrum resource and greatly increased demand of spectrum for wireless communication services, more efficient spectrum management schemes in CRN are needed. In CRN, PUs have absolute priority to use their spectrum; meanwhile, when the spectrum is not occupied by PUs, SUs are allowed to opportunistically access that spectrum to enable communication or improve service quality [44] [45]. There are several major projects within the scope of dynamic spectrum access, such as DARPA XG program [46] [47], DIMSUMnet project [48], DRiVE/OverDRiVE project [49], TV white space [50], etc. In order to achieve high utilization of spectrum, CRN is required to implement the following spectrum management technologies [9] [51].

1. Spectrum sensing: SUs are required to sense the channel in order to identify spectrum hole before transmission. Once an idle channel is detected, it can be utilized and shared by the SUs. On the other hand, the SUs need to vacate the channel once the return of the PU is detected. Spectrum sensing is a basic functionality in CRN.

2. Spectrum decision: Once the available spectrum is identified, it is essential that SUs select the best available band according to their QoS requirements [52] and the spectrum quality (e.g. residual idle time, channel idle probability, and channel gain).

3. Spectrum sharing: The transmissions of SUs should be coordinated by spectrum sharing functionality to prevent multiple users colliding in overlapping portions of the spectrum. Spectrum sharing allows the SUs to coexist with the PU as long as the interference caused to the PU is below the unacceptable level. Spectrum sharing includes channel and power allocations to avoid interference caused to the primary network and a CR medium access control (MAC) protocol along with spectrum sensing.

4. Spectrum handoff: If the specific portion of the spectrum in use is required by a PU, the communication must be switched to another vacant spectrum. This requires spectrum handoff and connection management schemes closely coupled with spectrum sensing, neighbor discovery in a link layer, and routing protocols.

2.1 Local and Cooperative Spectrum Sensing

Cognitive radio [7] [41] has evolved as a promising technology to attain much higher spectrum utility by Opportunistic Spectrum Access (OSA) (which allows the SUs to utilize the channel only when it is detected to be idle [53]) and Spectrum Sharing (SS) (which allows the SUs to coexist with the PU under condition of an acceptable interference [54]). Perhaps the most appealing property of the CR is its ability to detect and characterize its wireless environment and adapt accordingly. With these capabilities, CR lends itself very well to detect the temporarily unused spectrum and operation in the licensed channels without causing any interference to the high priority users. The main goal of spectrum sensing is to obtain awareness about the spectrum usage and the existence of the PUs in order to adapt their transmission power to avoid causing harmful interference [24].

2.1.1 Sensing Methods

To implement without interference to the PUs and the transmitting SUs, spectrum sensing should be performed before accessing the channels. To enhance the performance of spectrum sensing, many techniques have been developed in the literature, a brief survey can be found in [55]. Currently, the spectrum sensing techniques can be mainly classified into matched filter, covariance matrix based detection, cyclostationary detection and energy detection [56] [57]. Matched filter detection is considered as optimal for detection of PU when the transmitted signal is known because it maximizes the received Signal to Noise Ratio (SNR) [58]. However, one drawback of this method is that it requires perfect knowledge of the PU's signaling features such as operating frequency, modulation type and order. Energy detection is the most common way of spectrum sensing due to its low computational and implementation complexity [56] [59] [60] [61] [62] [63] [64] [65] [66] [67]. The signal is detected by comparing the output of the energy detector with a threshold which depends on the noise [60]. However, it is well known that energy detection is not robust to noise and incapable of differentiating signal types. Cyclostationarity feature detection is a method for detecting PU transmissions by exploiting the cyclostationarity features of the received signals [61] [68] [69] [66] [70] [71]. Although it requires a priori knowledge of the signal characteristics, cyclostationary feature detection is robust to the noise and capable of distinguishing the CR transmissions from various types of PU signals [72] [73] [74]. Covariance matrix based detection is also a common used approach [75] [76] [77]. In [78], a matrix based detection algorithm is proposed to perform spectrum sensing under less than SNR -30dB. In order to mitigate the weaknesses of these detection techniques while exploiting the individual strength, it is better to combine two or more methods. Two-stage detection method performs energy detection in the first stage, followed by cyclostationary detection has been proposed in [79] [80].

2.1.2 Sensing Performance Measurement

Sensing performance is always measured by the detection probability (i.e., the probability that, if there are primary activities, the SUs can detect them successfully) and false alarm probability (i.e., the probability that the SUs falsely declare the idle channel as busy.) [15] [14] [81]. Apparently a higher detection probability can give PUs more protection and a lower false alarm probability leads to more chances of reusing the channel when it is available, which is required to maintain a high spectrum utilization of cognitive radio system. In particular, different methods have been proposed for different objectives, such as maximizing the detection probability while keeping the false alarm probability to an acceptable level, or minimizing the false alarm probability for a pre-determine detection probability. In [82], the authors propose an optimal linear cooperation framework for spectrum sensing in which the sensing problem is formulated as a nonlinear optimization problem with the objective of minimizing the interference to the primary radio while meeting the requirement of opportunistic spectrum utilization. In [16], a novel threshold selection scheme for OR-rule based spectrum sensing with energy detection is proposed under a more general framework of possibly different average SNRs and different noise power levels at each SU. This iterative threshold selection scheme is shown to significantly outperform the common-threshold approach in terms of the total error probability. Moreover, in [83] the authors investigate the minimization of the total error probability in terms of the fusion parameter, energy detection threshold and the number of cooperative SUs.

2.1.3 Cooperative Spectrum Sensing

It is well known that the detection performance of local spectrum sensing is usually limited due to channel multipath fading and shadowing as illustrated in Figure 1.2. As shown in the figure, SU1 and SU2 are located inside the transmission range of the primary transmitter (PU TX) while SU3 is outside the range. Owing to multiple attenuated copies of the PU signal and the blocking of a house, SU1 experiences multipath and SU2 experiences shadow fading such that the PU's signal may not be correctly detected. Moreover, since SU3 is out of the transmission range of PU TX, it suffers from the PU receiver (RX) uncertainty problem. As a consequence, SU3 may start its own transmission and interfere with the reception at PU RX. However, due to spatial diversity, it is unlikely for the SUs in the system to concurrently experience the fading or receiver uncertainty problem. If some of the SUs can detect a strong PU signal like SU4 in the figure, can cooperate and share its sensing result with other SUs. Thus, the overall detection performance can be greatly improved. This so called cooperative spectrum sensing (CSS) [84] [85], which has been shown to be an attractive and effective approach to combat multipath fading and shadowing and mitigate the receiver uncertainty problem. By taking advantage of spatial diversity with cooperative sensing, the reliability of spectrum sensing can be greatly improved [86] [87] [88] [85] [89]. Multiple SUs sense the spectrum independently, and send the results to a FC, which will make the final estimation on whether there are primary activities in the channel. Two common decision-combining approaches have been proposed, hard decision (e.g. Each SU performs independent local spectrum sensing and reports the binary decision to the FC.) and soft decision (e.g. Each SU is required to send the full observation result to the FC.) [85] [90] [91].

To accurately detect the active PU, many technologies have been developed to combine the local decision results. In [85], the AND fusion rule (The PU is declared as active by the FC if all of the cooperative SUs infer that) is introduced and it has been shown that sensing performance of CSS can be significantly improved. Performance of CSS based on the OR Rule (The FC makes a decision on the presence of PU if at least one of the SUs infers that) under a fading channel is analyzed in [89]. In [87] [88], the relay-based cooperative sensing is investigated, in which the effect of the Amplify-and-Forward (AF) cooperation protocol on the spectrum sensing capabilities of CRN is studied. In order to accurately detect the weak primary signal, an optimal linear cooperation framework for spectrum sensing is proposed in [82]. In particular, if K or more of the decisions indicate that the PU is active, then the final decision made by the FC infers that there is an active PU; otherwise, the FC will infer the absence of the PU. This is the so called K-out-of-N fusion rule and its performance analysis is investigated in [92] [93]. Note that the proposed AND rule [85] and OR rule [89] are two special cases of this general counting rule. It is noted that CSS generates a lot of sensing overhead, since each SU is required to send its own decision result to the FC. Thus, to reduce the sensing overhead, in [18], a cluster-based fusion rule based on selection is proposed, in which only the SUs who have sufficient information are required to send their 1-bit decisions to the FC. This cluster-based CSS will be further discussed next. When the soft decision is used, the optimal fusion rule is Chair-Varshney rule based on log-likelihood ratio test [94]. Refer to [95] for more recent techniques in combining the soft decisions.

2.2 Cluster-Based Adaptive Sensing and Access

2.2.1 Cluster-Based Cooperative Spectrum Sensing

In conventional CSS systems, each SU reports the observation to the FC through perfect channels, which is impractical since the channels between the SUs and the FC are usually subject to shadowing and fading [96]. A cluster-based CSS is proposed to improve the sensing performance [18]. All SUs are divided into a few clusters, in each cluster user selection diversity is exploited by selecting the most favorable user with the largest reporting channel gain as cluster head (CH), who is responsible for collecting the sensing results, makes cluster decisions and forwards results to the FC. By employing such selection technique, the reporting error due to the fading and shadowing can be reduced. In [97], a cluster-based cooperative sensing scheme is proposed to decrease the cooperation overhead and improve the spectrum utilization. In most of works, local decisions of each SU are required to report to the FC directly. However, some SUs may be placed far away from the FC, thus in order to ensure their results are received correctly, much transmission power is required because signal will be decayed with the increase of transmission distance. To reduce the transmission energy consumption, in [21] an cluster-based energy efficient transmission scheme is proposed, in which all the SUs in the same cluster report their results to the CH. Thus the transmission energy consumed by the SUs will be reduced significantly because most of them are closer to the CH than to the FC, therefore much less power is needed to transmit local decisions. Moreover, [22] only allows the SUs with enough information in each cluster to send the sensing results to the CH. Cluster-based sensing strategies are further investigated in [19] [20] [98] [99].

2.2.2 Spectrum Sharing

Recently, the optimization of spectrum sensing and access in CRN under perfect sensing has been studied by a lot of reseachers. In [2], an Adaptive Spectrum Assessment (ASA) approach is proposed to decide how to seek spectrum opportunity effectively. A set of channels is sensed every time a discovery of new spectrum opportunity is triggered. The optimal number of sensed channels is derived with the aim of keeping the overhead low as well as increasing the likelihood of discovering spectrum opportunity. In [3], spectrum is searched by sensing the channels one by one until an idle channel is detected. The optimum sensing time for channel-search and channel-monitoring is obtained so as to maximize the average throughput for the SU while protecting the PU from harmful interference. However, previous studies on spectrum sensing and access in CRNs have focused primarily on the utilization of some portions of the licensed spectrum provided that the PU is absent. A CRN is formed by either allowing the SUs to opportunistically operate in the idle spectrum originally allocated to a PU (referred to as Opportunistic Spectrum Access (OSA)) or by allowing the SUs to coexist with the PUs as long as the interference caused by the SUs to the PUs is properly regulated (referred to as Spectrum sharing (SS)). SS has been widely studied recently, e.g. [24] [100] [101] and has been shown to improve the performance in terms of increasing the achievable throughput for SUs. In [24], the evaluation of the ergodic capacity of the SUs is formulated as an optimization problem over the transmission power and the sensing time, under this model, the SUs can adjust its transmission power depending on whether the PU is active. SS problem is further investigated in [100], in which a novel receiver and frame structure for CRNs is introduced. It has been shown to significantly improve the achievable throughput under both average transmission and interference power constraints. From the PU's perspective, SU is allowed to utilize the channel as long as the interference does not degrade the quality of service (QoS) of the PU to an unacceptable level. From the SU's perspective, the SU should adapt its transmission power in order to achieve a reasonably high transmission rate without causing too much interference to the PU.

2.3 MAC Spectrum Sensing Protocol Design

2.3.1 Collision Probability

In order to evaluate the spectrum sensing performance, two metrics are of great interest: detection probability and false alarm probability as discussed in Section 2.1.2. However, some researchers have focused on how to design the sensing-transmission control strategy using collision probability as a protection metric with perfect spectrum sensing [36] [37]. It should be noted that, even if perfect sensing is performed, collision may also happen in the following scenario: the SU successfully detects the available transmission opportunity when the channel is idle and starts to transmit. However, the PU returns before the SU completes its transmission. In [37], the authors study the data capacity of cognitive radio users in OSA under stringent intrusion constraints on collision probability and the overlapping collision time, a closed-form expression for the collision probability of the PU is obtained. In [36], the authors study the design of transmission frame duration with the aim of achieving the maximum throughput for the CRN while ensuring that the collision probability for PUs is less than a threshold. [102] studies the tradeoff between spectrum utilization and collision on the basis of different traffic models of the SU with the aim of maximizing the utilization of SU and ensuring that the collision rate to the PU is below a given threshold. Moreover, collision may also occur owing to imperfect spectrum sensing. The SU may mistakenly declare the active PU as idle and transmit its packet, such that collision will happen at the beginning of the transmission. In [103], a cost and reward-based access policy has been proposed with the aim of maximizing the utility for both perfect and imperfect sensing. In [4], the design of the optimal sensing-transmission strategies on a single channel is investigated under imperfect sensing, where the total collision probability is restricted to satisfy the protection required by the PU.

2.3.2 MAC Channel Sensing and Contention

One challenge faced by co-existing CRNs is how to alleviate the inter-network media contention (with PU using spectrum sensing) and intra-network contention (with other SUs via e.g. CSMA/CA mechanism). In [104], the authors design a CSMA/CA-based cognitive radio MAC protocol which uses channel statistics to determine the optimal access range and the number of channels to access. The joint consideration of both MAC-layer sensing and channel contention access has been studied by many researchers. The common method, called Opportunistic Spectrum Access-MAC or OSA-MAC in short, allows the SUs to perform channel contention before spectrum sensing. This may result in contending for unavailable channel and wasting system resource. On the other hand, in [27] [28] [29] [30], spectrum sensing is carried out at the beginning of each frame to detect the presence of the PU followed by channel contention which can benefit from the up-to-date sensing information. More specifically, in [27], an effective protocol design that adapts the standard 802.11 Distributed Coordination

Function (DCF) is provided for channel contention after spectrum sensing. An analytical derivation of the saturated throughput and various delay performance indicators for the DCF-OSA design is obtained. In [28], the authors propose a novel class of carrier sense multiple access (CSMA) based MAC protocols for the CRN with a feasible adaptive PHY transmission scheme, and the results show that the throughput for the CRN can be significantly improved. In [29], the cognition capability and CSMA are introduced into multichannel MAC for CRN. The proposed cognitive CSMA-based multichannel MAC protocol utilizes sensing and adaptation functionalities to extract both inter and intra system information and optimize the performance. However, due to the random arrival of the primary packets, the PU will transmit without sensing and contention whenever it becomes active resulting in severe interference with the SU who wins the channel and attempts to transmit. Thus, the sensing and contention protocols provided in [27] [28] [29] [30] still have much left for improvement.

2.4 Sequential Sensing Based Spectrum Handoff

2.4.1 Spectrum Handoff

Owing to the high priority of the PU, the SU is required to vacate the occupied channel when the PU reappears and determine a new suitable channel to resume its unfinished transmission. This process is referred to as spectrum handoff. Compared with other major functionalities: spectrum sensing, spectrum decision and spectrum sharing, spectrum handoff is less well explored in the research community. In general, the spectrum handoff can be categorized in two kinds [33]: 1) Proactive spectrum handoff which decides the target channel before the interruption happens according to the long term traffic statistics [105] [106] [107]; 2) Reactive spectrum handoff which selects the target channel when it is required via spectrum sensing [108] [109]. After a spectrum handoff is required, spectrum sensing is performed to help the SU find a new channel to resume its unfinished data transmission. Both spectrum handoff schemes have their own advantages and disadvantages. One issue related to proactive spectrum handoff is that the preselected channel may become no longer available at the moment that spectrum handoff is initiated. While for reactive spectrum handoff, additional time is required for spectrum sensing to search for spectrum holes and discover an idle channel. A quantitative comparison of the two spectrum handoff schemes is provided in [110]. In [111], the authors propose a new type of spectrum handoff referred to as Voluntary Spectrum Handoff (VSH) to reduce temporary communication disruption time due to spectrum handoff by voluntarily changing the spectrum without conflicting with PUs. More specifically, the performance of spectrum sensing has been analyzed by many researchers. In [112], both opportunistic and negotiated spectrum handoff strategies are investigated, the performance in terms of link maintenance probability, the number of spectrum handoff, switching delay, and non-completion probability are explored. Study on spectrum handoff where the SU greedily selects the target channel which results in minimum transmission latency has been done in [110] [113] [114]. In [114], a spectrum decision analytical model is proposed based on the preemptive resume priority (PRP) M/G/1 queueing theory to evaluate the effects of multiple interruptions from the PU. With the objective of minimizing the overall system time of the SUs, the optimal number of candidate channels and the optimal channel selection probability for the sensing-based and the probability-based spectrum decision schemes are obtained, respectively. In [115] the channel with the highest probability of being idle is selected to resume the unfinished transmission.

2.4.2 Sensing Order for Sequence Spectrum Sensing

Recently, study on the optimization of spectrum sensing in CRN has attracted much attention. There are two approaches that are commonly used to schedule the spectrum sensing [116]. The first one is periodic spectrum sensing [14] [26], in which the SUs perform spectrum sensing at the beginning of each frame and transmit if the channel is detected as idle. Otherwise, the SUs have to wait until the next frame. The other approach is sequential spectrum sensing (SSS) [3] [116] [35] [117]. In this case, spectrum is searched by sensing the channels one by one until an idle channel with satisfied quality is detected. This approach allows SUs to explore diversity in the licensed spectrum by quickly continuing to identify another spectrum opportunity in case one channel is sensed busy. Hence, if one channel is sensed to be busy, the SU can quickly continue to sense the next spectrum opportunity without waiting until the next frame as in the case of periodic sensing. Due to the above reasons, SSS is of concern in Chapter 5.

To implement a better spectrum handoff in the event of PU activity with seamless communication, wideband sensing is essential for designing a maximally effective cognitive network. It can detect multiple opportunities and enable the choice of the best available channel. However, the literature of wideband spectrum sensing for CRNs is very limited. In [118], sequential sensing is introduced, in which a wideband radio channel is sensed using tunable narrowband bandpss filter at the RF front-end to sense one narrow frequency band at a time. There have also been studies on sensing different frequency bands simultaneously. In [119], multiband joint detection approach is proposed where the wideband channel is divided into K nonoverlapping narrow subbands. In [120], an optimal algorithm is presented for wideband spectrum sensing with the aim of maximizing the achievable throughput for the SU while keeping the interference with the primary network bounded to a reasonably low level. One important issue related to wideband spectrum sensing is the optimal sensing order problem. For SSS, a SU may have a number of potential channels, and the SU can only sense one channel at a time. Thus one task is to determine which channel and in what sequence the channel should be observed at a given time so as to fully utilize the spectral opportunities. In [121], an analytical framework for opportunistic spectrum access based on the theory of Partially Observable Markov Decision Process (POMDP) is developed. In [122], an optimal channel probing and transmission policy is derived, with the goal of determining which channels to probe, in what sequence, and which channel to use for transmission under the assumption that recall (i.e., using one of the previously sensed channels) and guess (i.e., using a channel that has not been sensed yet) are allowed. In [34], the multi-channel sensing problem is formulated as an optimal stopping rule problem and it is shown that the optimal sensing order does exist in some special scenarios for the single user case. In [35], the authors extend the sensing order issue to two-user multi-channel case. The problem is still open for multiple SUs case. For the case without adaptive modulation, low-complexity algorithms have been proposed. For the case with adaptive modulation, it is shown that the sensing order setting should be jointly designed from a systematic point of view. In [115] and [123], the authors propose the spectrum switching algorithm according to descending order of channel idle probability. When PU appears on the current operating channel, the SU must vacate the channel immediately and resume its transmission on the channel which has the highest idle probability. This approach has proven that the spectrum switching delay can be significantly reduced. However, if multiple SUs perform spectrum sensing at the same time, these channel switching according to the descending order of channel idle probability may no longer be optimal, since these selection will cause collisions among SUs.

Chapter 3

Cluster-Based Adaptive Multi-Spectrum Sensing and Access

In this chapter, the author proposes a cluster-based adaptive multi-spectrum sensing and access strategy for a CRN, in which the SUs seeking to access the channel can select a set of channels to sense and access with adaptive sensing time. The overall objective is to jointly design the sensing and access strategy to maximize the utility of the SUs so as to balance the twin requirements of keeping the sensing overhead minimal and achieving maximum throughput. The sensing strategy specifies the number of channels that should be sensed. The access strategy determines the expected number of channels that can be utilized and shared by the SUs under the interference power constraints to the PU and the transmitting SUs. Specifically, the spectrum sensing and access problem is formulated into an optimization problem and the optimal number of sensed channels is obtained numerically. Moreover the author explicitly calculates the expected number of channels that are detected to be idle, or being occupied by the PUs or being occupied by the transmitting SUs. Spectrum sharing with the primary and transmitting SUs is accomplished by adapting the transmission power to keep the interference to an acceptable level. Simulation results demonstrate the effectiveness of the proposed cluster-based sensing and access strategy as well as its advantage over conventional sensing and access methods in terms of improving the achievable throughput and keeping the sensing overhead low.

In the following section, the system model is revisited. Section 3.2 introduces some performance evaluation metrics: cooperative sensing overhead, average achievable throughput, utility and error rate. The problem analysis is presented in Section 3.3 which includes calculating the expected number of channels that are idle, or being occupied by the PUs or being occupied by the transmitting SUs and designing adaptive sensing time scheme. Section 3.4 is used to provide additional insights into the cluster-based spectrum sensing through simulation following which important conclusions are drawn in Section 3.5.

3.1 System Model

In this section, the author considers a simple CRN consisting of M PUs/channels and N SUs. The PUs are the licensed holders and have the absolute priority to access the channels. However, the SUs can opportunistically utilize the idle channels as well as share the occupied channels by adapting their transmitting powers to avoid causing unacceptable level of interference to the PUs. In the proposed model, as defined earlier, *transmitting SU* refers to the SU who is currently transmitting on the detected channels. The other SUs who attempt to share the same channel as the transmitting SU should satisfy the interference power constraint.

The system architecture is illustrated in Figure 3.1. The author assumes that the SUs are divided into K clusters by some distributed algorithms, which is out of the scope of this work, examples of which may be found in [124] [125], where each cluster

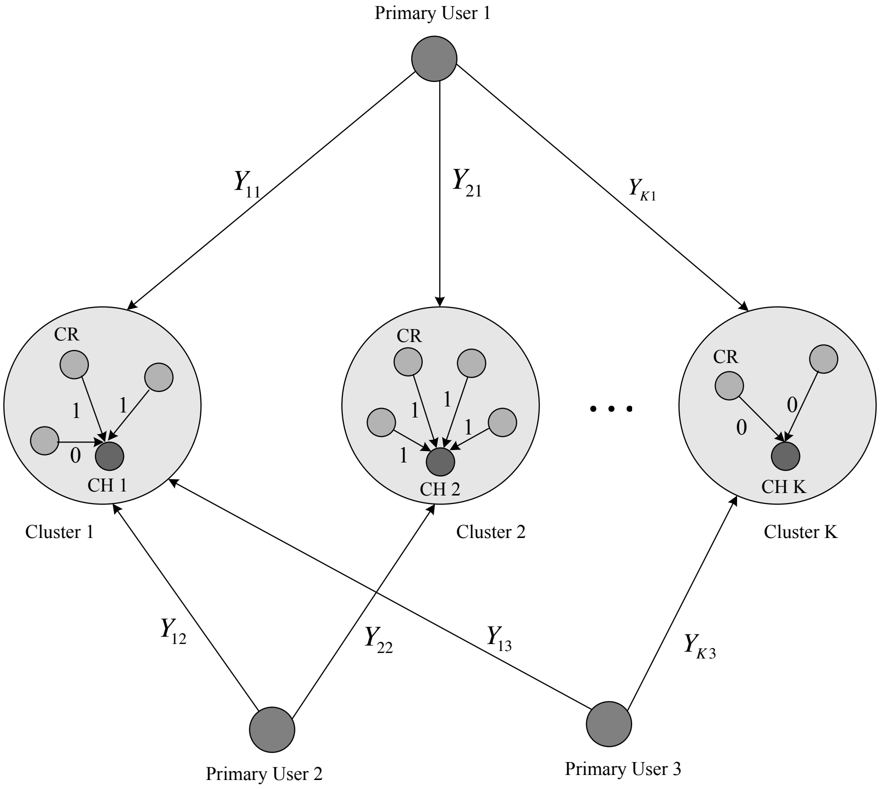

Figure 3.1: The cluster-based system model for cognitive radio network.

has N_i SUs ($i = 1, 2, .., K$) and one of them is selected as the cluster head (CH). From the beginning of each frame, cluster i will select l_i spectrum bands to sense. The set of channels to be sensed is selected by the CH and is distributed to the SUs in the cluster.

Similar to [14], the author assumes that the SUs operate in a slotted frame structure. Each basic frame of a SU consists of a sensing phase and a data transmission phase, as shown in Figure 3.2. The frame duration is denoted as T. Spectrum sensing is a key element in cognitive radio communications as it should first be performed before allowing opportunistic spectrum access and sharing. The author assumes that each SU performs local spectrum sensing independently and in the following the author takes the analysis of cluster i as an example. Suppose the received signal is sampled with

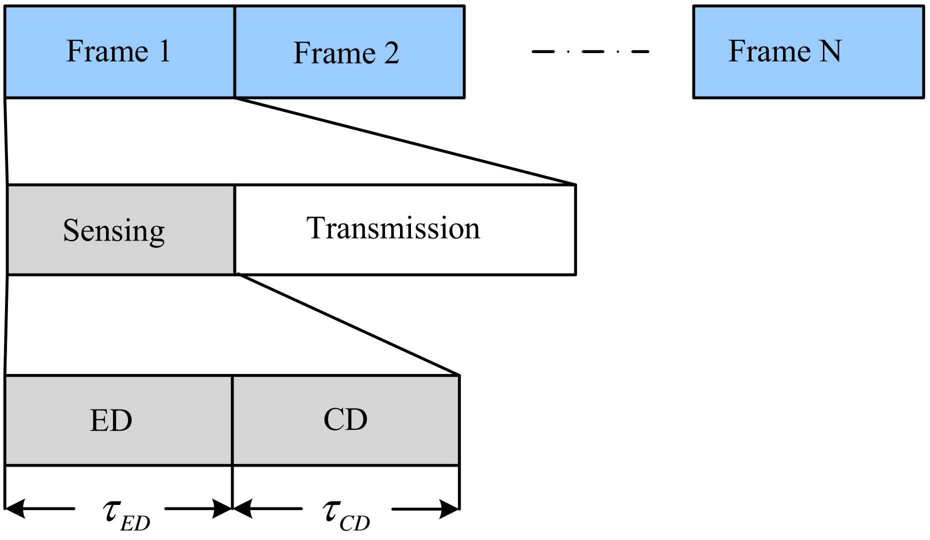

Figure 3.2: Frame structure for CRNs with periodic spectrum sensing (τ_{ED}: sensing duration for Energy Detection (ED); τ_{CD}: sensing duration for Cyclostationary Detection (CD)).

sampling frequency f_s, then the sampled received signal of the SUs in cluster i for channel j ($1 \leq j \leq l_i$) has two hypotheses:

$$\begin{aligned} H_{1,(ij)}: &\quad y_{i,j}(n) = g_{ij} r_{i,j}(n) + u_{i,j}(n) \\ H_{0,(ij)}: &\quad y_{i,j}(n) = u_{i,j}(n) \end{aligned}$$

where $H_{0,(ij)}$ and $H_{1,(ij)}$ represent the channel is idle and busy, respectively. g_{ij} is the channel gain over the sensing channel j. n is the sample index ranging from $1 \leq n \leq \tau_i f_s$, τ_i is the sensing time of cluster i. $r_{i,j}(n)$ is the detected signal in channel j received by SUs in cluster i with zero mean and variance $\sigma^2_{r_{i,j}}$. $u_{i,j}(n)$ is the independent white Gaussian noise experienced by the SUs in cluster i from channel j with zero mean and variance $\sigma^2_{u_{i,j}}$. It is further assumed that the detected signal $r_{i,j}(n)$, regardless of primary signal or secondary signal, is independent of the noise $u_{i,j}(n)$. The power transmitted by the PU is received at the SU and the ratio of received power to the power of noise at the SU is defined as the SNR at the SU energy detector. More

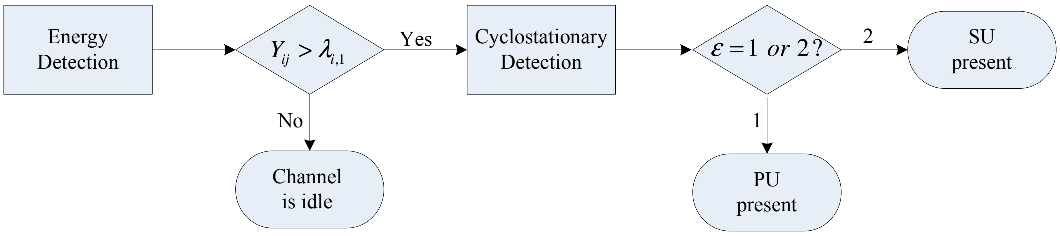

Figure 3.3: The model of two-stage sensing method with energy detection in the first stage, followed by cyclostationary detection.

specifically, the received SNR is defined as

$$\gamma_{i,j} = \frac{E[|g_{ij}|^2]\sigma^2_{r_{i,j}}}{\sigma^2_{u_{i,j}}}$$

A two-stage sensing strategy based on energy detection and cyclostationary detection is considered in this work as shown in Figure 3.3. At the first stage, energy detection is used, if the measured energy is below a certain threshold $\lambda_{i,1}$, the channel is declared as idle. The idle channel can be utilized by SU without causing any harmful interference to the PU and transmitting SU. On the other hand, the channels with detected energy that surpasses $\lambda_{i,1}$ are passed to the second stage where cyclostationary detection is used to distinguish between PU and SU. If the signals belong to the PUs, the SU can share the channels by keeping the interference to the PUs at an acceptable level. Otherwise, the channels are categorized as being occupied by the transmitting SUs. Therefore, other SUs who attempt to utilize these channels should adapt their transmission power to satisfy the power constraints. The proposed mechanism of two-stage spectrum sensing scheme is shown in Figure 3.3, and the detailed analyses of the energy detection, cyclostationary detection are discussed in the following Section 3.1.1 and Section 3.1.2.

3.1.1 Energy Detection

The first stage of the proposed two-stage spectrum sensing approach is based on energy detection where the detector accumulates the energy of all the samples and then compares it with a certain threshold $\lambda_{i,1}$ to identify whether the channel is idle or not. For simplicity, we set $\tau_{ED} = \tau_{CD} = \tau_i$ for all the SUs in cluster i. The test decision statistic at the SU belonging to cluster i for channel j can be represented by

$$Y_{i,j} = \frac{1}{f_s\tau_i}\sum_{n=1}^{f_s\tau_i} |y_{i,j}(n)|^2 \tag{3.1}$$

The decision rule used by the energy detection is given by

$$Y_{i,j} \underset{H_{1,(ij)}}{\overset{H_{0,(ij)}}{\lesseqgtr}} \lambda_{i,1} \tag{3.2}$$

Under the hypothesis $H_{0,(ij)}$, $Y_{i,j}$ follows a Chi-square distribution with $2f_s\tau_i$ degrees of freedom, e.g. $Y_{i,j}|H_{0,(ij)} \sim \chi^2_{2f_s\tau_i}$ and a noncentral chi-square distribution with $2f_s\tau_i$ degrees of freedom and non-centrality parameter of $2f_s\tau_i\gamma_{i,j}$ under hypothesis $H_{1,(ij)}$ [126]. Therefore, the probability density function of random variable $Y_{i,j}$ under hypotheses $H_{0,(ij)}$ and $H_{1,(ij)}$ can be given as [127]

$$f_{Y_{i,j}}(y) = \begin{cases} \frac{y^{\tau_i f_s} e^{(-y/2)}}{2^{\tau_i f_s}\Gamma(\tau_i f_s)} & H_{0,(ij)} \\ \\ \frac{1}{2}(\frac{y}{2\tau_i f_s \gamma_{i,j}})^{(\tau_i f_s - 1)/2} e^{-(y+2\tau_i f_s\gamma_{i,j})/2} I_{\tau_i f_s}(\sqrt{(2\tau_i f_s y \gamma_{i,j})}) & H_{1,(ij)} \end{cases}$$

where $\Gamma(\cdot)$ is the gamma function and the $I_{\tau_i f_s}(\cdot)$ is the modified Bessel function. According to central limit theorem, when $f_s\tau_i$ tends towards infinity (practically when $f_s\tau_i \geq 10$ [46]), $Y_{i,j}|H_{0,(ij)}$ can be approximated by a Gaussian distribution with mean and variance as [14]

$$\mu_{0,(i,j)} = \sigma^2_{u_{i,j}} \quad and \quad \sigma^2_{0,(i,j)} = \frac{1}{f_s\tau_i}[E|u_{i,j}(n)|^4 - \sigma^4_{u_{i,j}}]$$

If the noise $u_{i,j}(n)$ is Circular Symmetric Complex Gaussian (CSCG), then $E|u_{i,j}(n)|^4 = 2\sigma^4_{u_{i,j}}$, thus

$$\mu_{0,(i,j)} = \sigma^2_{u_{i,j}} \quad and \quad \sigma^2_{0,(i,j)} = \frac{1}{f_s\tau_i}\sigma^4_{u_{i,j}}$$

Thus the false alarm probability $P^1_{f,(i,j)}$ which is defined as the probability of the SU falsely declaring the presence of PU or the transmitting SU in channel j under $H_{0,(ij)}$ is given by [14]

$$\begin{aligned} P^{(1)}_{f,(i,j)} &= P[Y_{i,j} > \lambda_{i,1}|H_{0,(ij)}] = \int_{\lambda_{i,1}}^{\infty} f_{Y_{i,j}|H_{0,(ij)}}(y)dy \\ &= Q((\frac{\lambda_{i,1}}{\sigma^2_{u_{i,j}}} - 1)\sqrt{f_s\tau_i}) \end{aligned} \tag{3.3}$$

where the superscript $'1'$ means the sensing stage. $Q(x)$ is the tail probability of the standard normal distribution [128], which is defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{t^2}{2}}dt$$

Furthermore the detection probability $P^1_{d,(i,j)}$ which is defined as the probability that the SU correctly detects the busy status of channel j under $H_{1,(ij)}$ can be expressed as [14]

$$\begin{aligned} P^{(1)}_{d,(i,j)} &= P[Y_{i,j} > \lambda_{i,1}|H_{1,(ij)}] = \int_{\lambda_{i,1}}^{\infty} f_{Y_{i,j}|H_{1,(ij)}}(y)dy \\ &= Q((\frac{\lambda_{i,1}}{\sigma^2_{u_{i,j}}} - 1 - \gamma_{i,j})\sqrt{\frac{f_s\tau_i}{2\gamma_{i,j}+1}}) \end{aligned} \tag{3.4}$$

where $\gamma_{i,j}$ is the measured SNR of the detected signal in channel j received by SU in cluster i. Observe that the detection probability $P^1_{d,(i,j)}$ is monotonically increasing with regards to the sensing interval τ_i and the SNR $\gamma_{i,j}$.

In order to protect the high priority users from interference by the SUs, the detection probability in the first stage should not be less than a predefined threshold, that is $P^1_{d,(i,j)} \geq \alpha \geq 0.9$, for $\forall i, j$. Note that the author sets $\gamma_{i,j} = min(\gamma^s_{i,j}, \gamma^p_{i,j})$, where $\gamma^s_{i,j}$ and $\gamma^p_{i,j}$ denote the received SNR of the transmitting SU and PU in channel j, respectively. Owing to the fact that the detection probability is a monotonically increasing function of SNR, to guarantee a target detection probability of the signal with smaller SNR will allow both the PU and the transmitting SU to be well protected. The false alarm probability can be rewritten as a function of α, that is

$$P^{(1)}_{f,(i,j)} = Q(\sqrt{2\gamma_{i,j} + 1}Q^{-1}(\alpha) + \gamma_{i,j}\sqrt{f_s\tau_i}) \tag{3.5}$$

3.1.2 Cyclostationary Detection

The second stage of the proposed two-stage sensing method performs cyclostationary detection to differentiate the signal types: for all the channels that are previously identified as busy, the author estimates whether the channels are occupied by the PUs or the SUs. In order to lower power consumption and speed up spectrum sensing, one-order cyclostationary detection scheme which exploits the mean characteristics of the received signals is used [80]. Suppose the received signal can be modeled as

$$y^{(\epsilon)}_{i,j}(n) = r^{(\epsilon)}_{ij} e^{j(2\pi f^{(\epsilon)}_{ij} n + \theta^{(\epsilon)}_{ij})} \tag{3.6}$$

where $r^{(\epsilon)}_{ij}$, $f^{(\epsilon)}_{ij}$, and $\theta^{(\epsilon)}_{ij}$ are the amplitude, frequency and phase of the received signal on channel j. The superscript $\epsilon = 1, 2$ represents the primary or the secondary signals, respectively. The mean function of $y_{i,j}^{(\epsilon)}(n)$ can be expressed as

$$M_{i,j}^{(\epsilon)}(n) = \frac{1}{2\tau_i f_s + 1} \sum_{n=0}^{2\tau_i f_s} y_{i,j}^{(\epsilon)}(n) \tag{3.7}$$

The operation of this one-order cyclostationary detection is to measure the envelope of the mean $M_{i,j}^{(\epsilon)}(n)$, and compare it with the predetermine threshold $\lambda_{i,2}$. Then the false alarm probability, the detection probabilities for PU and SU are given by

$$P_{f,(i,j)}^{(2)} = 1 - exp(-\frac{(2\tau_i f_s + 1)\lambda_{i,2}^2}{2\sigma_{u_{i,j}}^2}) \tag{3.8}$$

$$P_{d_p,(i,j)}^{(2)} = Q(\frac{\sqrt{2\gamma_{ij}^p}}{\sigma_{u_{i,j}}}, \frac{\lambda_{i,2}\sqrt{2\tau_i f_s + 1}}{\sigma_{u_{i,j}}}) \tag{3.9}$$

$$P_{d_s,(i,j)}^{(2)} = Q(\frac{\sqrt{2\gamma_{ij}^s}}{\sigma_{u_{i,j}}}, \frac{\lambda_{i,2}\sqrt{2\tau_i f_s + 1}}{\sigma_{u_{i,j}}}) \tag{3.10}$$

where $Q(\iota, \kappa)$ the generalized Marcum Q-function, which is defined as

$$Q(\iota, \kappa) = \int_{\kappa}^{\infty} x e^{-(x^2+\iota^2)} I_0(\iota x) dx$$

where $I_0(x)$ is the first-order Bessel function.

In this two-stage sensing method, a false alarm happens under hypothesis $H_{0,(ij)}$, if false alarm occurs at both stages, hence the overall false alarm probability is given by

$$P_{f,(i,j)} = P_{f,(i,j)}^{(1)} P_{f,(i,j)}^{(2)} \tag{3.11}$$

Similarly, the overall detection probabilities for SU and PU are given by

$$P_{d_s,(i,j)} = P^{(1)}_{d,(i,j)} P^{(2)}_{d_s,(i,j)} \tag{3.12}$$

$$P_{d_p,(i,j)} = P^{(1)}_{d,(i,j)} P^{(2)}_{d_p,(i,j)} \tag{3.13}$$

Then, the classification of the PU and the SU is carried out using amplitude $r^{(\epsilon)}_{ij}$, frequency $f^{(\epsilon)}_{ij}$ and phase parameters $\theta^{(\epsilon)}_{ij}$. [129] proposes an identification algorithm to classify the signal types (as depicted in Figure 1 of [129]). The author do not fully introduce this method here as the detailed implementation is found in [129]. Moreover, if the SU has prior knowledge of signal modulation type, cyclostationary features analysis, such as Spectral Correlation Density (SCD) and Spectral Coherence Function (SCF) can be viewed as a useful tool for signal classification due to its important property that different modulated signals with the same power spectral density have highly distinct SCDs/SCFs [130]. That is, the signal r_{ij} is declared to be present if a spectral component is detected at the corresponding cycle frequency. For an example, one can refer to [130].

3.1.3 Cluster-Based Cooperative Spectrum Sensing

As discussed in Section 2.1.3, one of the most important challenges for implementing spectrum sensing is the hidden terminal problem, which happens when the SUs are in a fading and shadowed environment. Cooperative spectrum sensing is therefore adopted to address this issue. There are N_i SUs in cluster i and one of them is chosen as CH who will act as FC. In general, each SU in cluster i performs local spectrum sensing independently and then makes a binary decision $D_{ij} \in \{0, 1\}$ $i = 1, 2, ..., N_i - 1$ for channel j, where 0 and 1 denote the absence and presence of the PU, respectively. Thereafter, all the SUs report their decision results to the CH, who then combines these results with its own decision to make the final decision, $H_{0,(ij)}$ or $H_{1,(ij)}$, which infers the absence or presence of the PU on channel j, respectively [126]. Based on all the received D_{ij}, the FC can make the final decision D_j with a proper fusion rule. In particular, if κ or more of the decisions indicate that the PU is active, then the final decision made by the FC infers that there is an active PU, i.e. $H_{1,(ij)}$; otherwise, the FC will infer the absence of the PU, i.e. $H_{0,(ij)}$. For example,

$$D_j = \begin{cases} 1 & \sum_{i=1}^{N_i} D_{ij} \geq \kappa \\ \\ 0 & \sum_{i=1}^{N_i} D_{ij} < \kappa \end{cases} \tag{3.14}$$

This is the so called κ-out-of N_i rule. Specifically, κ can take any value between 1 and N_i which demonstrates that the *OR* rule corresponds to the case when $\kappa = 1$ and the *AND* rule corresponds to the case when $\kappa = N_i$.

Figure 3.1 describes the system structure of the proposed cluster-based spectrum sensing and access method. At first, all the SUs in cluster i carry out local two-stage spectrum sensing and make individual decision. Then the CH collects and combines the sensing observations from the SUs in the cluster, makes the decision on the availability of the spectrum and then disseminates the results. The author assumes that cooperative spectrum sensing is adopted within the cluster. As been discussed in Section 2.1.3, the performance of fusion rules has been widely investigated [131] [132] for combining the hard decisions from all the cooperative SUs in terms of either minimizing the error rate or maximizing the achievable throughput for SUs. With the purpose of protecting the PU and the transmitting SU, *OR* decision fusion rule is used. This rule means the CH informs that the signal is being transmitted, when there exists at least one SU inferring that. Therefore, the cooperation detection probabilities for primary signal and secondary signal is given by

$$Q_{d_p,(i,j)} = 1 - \prod_{h=1}^{N_i}(1 - P_{d_p,(i,j)}) \tag{3.15}$$

$$Q_{d_s,(i,j)} = 1 - \prod_{h=1}^{N_i}(1 - P_{d_s,(i,j)}) \tag{3.16}$$

Similarly, for OR decision fusion rule, cooperative false alarm probability happens if at least one of the SUs infers that the idle channel is busy. Thus the cluster-based cooperative spectrum sensing false alarm probability is formulated as

$$Q_{f,(i,j)} = 1 - \prod_{h=1}^{N_i}(1 - P_{f,(i,j)}) \tag{3.17}$$

It can be observed from Eqns. (3.15), (3.16) and (3.17) that as the number of cooperative SUs N_i increases, the cooperative detection probability of a cluster also increases, and as a result the accuracy of detecting the active PU also increases. However, the higher N_i is, the larger is the cooperative false alarm probability which leads to a higher chance of wasting the transmission opportunity. One should note that the proposed cluster-based sensing and sharing scheme differs from other existing conventional cluster-based sensing methods [18] in the following ways:

1. Cooperative spectrum sensing only happens within the same cluster. There is no FC, thus CHs are not required to forward their decision to the FC. By doing so, all the SUs experience a reduction in the latency and energy consumption.
2. Each cluster can select its sensing time adaptively according to the conditions, e.g. traffic load and channel gain, which will be further discussed. Moreover,

there is no synchronization among clusters. Each cluster can determine when to start and finish spectrum sensing.

3. Each cluster can select a set of channels to sense and all these detected spectrum bands are shared by the SUs in the same cluster. One example of sharing the detected channels may be found in [133]. The author assumes that all the SUs in the same cluster are of the same quality in terms of detection characteristic and the transmission rate. Two-stage detection method is used to differentiate if the channel is occupied by the PU or the transmitting SU.

3.1.4 Traffic Load of Primary and SUs

There may be multiple clusters in the network all of which simultaneously seek spectrum opportunities in all the channels. It is assumed that the secondary traffic in cluster i is generated according to the Poisson process with arrival related to the parameter ς_i (there are N_i SUs in cluster i, thus the total traffic arrival rate is $N_i\varsigma_i$). The duration of service time is exponentially distributed with parameter μ_i. Therefore, let $\eta_i = \frac{N_i\varsigma_i}{\mu_i}$ represent the traffic load of cluster i.

The primary activity also has an effect on the spectrum sensing performance. Experimental results indicate that modeling the traffic of Wireless Local Area Network (WLAN) users as a continuous-time semi-Markov process is shown to be a good approximation [134] [135] [136] [137] [138]. In particular, as explained in [135], the simplifying Markovian assumption, though not necessarily accurate across the entire traffic regime, seems to have a reasonably good fit with the measured data. Therefore, in the proposed method, the PU's traffic on the channel is assumed to follow a continuous time Markov chain with two states: idle (OFF) and busy (ON) states. The time distributions of the idle and busy states of the PU are assumed to be exponential distributions with parameters ς_p and μ_p, respectively. That is

$$f_I(t) = \frac{1}{\mu_p} exp(-\frac{t}{\mu_p}) \tag{3.18}$$

$$f_B(t) = \frac{1}{\varsigma_p} exp(-\frac{t}{\varsigma_p}) \tag{3.19}$$

Let $\rho = \frac{\varsigma_p}{\mu_p}$ denote the traffic load of the PU. The average probability that a spectrum is being used by the PU can be approximated as [25] [37]

$$P_b = \frac{\varsigma_p}{\varsigma_p + \mu_p} = \frac{\rho}{1+\rho} \tag{3.20}$$

3.2 Performance Evaluation Metrics

3.2.1 Cooperative Sensing Overhead

Each basic frame structure T of the SUs consists of a sensing phase, a cooperation phase and a data transmission phase. Let τ_i be the local sensing time, which is the time consumed by each SU to sense each channel for each stage. The author considers that cluster i can select l_i spectrum bands to sense among the M bands. Thus the sensing time is related to l_i. T_r^i denotes the cooperation time which contains the reporting time to the CH, the fusion time to make a final decision and the dissemination time to disseminate the result to the cluster members. Both τ_i and T_r^i will be further analyzed.

The cooperative sensing overhead of detecting available spectrum by sensing l_i channels can be expressed as

$$T_c^i = 2N_i l_i \tau_i + T_r^i \tag{3.21}$$

where T_r^i mainly depends on the number of cooperative users in cluster i. For simplicity, the author assumes $T_r^i = N_i T_p$, where T_p denotes the average time consumed by each SU from the time it starts to forward the sensing result to the CH until a final decision is obtained. Thus T_c^i is given by

$$T_c^i = N_i(2\tau_i l_i + T_p) \tag{3.22}$$

Then the actual amount of time within a frame to be used for data transmission is $T - 2l_i\tau_i - T_p$. As seen from Eqn. (3.22), the differences in the time overhead among the clusters are independent of T_p which is fixed for each SU. Therefore, the cooperative sensing overhead T_c^i is mainly determined by the local sensing time τ_i, the number of cooperative SUs and the number of channels that ought to be sensed.

3.2.2 Average Achievable Throughput

In the following, the author describes how the proposed cluster-based sensing and sharing scheme operates and presents the transmission rate of the SUs based on the decision made by spectrum sensing. At the beginning of each frame, an initial spectrum sensing is carried out to detect the status of the frequency bands. Based on the decision of the spectrum sensing, the SUs will communicate using higher power P_0 if both the PU and the transmitting SUs are detected to be absent ($H_{0,(ij)}$). While a lower power P_1 will be selected if the spectrum is sensed to be occupied by the transmitting SU ($\epsilon = 2$) and the lowest power P_2 is chosen if the PU is detected ($\epsilon = 1$). Note that $P_0 > P_1 > P_2$ since the PU has the highest priority and hence more protection should be accorded. Following the definition in [54] [100] [101] [139], the instantaneous transmission rates of the SUs on channel j, denoted by $r_{0,(ij)}$ for the case of $H_{0,(ij)}$, by $r_{s,(ij)}$ for the case of $\epsilon = 2$ and by $r_{p,(ij)}$ for the case of $\epsilon = 1$, are given by

$$r_{0,(ij)} = \log_2(1 + \frac{|g_{ij}|^2 P_0}{\sigma^2_{u_{i,j}}}) \tag{3.23}$$

$$r_{s,(ij)} = \log_2(1 + \frac{|g_{ij}|^2 P_1}{\sigma^2_{u_{i,j}} + |g_{ij}|^2 P_0}) \tag{3.24}$$

$$r_{p,(ij)} = \log_2(1 + \frac{|g_{ij}|^2 P_2}{\sigma^2_{u_{i,j}} + |g_{ij}|^2 P_p}) \tag{3.25}$$

where P_p denotes the received power from the PUs. As discussed before, cluster i can select l_i spectrum bands to sense among the m bands. Let X_i, Y_i and Z_i be the random variables that represent the number of channels that are detected to be idle, being occupied by the PUs and being occupied by the transmitting SUs. The values depend on the activities of the PUs and the transmitting SUs and the detected results. Their expected values are denoted by $E[X_i]$, $E[Y_i]$ and $E[Z_i]$ and their corresponding number of channels that can be shared are denoted by $E[X_i^*]$, $E[Y_i^*]$ and $E[Z_i^*]$ respectively given that the average interference power constraints are upheld. An Ergodic Selection Algorithm is developed in the next section to show how to obtain $E[X_i^*]$, $E[Y_i^*]$ and $E[Z_i^*]$ from $E[X_i]$, $E[Y_i]$ and $E[Z_i]$.

Then the average achievable throughput of cluster i is given by

$$R_i = \frac{T - 2l_i\tau_i - T_p}{T}(E[X_i^*]r_{0,(ij)} + E[Y_i^*]r_{p,(ij)} + E[Z_i^*]r_{s,(ij)}) \tag{3.26}$$

3.2.3 Sensing and Access Utility Function

The main objective of this work is to develop a multi-channel sensing and access scheme that allows the CH to determine the optimal number of channels that should be sensed with minimal sensing overhead as well as maximum achievable throughput. On one hand, by increasing the number of sensed channels, the more transmission opportunities can be discovered and more throughput can be achieved. On the other hand, the overhead incurred in the CSS increases when the number of selected sensed channels becomes larger and larger. Hence it is an important issue to balance between the desire to improve the achievable throughput and the need to keep the sensing overhead low. The author will introduce an utility function that represents the tradeoff between these two aspects and determine the optimal number of channels that ought to be sensed such that the utility can be maximized.

The utility function is defined as

$$U_i(N_i, \tau_i, l_i) = R_i(N_i, \tau_i, l_i) - T_c^i(N_i, \tau_i, l_i) \tag{3.27}$$

Since the priority of a CRN is to protect the quality of service (QoS) of the PUs, an interference power constraint should be imposed for protection. Therefore, it is necessary to limit the number of SUs transmitting over the same busy channel to meet this constraint. Let S_j be the set of SUs who are transmitting on channel j which is detected to be occupied by the PU. Then the average interference power to the PU should be limited by $Q_{av,j}$, that is

$$E[\sum_{h \in S_j} g_{hj} P_2] \leq Q_{av,j} \tag{3.28}$$

Similarly, the average interference power to the transmitting SU must be considered as well. Let F_k be the set of SUs who are transmitting on channel k which is declared to be occupied by the transmitting SU, then the average interference power impacting this transmitting SU will be bounded by $P_{av,k}$, that is

$$E[\sum_{h \in F_k} g_{hk} P_1] \leq P_{av,k} \tag{3.29}$$

where $Q_{av,j}$ and $P_{av,j}$ stand for the average interference power limits to the PU and the transmitting SU on channel j, respectively.

Then the multi-channel sensing and access scheme can be formulated as an optimization problem, which maximizes the utility under some constraints on the interference to the PU and the transmitting SU. The basic idea is as follows: At the beginning of each frame, the CH will select a set of channels for sensing. Based on which, the expected number of channels that are idle, being occupied by the PUs and the transmitting SUs are derived. The question arising here is which channels can be shared such that the constraints on the interference power to the PU and the transmitting SUs are upheld. The problem can be formulated as

Problem P1

$$\begin{aligned} \max_{l_i} \quad & U_i(N_i, \tau_i, l_i) \\ s.t. \quad & E[\sum_{h \in S_j} g_{hj} P_2] \leq Q_{av,j} \\ & E[\sum_{h \in F_k} g_{hk} P_1] \leq P_{av,k} \\ & 1 \leq j, k \leq l_i \end{aligned} \tag{3.30}$$

The objective and constraint functions in **P1** are generally nonconvex, making it difficult to efficiently solve for the global optimum. In this work, numerical method is introduced to solve the optimization problem **P1** to find the optimal number of sensed channels such that the utility can be maximized.

3.2.4 Error Rate

As will be discussed in the next section, the analysis of the case when missed detection of the PU and the transmitting SUs is ignored. However, the sensing performance is always measured by the error probability. Apparently, the higher the miss detection, the more serious impact the interference will cause. Imperfect detection may interfere with the transmission of the PU and the transmitting SU. Therefore, the error due to missed detection should be taken into consideration. To do this, the error rate is defined as

$$\xi_i = \frac{l_i - (E[X_i] + E[Y_i] + E[Z_i])}{l_i} \tag{3.31}$$

Note that due to missed detection, $E[X_i] + E[Y_i] + E[Z_i] \leq l_i$. Thus, the difference between the number of selected sensed channels l_i and the sum of the expected number of channels that are sensed to be idle, being occupied by the PUs and being occupied by the transmitting SUs provides an insight into the amount of errors that can be tolerated.

3.3 Cluster-Based Adaptive Sensing and Access Problem Statement and Analysis

For each frame, depending on the activities of the PUs and the sensing results of the SUs, there exist six cases for cluster i, when performing spectrum sensing:

Case 1: The PUs are all active in the selected l_i spectrum bands, and the SUs make a successful detection of the primary signals. Then the SUs will utilize these channels with transmit rate $r_{p,(ij)}$ under the interference power limit given by Eqn. (3.28), for $j = 1, 2, ..., l_i$.

Case 2: The PUs are all active in l_i spectrum bands, and all the SUs fail to declare some of this busy condition. In order to protect the PU, OR fusion rule is used, such that missed detection happens if and only if all the SUs in cluster i mistake the busy channels as idle. The author will neglect this case in analysis. Evaluation of missed detection will be conducted in the simulation.

Case 3: The l_i spectrum bands are all occupied by the transmitting SUs and can be successfully detected by the SUs in cluster i. Then the SUs will transmit with rate $r_{s,(ij)}$ over the l_i channels, under the interference power constraint given by Eqn. (3.29), for $j = 1, 2, ..., l_i$.

Case 4: The l_i spectrum bands are all occupied by the transmitting SUs. However, missed detection happens. As per Case 2, the author will not consider this case in the analysis.

Case 5: At least one or more spectrum bands are idle and cluster i can correctly detect the transmission opportunity (not false alarm). Let $E[X_i]$ be the expected number of idle spectrum bands that are detected, then $E[X_i]$ spectrum bands can all be used by the SUs with transmission rate $r_{0,(ij)}$.

Case 6: At least one or more spectrum bands are idle. However, false alarm occurs, thus SUs will transmit with lower power to avoid causing harmful interference to the PU or the transmitting SUs.

In the following, an adaptive sensing time scheme based on their own traffic loads and channel gains is proposed. The main goal is to determine the likelihood that a given cluster finds some available channels. To make the mathematical analysis more tractable and easy to deal with, the author breaks the problems into two steps. In the first step, the probability that a particular spectrum band is detected to be idle, e.g. neither occupied by the PU nor the transmitting SU is calculated. In the second step, the expected number of idle channels is obtained. Furthermore, the expected number of spectrum bands that are occupied by the PU and the transmitting SUs is also achieved. The author will introduce an ergodic algorithm to select the channels that can be shared by the SUs such that the interference power constraints are satisfied.

3.3.1 Adaptive Sensing Time Scheme

In most existing work, researchers often assume that each SU has the same sensing time. However, the conditions of SUs are different from one another, which implies that the sensing overhead may be reduced if the sensing duration of each SU adapts to its own condition. Consequently, an adaptive sensing time scheme is proposed for each cluster to detect the status of the channel.

According to the above analysis, the search time of cluster i is given by

$$\tau_i = \vartheta(\eta_i, g_i)\tau \tag{3.32}$$

where τ is the identical local sensing time and $\vartheta(\eta_i, g_i)$ can be defined and set by the system designer. Intuitively, this factor depends on the characteristics of cluster i and should increase with η_i for a given g_i. It is reasonable since η_i can characterize the traffic load of cluster i. With a larger η_i, cluster i may keep transmitting for an amount of time, which implies that reliable and effective utilization of the channel is critical. The author increases the sensing time in order to guarantee a lower collision probability as well as to decrease the false alarm probability which can alleviate the waste of transmission opportunity. On the contrary, if η_i is very small, which indicates that the traffic load of cluster i is low, the author decreases the sensing time to avoid unnecessary spectrum sensing. On the other hand, the detection probability for a PU to be present or absent in a licensed channel can be different among clusters due to their different geographical locations. For example, SUs in a cluster which is further away from a PU may have poorer detection quality than the cluster that is closer to the PU. Thus more sensing time is required to collect more samples by the SUs in the cluster farther away from the PU to improve the sensing performance. Therefore, as the distance increases, the factor $\vartheta(\eta_i, g_i)$ should increase as well to indicate that more sensing time is required due to the need to have more sampling observations, which enables the detection of very weak signals from the PU. In this work, the function $\vartheta(\eta_i, g_i)$ is chosen as

$$\vartheta(\eta_i, g_i) = \frac{\eta_i}{g_i} \tag{3.33}$$

where the channel gain g_i is decreased proportionally with the distance.

Therefore, the sensing time can be adaptive according to the characteristics of the SUs to reduce the sensing overhead as well as to improve the sensing performance.

3.3.2 Idle Probability of a Particular Spectrum

Here, the author uses Markovian analysis to model the spectrum condition with 2^{l_i} states given that no PU exists [2]. The model suggests that the SU activity forms an M/M/l_i/0 queuing system. The author denotes the system state as Q=$(\phi_1, \phi_2, ..., \phi_{l_i})$ which is an l_i-uplet of binaries, where ϕ_j, $j = 1, 2, ..., l_i$ denotes if spectrum j is occupied by a transmitting SU or not, that is

$$\phi_j = \begin{cases} 1 & \textit{if channel } j \textit{ is idle} \\ 0 & \textit{if channel } j \textit{ is occupied} \end{cases} \tag{3.34}$$

Let Q_k denote the set of all the $\binom{l_i}{k} = \frac{l_i!}{(l_i-k)!k!}$ states that have exactly k spectrum bands occupied by the transmitting SUs. Let π_k denote the steady state probability distribution representing that k channels are being occupied by the transmitting SUs. Referring to the Erlang loss formula [140] [141]

$$\pi_k = \frac{\frac{\eta^k}{k!}}{\sum_{I=0}^{l_i} \frac{\eta^I}{I!}}, \quad k = 0, 1, ..., l_i \tag{3.35}$$

where $\eta = \sum_{i=1}^{K} \eta_i$ is the overall traffic load of all the clusters, the probability that a particular spectrum band j_0 is busy due to being occupied by the transmitting SU is equal to the probability that the spectrum j_0 belongs to the set of spectrum bands that comprised Q_k, which is

$$\pi_{j_0} = \frac{\binom{l_i-1}{k-1}}{\binom{l_i}{k}}\pi_k = \frac{k}{l_i}\pi_k \tag{3.36}$$

Then the probability that the channel is not occupied by SUs given that no PU exists, is

$$p_{i,s} = \sum_{k=0}^{l_i} \pi_{j_0} = \sum_{k=0}^{l_i} \frac{k}{l_i} \frac{\frac{\eta^k}{k!}}{\sum_{I=0}^{l_i} \frac{\eta^I}{I!}} \tag{3.37}$$

Let G_{j_0} denote the event that channel j_0 is occupied by the PU

And H_{j_0} denote the event that channel j_0 is occupied either by the PU or SUs.

Thus it has $Pr\{G_{j_0}\} = P_b$, $Pr\{H_{j_0}|\bar{G_{j_0}}\} = p_{i,s}$ and $Pr\{H_{j_0}|G_{j_0}\} = 1$. According to the total probability formula, $Pr\{H_{j_0}\}$ can be obtained as

$$\begin{aligned} Pr\{H_{j_0}\} &= Pr\{H_{j_0}|G_{j_0}\}Pr\{G_{j_0}\} + Pr\{H_{j_0}|\bar{G_{j_0}}\}Pr\{\bar{G_{j_0}}\} \\ &= Pr\{H_{j_0}|G_{j_0}\}P_b + Pr\{H_{j_0}|\bar{G_{j_0}}\}(1-P_b) \\ &= P_b - (1-P_b)\sum_{k=0}^{l_i} \pi_{j_0} \end{aligned} \tag{3.38}$$

Thus, the probability that a particular spectrum band j_0 is detected as idle, e.g. neither occupied by the PU nor the transmitting SU can be obtained as

$$p_{i,0} = 1 - Pr\{H_{j_0}\} = 1 - \frac{\varsigma_p}{\varsigma_p + \mu_p} - \frac{\mu_p}{\varsigma_p + \mu_p} \sum_{k=0}^{l_i} \frac{k}{l_i} \frac{\frac{\eta^k}{k!}}{\sum_{I=0}^{l_i} \frac{\eta^I}{I!}} \tag{3.39}$$

3.3.3 Expected Number of Idle Spectrum Bands

In this subsection, the expected number of idle channels will be obtained. First, a spectrum band is considered actually idle if and only if 1) this spectrum band is not occupied by the PU; 2) the spectrum band is not occupied by the transmitting SU. Note that the second condition should be contained because all the SUs compete for the spectrum. Secondly, an idle spectrum is assessed as idle through spectrum sensing if and only if a false alarm does not occur.

Two events are introduced in the following:

A_i: x_i spectrum bands are detected as idle for cluster i.

B_i: a_i spectrum bands are actually idle among the selected l_i spectrum bands, $x_i \leq a_i \leq l_i$.

The probability that x_i spectrum bands are detected as idle can be obtained using the law of total probability, that is

$$\begin{aligned} Pr\{X_i = x_i\} &= \sum_{a_i=0}^{l_i} Pr\{A_i|B_i\}Pr\{B_i\} \qquad (3.40) \\ &= \sum_{a_i=0}^{l_i}[\binom{a_i}{x_i} Q_{f,(i,j)}^{a_i-x_i}(1-Q_{f,(i,j)})^{x_i} \sum_{\Lambda\subset\Omega}[\prod_{\alpha\in\Omega-\Lambda}(1-p_{i,0}^{(\alpha)}) \prod_{\beta\in\Lambda} p_{i,0}^{(\beta)}]] \end{aligned}$$

where Ω denotes the set of spectrum bands that are selected by cluster i to be sensed at each frame, $|\Omega| = l_i$ and Λ is the set of spectrum bands that are actually not occupied by the PUs and the transmitting SUs, $|\Lambda| = a_i$.

Therefore, the expected number of idle spectrum bands detected by cluster i is given by

$$E[X_i] = \sum_{x_i=0}^{l_i} x_i Pr\{X_i = x_i\} \qquad (3.41)$$

3.3.4 Expected Number of Spectrum Bands Occupied by PUs

Two events are introduced in the following:

C_i: y_i spectrum bands are detected as occupied by the PUs.

D_i: b_i spectrum bands are actually busy due to the occupation of the PUs among the selected l_i spectrum bands of cluster i, $y_i \leq b_i \leq l_i$.

The probability that y_i spectrum bands are detected to be occupied by the PUs can be obtained using the law of total probability, that is

$$\begin{aligned} Pr\{Y_i = y_i\} &= \sum_{b_i=0}^{l_i} Pr\{C_i|D_i\}Pr\{D_i\} \\ &= \sum_{b_i=0}^{l_i}[\binom{b_i}{y_i}(1-Q_{d_p,(i,j)})^{b_i-y_i}Q_{d_p,(i,j)}^{y_i}\sum_{\Delta\subset\Omega}[\prod_{\alpha\in\Omega-\Delta}(1-P_b^{(\alpha)})\prod_{\beta\in\Delta}P_b^{(\beta)}]] \end{aligned} \tag{3.42}$$

where Δ is the set of spectrum bands that are actually occupied by the PUs, $|\Delta| = b_i$.

Therefore, the expected number of spectrum bands that are detected to be occupied by the PUs is given by

$$E[Y_i] = \sum_{y_i=0}^{l_i} y_i Pr\{Y_i = y_i\} \tag{3.43}$$

3.3.5 Expected Number of Spectrum Bands Occupied by Transmitting SUs

The same discussion as above applies, i.e., the probability that z_i spectrum bands are detected to be occupied by the transmitting SUs can be obtained using the law of total probability, that is

$$\begin{aligned} & Pr\{Z_i = z_i\} \\ = \ & \sum_{c_i=0}^{l_i} [\binom{c_i}{z_i} (1 - Q_{d_s,(i,j)})^{c_i - z_i} Q_{d_s,(i,j)}^{z_i} \sum_{\Psi \subset \Omega} [\prod_{\alpha \in \Omega - \Psi} (1 - p_{i,s}^{(\alpha)}) \prod_{\beta \in \Psi} p_{i,s}^{(\beta)}]] \end{aligned} \tag{3.44}$$

where Ψ is the set of spectrum bands that are actually occupied by the transmitting SUs, $|\Psi| = c_i \leq l_i$ and $p_{i,s}$ is the busy probability of a particular spectrum band due to the occupation of the transmitting SUs, that is

$$p_{i,s} = \sum_{k=0}^{l_i} \frac{k}{l_i} \frac{\frac{\eta^k}{k!}}{\sum_{I=0}^{l_i} \frac{\eta^I}{I!}} \tag{3.45}$$

The expected number of spectrum bands occupied by the SU is given by

$$E[Z_i] = \sum_{z_i=0}^{l_i} z_i Pr\{Z_i = z_i\} \tag{3.46}$$

One should note that $E[X_i] + E[Y_i] + E[Z_i] \leq l_i$, since missed detection is not considered. The throughput achieved due to missed detection is not taken into account because the throughput will be very small even through it is achievable [14] [15] [17].

3.3.6 Ergodic Selection Algorithm

In the following, an ergodic selection algorithm is proposed to derive the expected number of channels that can be shared while the interference power constraints imposed for the PU and the transmitting SUs are upheld. The algorithm is conducted in three steps:

1. First, all the detected idle channels can be utilized by the SUs in cluster i, since no interference will occur, thus $E[X_i^*] = E[X_i]$.

2. Secondly, set $E[Y_i^*] = 0$ and let R_i be a set that records the channels occupied by the PUs. Then check the condition

$$E[\sum_{I \in S_j} g_{Ij} P_2 + g_{ij} P_2] \leq Q_{av,j},\ \forall j \in R_i \tag{3.47}$$

if Eqn. (3.47) holds, it means that the average interference power to the PU is below the threshold $Q_{av,j}$ if the SU i transmits on this channel using power P_2, thus SU i can use this channel. Then it has

$$E[Y_i^*] = E[Y_i^*] + 1, \quad S_j = S_j \cup \{i\}$$

3. Thirdly, set $E[Z_i^*] = 0$ and let H_i be a set that records the channels occupied by the transmitting SUs. Then check the condition

$$E[\sum_{I \in F_k} g_{Ik} P_1 + g_{ik} P_1] \leq P_{av,k},\ \forall k \in H_i \tag{3.48}$$

if Eqn. (3.48) holds, then it has

$$E[Z_i^*] = E[Z_i^*] + 1, \quad F_k = F_k \cup \{i\}$$

3.4 Simulation Results

In this section, the author presents the simulation results and discussions for the proposed cluster-based multi-channel sensing and access strategy and compares it with Adaptive Spectrum Assessment (ASA) in [2] and Sequential Spectrum Sensing (SSS) in [3]. The parameters used in this system are as follows: the sampling frequency is fixed and set to $f_s = 6MHz$ and the frame duration is $T = 200ms$, the noise variance equals $\sigma_{u_{ij}}^2 = 1$ for all $j = 1, 2, ..., M$. These are the same as in [142], whereas the average cooperation time is assumed to be $T_p = 1ms$. The author further sets the identical local sensing time $\tau = 4.5ms$ and the transmission powers $[P_0, P_1, P_2, P_p] = [1, 0.5, 0.2, 4]dB$.

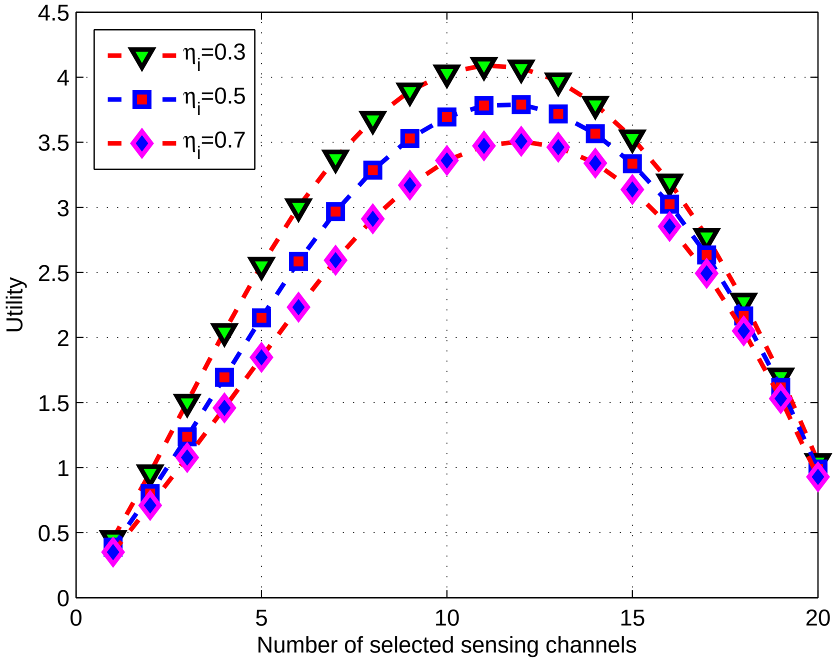

Figure 3.4: The utility vs the number of sensed channels for different SU traffic loads and $\rho = 0.5$.

3.4.1 Impact of SU Traffic Load

In Figure 3.4, the results for the utility of cluster i against the number of sensed channels for different SU traffic loads $\{0.3,0.5,0.7\}$ are presented. In this study, the PU traffic load is set to $\rho = 0.5$. It can be observed that there exists an optimal number of channels that should be sensed such that the utility can be maximized. On one hand, the smaller the number of sensed channels, the less the channels that can be utilized and shared by SUs, thus the lower the achievable throughput. On the other hand, increasing the number of sensed channels will improve the spectrum utilization but will incur a high overhead. Hence, the tradeoff phenomenon can be observed. Therefore,

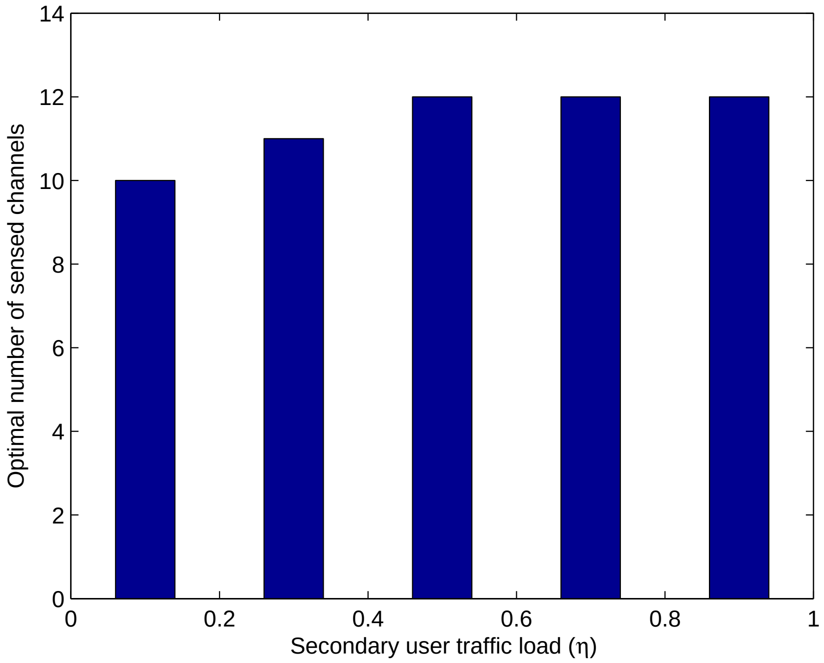

Figure 3.5: Optimal number of sensed channels vs SU traffic loads and $\rho = 0.5$.

the optimal number of sensed channels balances the conflict between improving the achievable throughput and reducing the sensing overhead. Moreover, it is easy to note that the utility decreases with an increase in the SU traffic load. This is reasonable due to the fact that a larger η_i indicates a higher probability that the channel is occupied by the transmitting SU and less chance that the SUs can transmit with a larger power.

Usually, the author is more interested in the operating point where the optimal number of sensed channels achieves the maximum utility for each SU traffic load. However, as discussed before, it is difficult to efficiently obtain the closed expression of the optimal number of sensed channels by solving Problem P1. Here, relying on numerical methods, the optimal number of sensed channels for the different SU traffic loads is plotted in Figure 3.5. It is evident from the figure that the higher the SU traffic

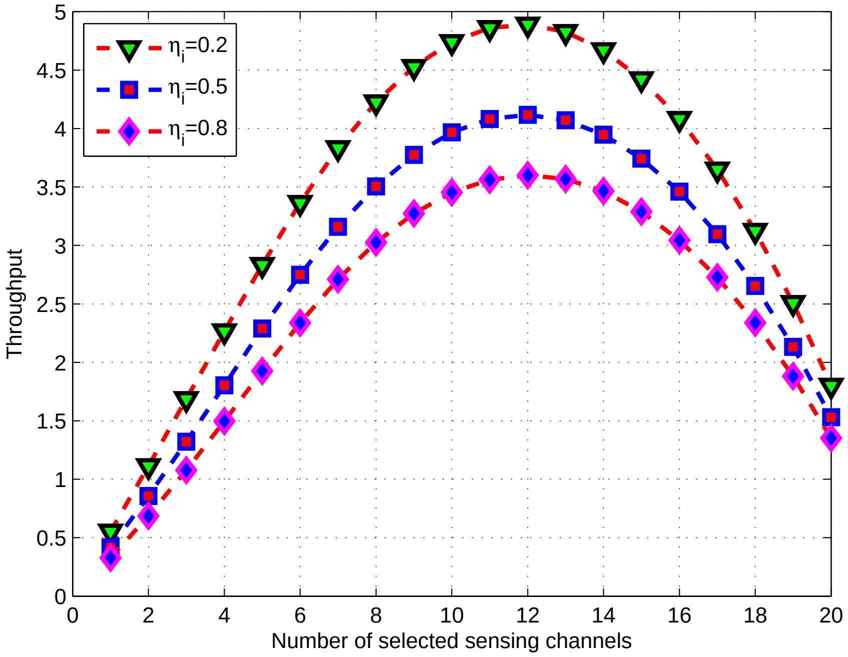

Figure 3.6: The throughput vs the number of sensed channels for different SU traffic loads.

load, the larger the number of channels that should be sensed in order to maximize the utility.

Figure 3.6 shows the throughput of cluster i defined in Equ.(3.26) against the number of sensed channels for different SU traffic loads. From Figure 3.6, it should be noted that there also exists an optimal number of channels that should be sensed in order to maximize the throughput.

3.4.2 Impact of PU Traffic Load

Figure 3.7 depicts the utility as a function of the number of sensed channels for different PU traffic loads {0.3,0.5,0.7}. In this study, the SU traffic load is set to $\eta_i = 0.5$. As illustrated in Figure 3.7, there exists an optimal value of the number of channels that

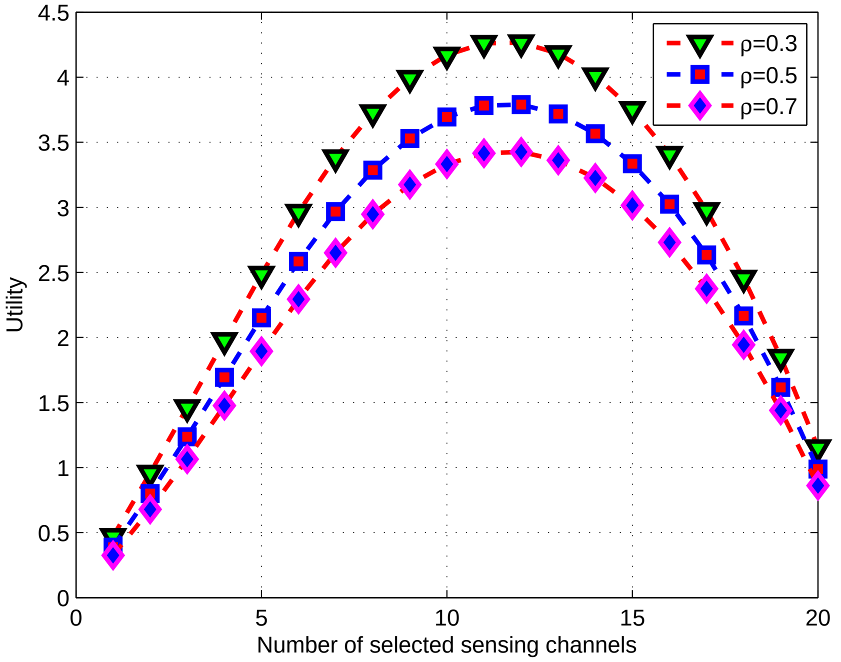

Figure 3.7: The utility vs number of selected sensed channels for different PU traffic loads and $\eta_i = 0.5$.

ought to be sensed, such that the utility can be maximized. This can be explained using the same arguments as the preceding subsection. As expected, the lower the PU traffic load, the higher the utility obtained. This is true because a smaller ρ means a higher probability that the channel is idle and hence more chance for the SU to transmit with a larger power.

3.4.3 Impact of ϑ

Next, the utility vs. the number sensed channels for different $\vartheta \in \{0.6, 0.8, 1.0\}$ is plotted in Figure 3.8. In this study, the traffic loads for both SU and PU are set to 0.5. As illustrated in Figure 3.8, there also exists an optimal value of the number of sensed channels. From Figure 3.8, it should be recognized that the optimal value of

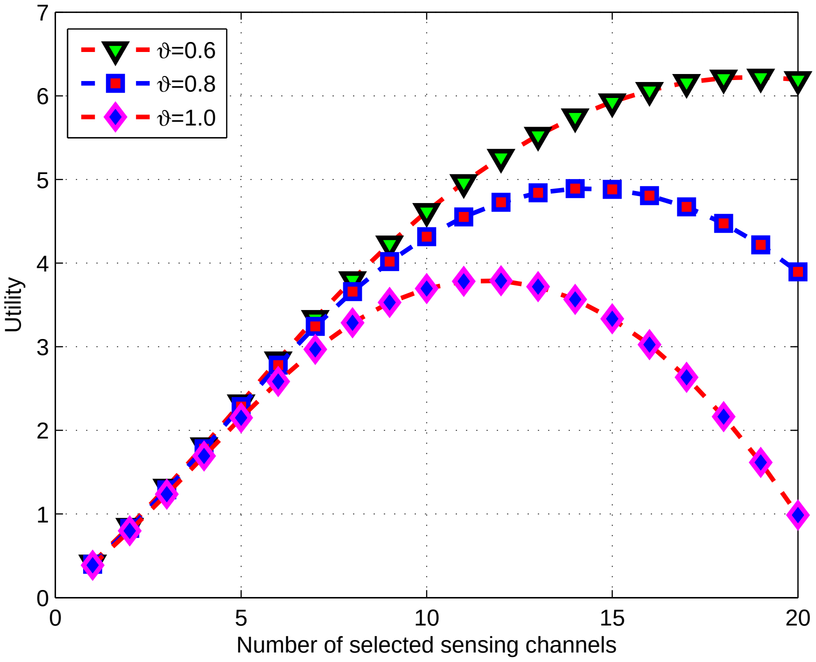

Figure 3.8: The utility vs the number of sensed channels for different adaptive parameters ϑ.

sensed channels decreases as ϑ increases. The reason is that, from Equ. (3.22), the cooperative sensing overhead is mainly determined by the sensing time and the number of sensed channels, thus to keep the overhead at a certain lever, when the sensing time increases, the number of sensed channels should decrease.

3.4.4 Evaluation of Error Rate

In the following, to provide a better understanding on how the proposed cluster-based adaptive multi-channel sensing and access scheme behaves, the sensing performance is evaluated by plotting the error rate as a function of the PU traffic load for different SU traffic loads $\eta_i \in \{0.3, 0.5, 0.7\}$ and $l_i = 20$. As shown in Figure 3.9, it is clear that the error rate is far below 0.02, which indicates that the missed detection is small. Thus

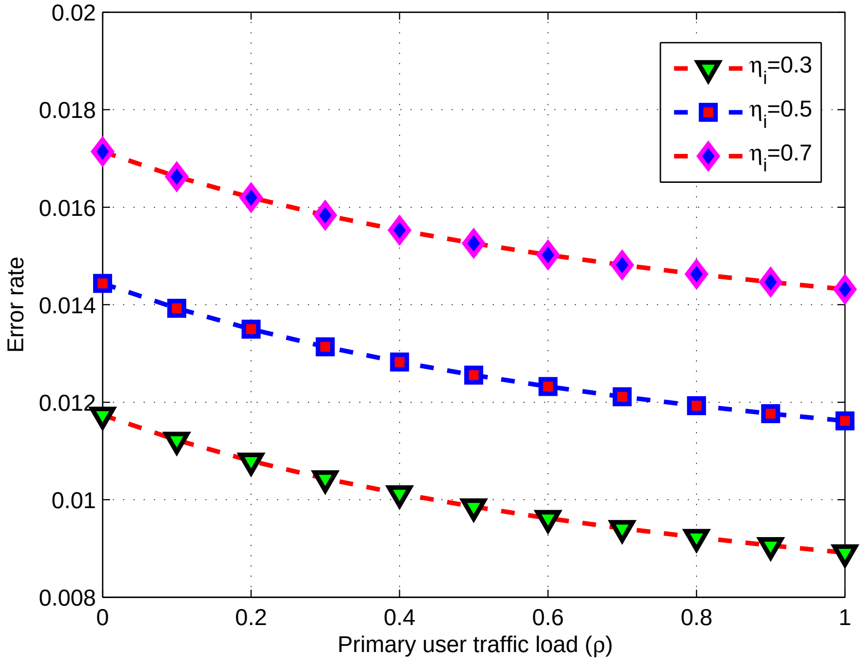

Figure 3.9: Error rate vs PU traffic load for different SU traffic loads and $l_i = 20$.

the proposed strategy can provide sufficient protection to the PUs and the transmitting SUs if the interference power constraints are satisfied.

3.4.5 Performance Comparisons

To compare the proposed cluster-based adaptive multiple channels sensing and access strategy with other schemes, e.g. ASA in [2] and SSS [3], it is assumed that there are $K = 5$ clusters in the system, with cluster sizes as $[10, 12, 8, 12, 8]$. For a fair comparison, the author also assumes that there are 5 communication groups seeking transmission opportunity in ASA and 5 independent SUs performing SSS to explore idle channels. These two methods are briefly summarized as follows.

The ASA approach provides the SUs with the capability of determining the optimal number of channels to be sensed when the discovery of new spectrum opportunities is triggered. If the communication group i successfully finds an opportunistic channel by sensing l_i channels, a reward (throughput) ω_i gets associated with a cost (overhead). Therefore, the utility is calculated as follows:

$$U_{ASA} = \sum_{i=1}^{K}[q_i(M)\omega_i - (l_i\tau N_i + N_iT_p)] \tag{3.49}$$

where $q_i(M)$ is the probability that communication group i finds one available channel when sensing l_i channels in the system. Note that, since full collaborative sensing is employed to protect the PU, the certainty factor defined in [2] that represents how collaborative the sensing approach is set as 1. ω_i is equal to $r_{0,(ij)}$ because the SU can transmit when channel j is idle at a rate of $r_{0,(ij)}$ in this proposed method. Note that ASA in [2] is a distributed strategy, in which all the SUs belonging to the same group exchange information for cooperation. Therefore, to implement full collaboration, each SU is required to exchange the sensing result with all the other SUs. On the other hand, in the proposed method, each cluster member only needs to exchange information with its CH, resulting in a low overhead. However, the cooperative overhead per SU for ASA is T_p, which is smaller than the actual. Thus the cooperative overhead discussed here for ASA becomes a lower bound.

In order to reduce the sensing overhead, a widely used SSS [3] is proposed here for comparison, in which the secondary transmission is ceased as the channels have to be sensed one by one until an idle channel is found. Let $\bar{T_i}$ denote the average time to sense the l_i channels, then $\bar{T_i}$ is given by

$$\begin{aligned} \bar{T_i} &= p_{i,0}\tau\sum_{k=1}^{l_i} k(1-p_{i,0})^{k-1} \\ &= \tau[\frac{1-(1-p_{i,0})^{l_i}}{p_{i,0}} - l_i(1-p_{i,0})^{l_i-1}] \end{aligned} \tag{3.50}$$

Then the utility for SSS is

$$\begin{aligned} U_{SSS} &= \sum_{i=1}^{K}[\sum_{k=1}^{l_i} p_{i,0}(1-p_{i,0})^{k-1} r_{0,(ij)} - (N_i\bar{T}_i + N_iT_p)] \\ &= \sum_{i=1}^{K}[[1-(1-p_{i,0})^{l_i}] r_{0,(ij)} - (N_i\bar{T}_i + N_iT_p)] \qquad (3.51) \end{aligned}$$

Figure 3.10 depicts the utility as a function of the number of channels in the system, obtained by the proposed strategy as well as the ASA in [2] and SSS in [3]. It can be observed that, from Figure 3.10, all of these methods have an optimal number of sensed channels such that the utility can be maximized. However, the optimal number of sensed channels derived for the proposed method is much higher than ASA and SSS. This can be explained as follows: the proposed strategy allows the SUs to access multiple idle channels and also coexist with the PUs and the transmitting SUs under some interference power constraints. Thus increasing the number of sensed channels will result in more transmission opportunities. As a result, the throughput can be improved despite increasing the sensing overhead. While for ASA and SSS, as long as the idle channel is discovered, increasing the number of sensed channels will lead to a larger sensing overhead only. Consequently, as expected, the proposed method has a larger value of optimal number of sensed channels.

It is evident from the the figure that the proposed strategy can achieve a much higher utility than that achieved by ASA and SSS. That is, the proposed method makes better use of the channel sensing and access by balancing the conflict between the achievable throughput and sensing overhead. By allowing multi-channel access and sharing, the SUs can utilize more channels by limiting the interference power to an acceptable level. Besides, the adaptive sensing time setting will further reduce the sensing overhead, thus the utility of the proposed strategy is higher than that of ASA and SSS. In addition, it is observed that SSS has better performance than ASA, due

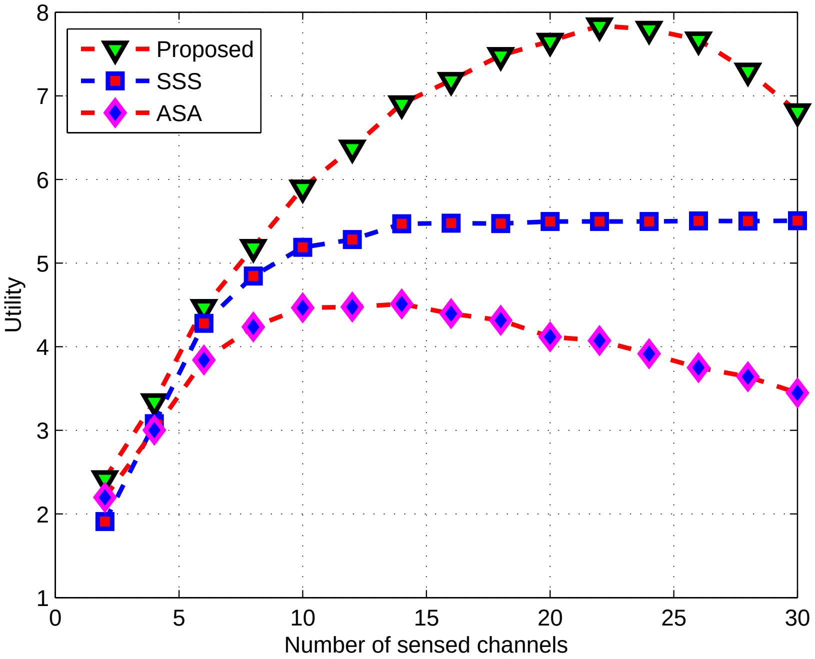

Figure 3.10: The utility of the whole system vs. the number of channels for the proposed strategy and existing ASA [2] and SSS [3]

to the fact that the spectrum sensing for SSS will be terminated as long as an idle channel is detected so as to avoid sensing the unnecessary channels. As for ASA, the selected channels will all be sensed, which increases the sensing overhead.

3.5 Conclusions

In this chapter, the author has studied the design of cluster-based multi-channel sensing and access strategy in CRN. The sensing strategy specifies the number of channels that should be sensed. The access strategy determines the expected number of channels that can be utilized and shared by the SUs under the interference power constraints imposed for the PUs and the transmitting SUs. It is assumed that the synchronization and cooperation only happen among the SUs who belong to the same cluster and no

FC is needed. In addition, each cluster can select non-identical sensing time adaptively in accordance to the traffic load and channel gain. As a consequence, the cooperative sensing overhead will be reduced. Besides, since multi-channel sensing and access is employed, by adapting the transmission power to avoid causing harmful interference, coexistence with the PU and the transmitting SUs is made possible. By doing so, the throughput can be improved. Moreover the expected number of channels that are idle, being occupied by the PUs and by the transmitting SUs is explicitly calculated. To the best of the author's knowledge, this is the the first work on the topic.

To investigate the performance of the proposed sensing and access method, the problem is formulated into an optimization problem to improve the achievable throughput and reduce the sensing overhead. Furthermore, quantitative method has been developed to obtain the optimal value for the number of sensed channels, such that the utility can be maximized. The performance of the proposed strategy has been examined quantitatively and is shown to outperform ASA [2] and SSS [3].

Chapter 4

MAC Spectrum Sensing Protocol Design for Data Transmission

MAC protocols to sense channels for data transmission have been widely investigated for the SUs to efficiently utilize and share the spectrum licensed by the PU. One important issue associated with MAC protocol design is how the SUs determine when and which channel they should sense and access without causing harmful interference to the PU. In this chapter, the author jointly considers the MAC-layer spectrum sensing and channel access. The SUs operate on a frame-by-frame basis, which consists of four phases: Normal Spectrum Sensing (NSS) Phase, Channel Contention Phase, Fast Spectrum Sensing (FSS) Phase and Data Transmission Phase. NSS is required to be carried out at the beginning of each frame to determine whether the channel is idle or occupied by the PU. On detecting the available channel, the SUs employ CSMA for channel contention. As soon as the SU wins the channel, FSS is performed to promptly detect the return of the PU. If no PU signal is detected, the SU can start to transmit its own data. Incorporating FSS into the MAC sensing and transmission protocol design can provide more protection to PU. A concrete protocol design is provided in this chapter, and the throughput-collision tradeoff, utility-collision tradeoff problems are formulated to evaluate its performance.

In the following, the system model is introduced in Section 4.1. The key part: the MAC sensing-transmission protocol design is elaborated in Section 4.2. Theoretical formulae for throughput-collision tradeoff, and utility-collision tradeoff to analyze the performance of the proposed protocol are detailed in Section 4.3. Analysis results and evaluation are given in Section 4.4. Finally, Section 4.5 concludes the this work.

4.1 System Model

In this chapter, the author considers a system with N SUs and one PU (one channel). The PU is the licensed holder and has the absolute priority to access the channel. However, the SU can opportunistically utilize the channel as far as it is detected as idle by means of spectrum sensing. It is assumed that the PU packet has an exponential ON-OFF traffic model and its packet arrives randomly as explained in the previous chapter. Whenever the PU has been determined as active, the SU will need to vacate the channel immediately. Unlike Chapter 3, to simplify analysis, in the following, the subscript 'i' is omitted, since the author assumes that the channel gain g_i for the SUs can be assumed to be i.i.d. (identical and independent distribution) random variables. The transmitted signal of the PU as well as the noise are assumed to be identical and independent random processes. (In practice, the SU is far away from the primary transmitter and thus it is reasonable to assume that the primary signal and the noise received at the SU are i.i.d [127] [143]).

Thus the false alarm probability which is defined as the probability of the SU falsely declaring the idle channel as busy can be represented by

$$P_f = P[Y > \lambda | H_0] = Q((\frac{\lambda}{\sigma_u^2} - 1)\sqrt{\tau f_s}) \tag{4.1}$$

And the detection probability which is defined as the probability that the SU correctly detects the busy status of channel can be expressed as

$$P_d = P[Y > \lambda | H_1] = Q((\frac{\lambda}{\sigma_u^2} - \gamma - 1)\sqrt{\frac{\tau f_s}{2\gamma + 1}}) \tag{4.2}$$

where τ is the sensing time, f_s is the sampling frequency, λ is the energy detection threshold, γ is the average SNR received by the SU defined in the previous chapter, and σ_u^2 is the noise variance.

Similar to Chapter 3, the author models the PU's traffic on the channel as a continuous time Markov chain with two states: idle (OFF) and busy (ON) states. The ON state and OFF state alternate on the channel. During the OFF state, if a primary packet arrives, the channel transits to the ON state, and the SU is required to vacate the channel. If the primary packet leaves, the channel transits from ON state to OFF state, which indicates that the channel can be utilized by the SU without causing harmful interference. The author further assumes that the time periods for ON and OFF states of primary traffic follow exponential distributions with expected values t_{on} and t_{off}, respectively [134] [135] [136] [137] [138]. Thus, at any time, the probability that the channel is busy can be approximated as

$$P_b = \frac{t_{on}}{t_{on} + t_{off}} \tag{4.3}$$

The performance of the proposed scheme is mainly dependent on the expected value of the busy and idle durations regardless of the kind of distribution that the primary traffic follows. Therefore, the proposed scheme can be easily extended to the other distributions.

4.2 MAC Sensing-Transmission Protocol

In this section, the design of MAC sensing-transmission protocol is elaborated. Different from Chapter 3, while each frame only consists of two phases: sensing phase and data transmission phase. In this work, as shown in Figure 4.1, each SU operates on a frame-by-frame basis, with each frame of duration T and divided into four phases: Normal Spectrum Sensing (NSS) Phase, Channel Contention Phase, Fast Spectrum Sensing (FSS) Phase and Data Transmission Phase. The SU first senses the channel for a duration τ_N by NSS. If the channel is declared as idle, then CSMA is invoked to contend for channel access. Thereafter, FSS is performed in order to quickly detect the return of the PU. If no active PU is detected, SUs can utilize the idle channel for data transmission. This protocol design overcomes the shortcoming of OSA-MAC that allows channel contention before spectrum sensing by reducing the probability of contending for available channels. Furthermore, it will improve the efficiency of MAC protocols in [27] [29] [30]. Owing to the random arrival of the PU, the channel may become busy anytime. FSS can avoid causing severe interference to the PU. The detailed design of the proposed MAC sensing-transmission protocol is described as follows.

4.2.1 Normal Spectrum Sensing (NSS)

NSS is carried out at the beginning of each frame. It focuses on the efficient detection and identification of the availability of the primary channel which can be opportunistically accessed by the SU. If the channel is indicated as occupied by the PU, the SU will

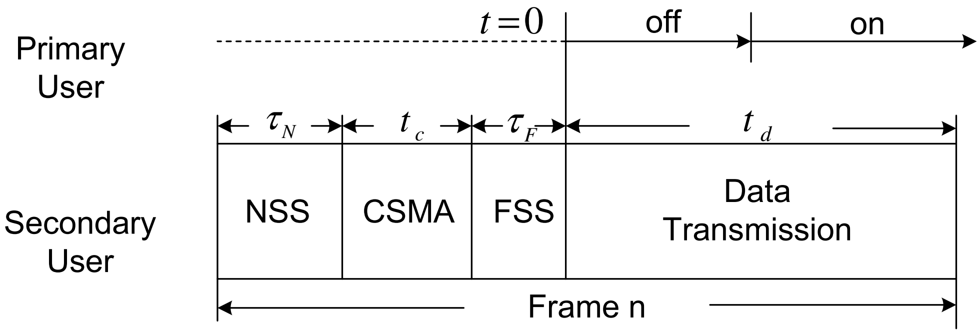

Figure 4.1: The frame structure of each SU.

keep silent until the next frame. Otherwise, if the channel is available, intra-network contention takes place where SUs contend for channel access. Let τ_N denote the sensing duration in NSS, then the sensing quality is measured by false alarm probability $P_{N,f}$ and detection probability $P_{N,d}$, which are given by

$$P_{N,f} = Q((\frac{\lambda}{\sigma_u^2} - 1)\sqrt{\tau_N f_s}) \tag{4.4}$$

$$P_{N,d} = Q((\frac{\lambda}{\sigma_u^2} - \gamma - 1)\sqrt{\frac{\tau_N f_s}{2\gamma + 1}})) \tag{4.5}$$

4.2.2 Carrier Sense Multiple Access (CSMA) [1]

Before transmitting a packet, the SU is required to monitor the channel to avoid collision with packets being transmitted by other SUs. If the channel is sensed idle for a specified period, i.e., the Distributed Inter-Frame Space (DIFS), then each SU generates a random backoff time. The discrete backoff counter is uniformly selected in the range of $(0, W - 1)$, where W is the contention window size. Initially, W is set to the minimum contention window W_{min}, after each unsuccessful transmission, W is doubled, up to the maximum contention window $W_{max} = 2^m W_{min}$, where m denotes the maximum contention backoff stage. The backoff timer counter is decremented by one every time the channel is sensed idle; and is *frozen* when a transmission is detected; and is *reactive* when the channel is observed as idle for a DIFS period. When the backoff counter reaches zero, the SU will attempt to transmit packet. Let t_c denote the duration of CSMA, which is a parameter that needs to be calculated.

4.2.3 Fast Spectrum Sensing (FSS)

In 802.22 standard [144] [145], FSS is proposed as a preliminary step before NSS with the aim of quickly determining whether a subsequent spectrum sensing is required. However, in this work, FSS is performed before the SU attempts to transmit packet during the channel contention phase when its backoff counter reaches zero. As the primary packet may arrive at any instant, and be transmitted without sensing and contention, the channel may become busy again, and need to be exclusively utilized by the PU. Thus spectrum sensing is required to be carried out frequently to protect the PU. Owing to the random value of t_c, t_c may be very large, such that the return of the PU will occur with high probability. Thus it is necessary to perform FSS with duration $\tau_F < \tau_N$ after the channel contention phase. The FSS provided here serves three-fold purposes. Firstly, to declare the channel busy if mis-detection happens in NSS. Secondly, to quickly detect the return of the PU after the t_c period. If the channel is still declared idle in FSS, SU will utilize the available channel to transmit its packet. FSS can prevent SU from transmitting on busy channel due to the return of PU after t_c, which enhances the QoS of the PU. Thirdly, if the channel is declared busy, the backoff counter is frozen at a special stage for a duration which is equal to the ON period of the primary packet, t_{on}, as shown in the Markov chain model for the backoff window size in Figure 4.2, then the SU keeps sensing until the channel is declared idle. This is another difference between NSS and FSS. FSS is a 'continuous' sensing strategy; due to its short sensing time, if the SU senses the channel busy, it will vacate the channel for t_{on} duration, then keeps sensing until the channel is declared idle. In such case, the rest of the available transmission opportunity can be utilized by the SU, which results in a more effective utilization of the available channel. The false alarm probability $P_{F,f}$ and detection probability $P_{F,d}$ for FSS are given by

$$P_{F,f} = Q((\frac{\lambda}{\sigma_u^2} - 1)\sqrt{\tau_F f_s}) \tag{4.6}$$

$$P_{F,d} = Q((\frac{\lambda}{\sigma_u^2} - \gamma - 1)\sqrt{\frac{\tau_F f_s}{2\gamma + 1}})) \tag{4.7}$$

There are two cases that the SU will access the channel to transmit packet: 1) When the channel is occupied by the PU but due to imperfect spectrum sensing, the SU may miss detecting this active PU (i.e. mis-detection); 2) When the channel is available, and the SU successfully detects the transmission opportunity. Thus the probability that the channel is declared idle during FSS is given by

$$P_{F,a} = (1 - P_{F,f})(1 - P_b) + (1 - P_{F,d})P_b \tag{4.8}$$

Similarly, the probability that the channel is declared busy is given by

$$P_{F,b} = P_{F,f}(1 - P_b) + P_{F,d}P_b \tag{4.9}$$

where the first term in the right side of Eqn. (4.9) corresponds to the false identification of idle channel as busy, and the second term represents successfully detecting the presence of the PU.

The two significant differences between FSS and NSS are elaborated as follows:

- First of all, NSS is performed before channel contention at the beginning of each frame to detect the available opportunity with sensing time τ_N; while FSS is carried out after the channel contention phase to detect the random return of the PU with sensing time $\tau_F < \tau_N$.
- Secondly, if the sensing result of NSS indicates that the channel is busy, all the SUs will keep silent until the next frame; while FSS is a 'continuous' sensing strategy, if the SU senses the channel busy, it will vacate the channel for t_{on} duration, then keep sensing until the channel is declared idle. This type of sensing will enhance the channel utilization by giving full access of the rest of the transmission opportunity to the SUs when the PU completes its service.

4.2.4 Markov Chain for Backoff Processing

Following the discussions in [146] [147], let $b(t)$ be the stochastic process that represents the backoff counter for the SU at time slot t. The value of backoff counter is uniformly selected in the range of $(0, W_i)$ at backoff stage i. Furthermore, let $s(t)$ be the stochastic process denoting the backoff stage within the range $[0, m]$, where m is the maximum backoff stage. Unlike [146], a state $\{-1, 0\}$ is added to model the situation in which the backoff counter reaches zero, and the FSS detects that the channel is occupied by the PU, and thus the SU will keep silent and vacate the channel for a period of t_{on}. The state transition diagram of the bi-dimensional process $\{b(t), s(t)\}$ can be modelled by a discrete-time Markov chain as shown in Figure 4.2.

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}$, $i \in (0, m)$, $k \in (0, W_i - 1)$ denote the stationary distribution of the Markov chain, and let p represent the intra-network collision probability with other SUs who also contend for the channel. Since state $\{-1, 0\}$ exhibits the main difference from [146] [147], its related transition probabilities

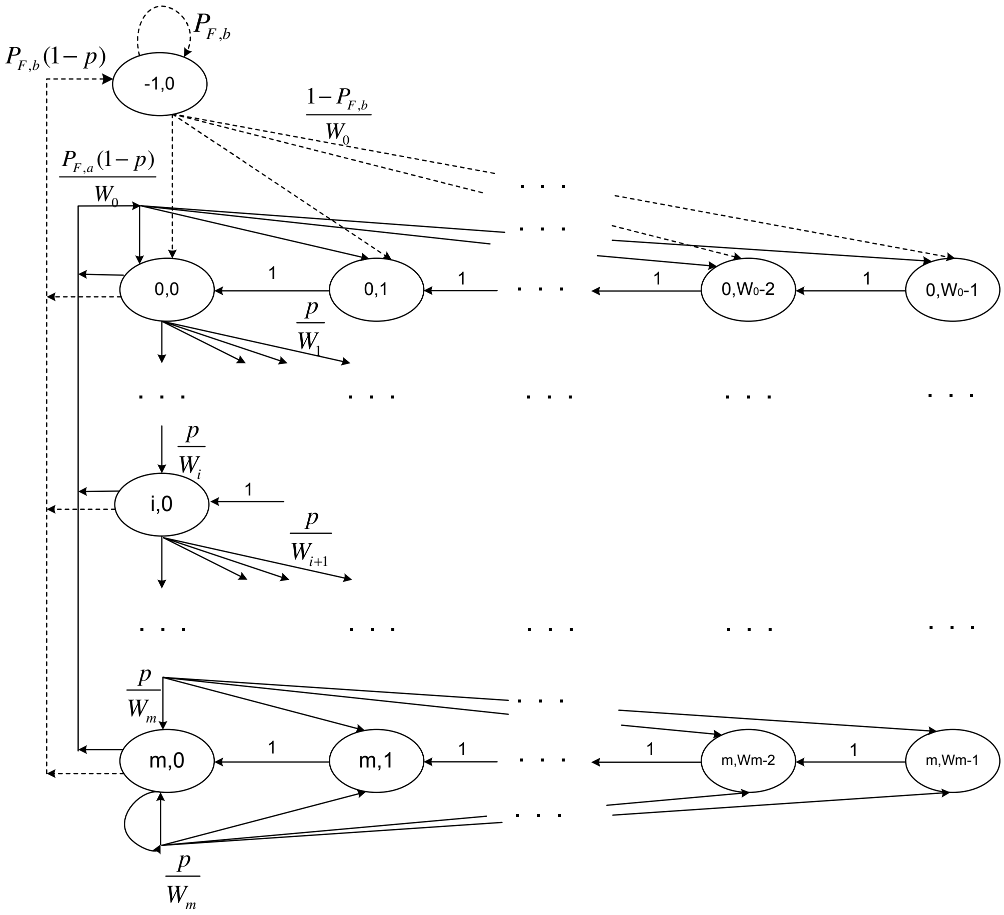

Figure 4.2: Markov Chain model for the backoff processing, where the solid line represents the backoff processing due to CSMA, while the dashed line indicates the state transition due to the sensing results of FSS which is always related to stage $\{-1, 0\}$.

are explained as follows:

1. The SU will freeze at state $\{-1, 0\}$ if it detects that the channel is occupied by the PU given that its previous stage is $\{-1, 0\}$.

$$P\{-1, 0| - 1, 0\} = P_{F,b}$$

2. The SU enters into the state $\{-1, 0\}$ if it wins the channel contention and if it

senses the channel is busy due to the return of the PU.

$$P\{-1,0|i,0\} = P_{F,b}(1-p) \quad 0 \le i \le m$$

3. The SU will transmit its packet and enter into stage 0 of the backoff procedure if it detects the channel is released by the PU during FSS.

$$P\{0,k|-1,0\} = \frac{1-P_{F,b}}{W_0} \quad 0 \le k \le W_0 - 1$$

Furthermore the following relationships hold:

$$b_{i,0} = p^i b_{0,0} \quad 0 \le i \le m \tag{4.10}$$

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad 0 \le i < m,\ 0 \le k \le W_i - 1 \tag{4.11}$$

$$b_{m,k} = \frac{W_m - k}{W_m} \frac{p^m}{1-p} b_{0,0} \quad 0 \le k \le W_m - 1 \tag{4.12}$$

$$b_{-1,0} = \frac{P_{F,b}}{(1-P_{F,b})} b_{0,0} \tag{4.13}$$

Thus, the normalization equation is

$$1 = b_{-1,0} + \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} \tag{4.14}$$

Using Eqns. (4.10)-(4.14) results in

$$[\frac{P_{F,b}}{(1-P_{F,b})}+\frac{\psi(W+1)+pW(1-(2p)^m)}{2\psi(1-p)}]b_{0,0}=1 \tag{4.15}$$

where $\psi = 1 - 2p$.

Then the expression of $b_{0,0}$ can be derived

$$b_{0,0}=\frac{2\psi P_{F,a}(1-p)}{2\psi P_{F,b}(1-p)+\psi P_{F,a}(W+1)+pWP_{F,a}[1-(2p)^m]} \tag{4.16}$$

It should be noted from Eqns. (4.8) and (4.9), $P_{F,a} + P_{F,b} = 1$.

Note that whenever the backoff counter reaches zero regardless of the backoff stage except stage $\{-1, 0\}$, the SU will attempt to transmit. Let τ_t denote the attempting transmission probability of SU, which is given by

$$\tau_t=\sum_{i=0}^{m} b_{i,0}=\frac{b_{0,0}}{1-p} \tag{4.17}$$

and the probability that the intra-network collision happens with two or more SUs can be expressed as

$$p = 1-(1-\tau_t)^{N-1} \tag{4.18}$$

Substituting Eqn. (4.18) into Eqn. (4.17), an equation with only one parameter τ_t is obtained. It can be solved using quantitative methods.

Note that before attempting transmission, FSS is carried out to check whether there is an active PU, without which a successful transmission occurs. Otherwise, the SU will go to state {-1,0} and stay silent for a period of t_{on}, then keep sensing until the PU finishes its transmission and an idle channel is detected. Let t_c denote the average

CSMA delay without taking into account the FSS sensing time, which is defined as the time interval from the point the SU starts the backoff process until the time that the SU can transmit the packet. It is a random variable depending on whether FSS indicates the presence of a PU and whether intra-network collision happens due to channel contention among SUs. Thus the average CSMA delay value of t_c is given by

$$E[t_c] = E[N_c]E(\chi) + E[N_F]t_{on} \tag{4.19}$$

where $E[N_c]$ is the expected number of intra-network collision occurring with other SUs when they attempt to contend for the channel. It can be calculated as

$$E[N_c] = \frac{1}{1-p} - 1 \tag{4.20}$$

N_F is the random variable representing the number of FSS needed to be carried out when the backoff counter reaches 0. Then the expected value of N_F is given by

$$E[N_F] = \frac{1}{P_{F,b}} - 1 \tag{4.21}$$

and $E(\chi)$ is the average backoff delay without considering state $\{-1, 0\}$. Suppose the backoff counter of a SU is at state $b_{i,k}$, then k time slots are needed for the backoff counter to reach zero. Hence the average value of χ is obtained as

$$E[\chi] = \sum_{i=0}^{m} \sum_{k=1}^{W_i-1} k b_{i,k} \tag{4.22}$$

Substituting Eqns. (4.20), (4.21) and (4.22) into Eqn. (4.19) and using Eqn. (4.16),

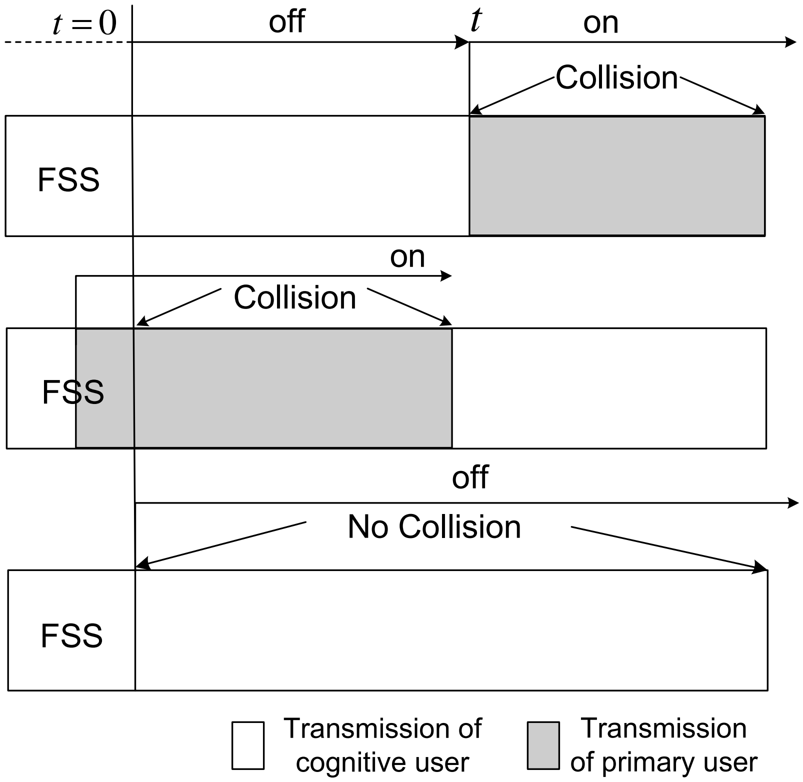

Figure 4.3: Example showing the SU experiences packet collision with the PU at the beginning of or during the transmission.

the expression of average CSMA delay t_c is derived as

$$E[t_c] \quad = \quad \frac{pt_{on}}{1-p} + (\frac{1}{6P_{F,b}} + \frac{1}{6(1-p)} - \frac{1}{3})(\frac{W^2}{1-4p} - \frac{1}{1-p})b_{0,0} \qquad (4.23)$$

For simplicity, it is assumed that DIFS and SIFS are negligible compared to τ_N, τ_F and T, and are thus not included in the calculation of t_c. Incorporating DIFS and SIFS in the above study is left for the future work.

4.2.5 Inter-Network Collision Probability P_c

The inter-network collision probability with PU consists of two parts: Owing to imperfect spectrum sensing, the SU may mistakenly declare the active PU as idle and transmit its packet, such that collision will happen at the beginning of the transmission (as shown in Figure 4.3), which is neglected in [36] [37] due to perfect sensing assumption. This part of collision probability $P_{c,1}$ is a result of imperfect spectrum sensing in FSS, which is given by

$$P_{c,1} = (1 - P_{F,d})P_b \tag{4.24}$$

Collision may also happen in the following scenario: the SU successfully detects the available transmission opportunity when the channel is idle and starts to transmit. However, the PU returns before the SU completes its transmission. Following the definition in [36] and [148], the end of the sensing slot in FSS is denoted by the starting point of time $t = 0$. Let t represents the time point that a primary packet arrives (as shown in Figure 4.3), thus the collision probability $P_{c,2}$ that a SU experiences collision during the packet transmission due to the arrival of a primary packet is

$$\begin{aligned} P_{c,2} &= (1 - P_{F,f})(1 - P_b)Pr\{0 < t < T - a\} \\ &= (1 - P_{F,f})(1 - P_b)\int_0^{T-a} f_i(t)dt \\ &= (1 - P_{F,f})(1 - P_b)[1 - e^{(-\frac{T-a}{t_{off}})}] \end{aligned} \tag{4.25}$$

where $a = \tau_N + t_c + N_F\tau_F$. Thus the inter-network collision probability with PU is obtained as

$$P_c = P_{c,1} + P_{c,2} \tag{4.26}$$

The author assumes that the SU can detect its collision with PU after transmission. For example, the packet is indicated to be successfully received if the SU receives an acknowledgement (ACK), and the absence of ACK indicates a collision. In the rest of this chapter, collision always refers to inter-network collision.

4.3 Performance Analysis of the Proposed Protocol

In this section, the author formulates the normalized achievable throughput-collision tradeoff problem and the utility-collision tradeoff problem for the SU to evaluate the performance of the proposed MAC sensing-transmission protocol with FSS. The author wants to determine the optimal value of frame duration that maximizes the utility of the SU with minimal degradation of the PU QoS. Furthermore, the author also analyzes the normalized throughput of the PU based on its traffic pattern and collision probability to provide an insight on how much more protection to the PU can be achieved.

4.3.1 Normalized Throughput of SU

The SU starts to transmit packet in the following two scenarios: 1) when the channel is occupied by the PU, but mis-detection happens, which may cause collision $P_{c,1}$; 2) When the channel is idle, and the SU can successfully detect this transmission opportunity and start to transmit. In this scenario, collision $P_{c,2}$ may happen if the PU turns on before the SU completes its transmission. Thus the normalized achievable throughput for the SU, $R(T)$, which is defined as the fraction of time that the SU can transmit packets without collision can be expressed as

$$R(T) = \frac{T - \tau_N - t_c - N_F \tau_F}{T}(1 - P_c(T)) \tag{4.27}$$

Throughput-Collision Tradeoff: Study in [36] shows that there is a tradeoff problem between collision and throughput for the SU for a fixed sensing time. On one hand, increasing the frame duration allows the SU to have more time for data transmission. On the other hand, the longer the frame duration, the more chance that the PU returns, thus increasing the collision probability with the PU, which will further reduce the achievable throughput for both the SU and the PU.

Thus the first objective is to determine the optimal frame duration T^*, such that the normalized throughput for the SU can be maximized, subject to sufficient protection to the PU.

Problem P1

$$\max_{T} \quad R(T) \tag{4.28}$$

$$s.t. \quad P_c(T) \leq \bar{P}_c \tag{4.29}$$

where $\bar{P}_c$ is the target collision probability.

The closed form of optimal frame duration T has been established in [36], such that the achievable throughput for the SU can be maximized, subject to sufficient protection provided to the PU. In this work, although the mis-detection of the presence of the PU is taken into account as part of the collision probability, the optimal frame duration T^* that provides the best collision-throughput tradeoff still exists under certain conditions.

Proposition 1. *There exists in Problem P1 an optimal frame duration T^* that can maximize the achievable throughput for the SU, that is*

$$T^* = arg\max_{T} R(T)$$

if

$$-T^3 + aT^2 + 2aT + 2at_{off} > 0$$

where $a = \tau_N + t_c + N_F\tau_F$.

Proof. Let $a = \tau_N + t_c + N_F\tau_F$, from Eqn. (4.27), the first order derivative of $R(T)$ with respect to T can be obtained as

$$\frac{dR(T)}{dT} = \frac{a}{T^2}(1 - P_c(T)) - \frac{T-a}{T}\frac{dP_c(T)}{dT} \tag{4.30}$$

where $P_c(T)$ is given by Eqn. (4.26), and the first order derivative of $P_c(T)$ with respect to T is given by

$$\frac{dP_c(T)}{dT} = \frac{(1 - P_{F,f})(1 - P_b)}{t_{off}} exp(-\frac{T-a}{t_{off}}) \tag{4.31}$$

Furthermore, differentiating on both sides of Eqn. (4.30) with respect to T results in the second order derivative of $R(T)$, which is

$$\begin{aligned} \frac{d^2R(T)}{dT^2} &= -\frac{2a((P_{F,d} - P_{F,f})P_b + P_{F,f})}{T^3} - exp(-\frac{T-a}{t_{off}}) \\ &\quad \frac{(1 - P_{F,f})(1 - P_b)[-T^3 + aT^2 + 2aT + 2at_{off}]}{T^3t_{off}^2} \end{aligned} \tag{4.32}$$

It should be recognized that, if Problem P1 has an optimal frame duration T^*, Eqn (4.32) has a negative value. Note that the first part of Eqn. (4.32) is less than 0, that is

$$-\frac{2a((P_{F,d} - P_{F,f})P_b + P_{F,f})}{T^3} < 0 \tag{4.33}$$

and

$$\frac{(1-P_{F,f})(1-P_b)}{T^3 t_{off}^2} exp(-\frac{T-a}{t_{off}}) > 0 \tag{4.34}$$

Thus, for the condition $\frac{d^2R(T)}{dT^2} < 0$ to be satisfied, it has

$$-T^3 + aT^2 + 2aT + 2at_{off} > 0 \tag{4.35}$$

In addition, the domain of constraint Eqn. (4.29) is further shown to be a convex set, that is

$$(1-P_{F,d})P_b + (1-P_{F,f})(1-P_b)[1 - exp(-\frac{T-a}{t_{off}})] \leq \bar{P}_c$$

$$\Rightarrow exp(-\frac{T-a}{t_{off}}) \geq 1 - \frac{\bar{P}_c - (1-P_{F,d})P_b}{(1-P_{F,f})(1-P_b)}$$

$$\Rightarrow -\frac{T-a}{t_{off}} \geq \log(1 - \frac{\bar{P}_c - (1-P_{F,d})P_b}{(1-P_{F,f})(1-P_b)})$$

$$\Rightarrow T \leq a - t_{off}[\log(1 - \frac{\bar{P}_c - (1-P_{F,d})P_b}{(1-P_{F,f})(1-P_b)})] \tag{4.36}$$

It should be noted that the right side of Eqn. (4.36) is independent of T, and the domain is a halfspace, which certainly is a convex set.

Thus if Eqn. (4.35) satisfies, the objective function in Problem P1 is concave and it takes the form of maximizing subject to a convex domain. It can then be concluded that Problem P1 is a convex optimization problem [149]. Thus an optimal solution exits. Now let $\frac{dR(T)}{dT} = 0$, the optimal frame duration T^* can be yielded by solving the following equation using quantitative methods

$$\frac{a[(P_{F,d}-P_{F,f})P_b+P_{F,f}]}{(1-P_{F,f})(1-P_b)}=\frac{T^2-aT-at_{off}}{t_{off}}exp(-\frac{T-a}{t_{off}}) \tag{4.37}$$

The value of frame duration T^* obtained by solving Eqn. (4.37) is considered to be optimal if both Eqns. (4.29) and (4.35) are satisfied.

This completes the proof. □

4.3.2 Utility of SU

Note that, collision will happen if the PU returns before the SU completes its transmission or mis-detection of the available transmission opportunity happens. An utility function for the SU to represent the reward of a successful transmission and the penalty of a collision is introduced [103]. Let a successful transmission yield to a benefit of C_1, and a collision be penalized with a penalty of C_2, it is reasonable to assume that $C_2 > C_1$, since the PU has a higher priority. Hence, the utility function of the SU is defined as

$$U(T)=\frac{T-a}{T}[(1-P_c(T))C_1-P_c(T)C_2] \tag{4.38}$$

where the first part in the square brackets denotes the benefit with successful transmission, and the second part represents the penalty due to collision. Note that, when there is no penalty i.e. $C_2=0$, the utility function becomes the normalized achievable throughput for the SU if $C_1=1$.

Utility-Collision Tradeoff: As explained in the throughput-collision tradeoff problem, a longer frame duration results in longer time for data transmission, which can yield more benefit. However, it also leads to a higher collision probability, which causes more penalty. Therefore, the frame duration setting directly impacts the tradeoff between collision and the utility for SU.

Thus the second objective is to determine the optimal frame duration T^*, such that the utility function for the SU can be maximized, subject to sufficient protection provided to the PU.

Problem P2

$$\max_{T} \quad U(T) \tag{4.39}$$

$$s.t. \qquad P_c(T) \leq \bar{P}_c \tag{4.40}$$

Proposition 2. *There exists in Problem P2 an optimal frame duration T^* that can maximize the utility for the SU, that is*

$$T^* = arg\max_{T} U(T)$$

if

$$-T^3 + aT^2 + 2aT + 2at_{off} > 0$$

where $a = \tau_N + t_c + N_F\tau_F$.

Proof. The first order derivative of $U(T)$ with respect to T is given by

$$\frac{dU(T)}{dT} = \frac{a}{T^2}C_1 - \frac{a}{T^2}(C_1 + C_2)P_c(T) - \frac{T-a}{T}(C_1 + C_2)\frac{dP_c(T)}{dT} \tag{4.41}$$

where $P_c(T)$ and $\frac{dP_c(T)}{dT}$ are given by (4.26) and (4.31), respectively. The second order derivative of $U(T)$ is

$$\begin{aligned}\frac{d^2U(T)}{dT^2} &= -\frac{2aC_1((P_{F,d}-P_{F,f})P_b+P_{F,f})}{T^3} - exp(-\frac{T-a}{t_{off}})\frac{(1-P_{F,f})(1-P_b)(C_1+C_2)}{T^3t_{off}^2} \\ &\quad \frac{[-T^3+aT^2+2aT+2at_{off}]}{T^3t_{off}^2} \qquad (4.42)\end{aligned}$$

Since both $C_1 > 0$ and $C_2 > 0$, therefore, as discussed in *Proposition 1*, for the condition $\frac{d^2U(T)}{dT^2} < 0$ to be satisfied, it has

$$-T^3 + aT^2 + 2aT + 2at_{off} > 0 \qquad (4.43)$$

Now let $\frac{dU(T)}{dT} = 0$ in Eqn. (4.41), the optimal frame duration T^* can be derived by solving the following equation, such that

$$\begin{aligned}&\frac{a[C_1-(C_1+C_2)(1-(P_{F,d}-P_{F,f})P_b-P_{F,f})]}{(1-P_{F,f})(1-P_b)} \\ = &\frac{T^2-aT-at_{off}}{t_{off}}(C_1+C_2)exp(-\frac{T-a}{t_{off}}) \qquad (4.44)\end{aligned}$$

It can be seen that, Eqn. (4.37) is a special case of Eqn. (4.44) if $C_1 = 1$ and $C_2 = 0$.

This completes the proof. □

4.3.3 Normalized Throughput of PU

The throughput for the PU refers to the successful transmission time normalized by the idle-busy period. Therefore, if no collision happens, all the primary packets can be successfully transmitted. Otherwise, collision happens due to the return of the PU or falsely declaring the transmission opportunity, such that even if the SU vacates the channel immediately, the throughput of the PU is still affected. In this case, the normalized throughput is strongly related to the frame duration. If $T < t_{on} + t_{off}$, the primary packet in the affected ON duration is considered lost and no primary packet will arrive within this frame duration, thus no throughput can be achieved; otherwise, it should be recognized that, the transmission time of a secondary packet is smaller than $t_{on} + t_{off}$. Therefore, if one frame duration consists of more than one PU busy periods, only one primary busy period will be affected by the operation of the SU. Thus the expected normalized throughput for the PU can be obtained as

$$R_p = \begin{cases} \frac{1}{t_{on}+t_{off}} t_{on}, & if\ 1 - P_c \\ (\frac{1}{t_{on}+t_{off}} - \frac{1}{T}) t_{on}, & if\ P_c\ and\ T > t_{on} + t_{off} \\ 0, & otherwise \end{cases} \tag{4.45}$$

Note that $P_b = \frac{t_{on}}{t_{on}+t_{off}}$ is the fraction of time that the PU is busy, thus it has $R_p < P_b$.

4.4 Analysis Results

In the following, the sampling frequency $f_s = 6MHz$ as in Chapter 3, the normal sensing time $\tau_N = 3ms$, the fast sensing time $\tau_F = 1ms$. The author considers a CRN that involves $N = 3$ SUs and 1 PU in the system. The expected ON/OFF durations for the PU are set to $t_{on} = 65ms$ and $t_{off} = 35ms$, respectively. A packet will be considered lost if collision happens at the beginning of or during the transmission.

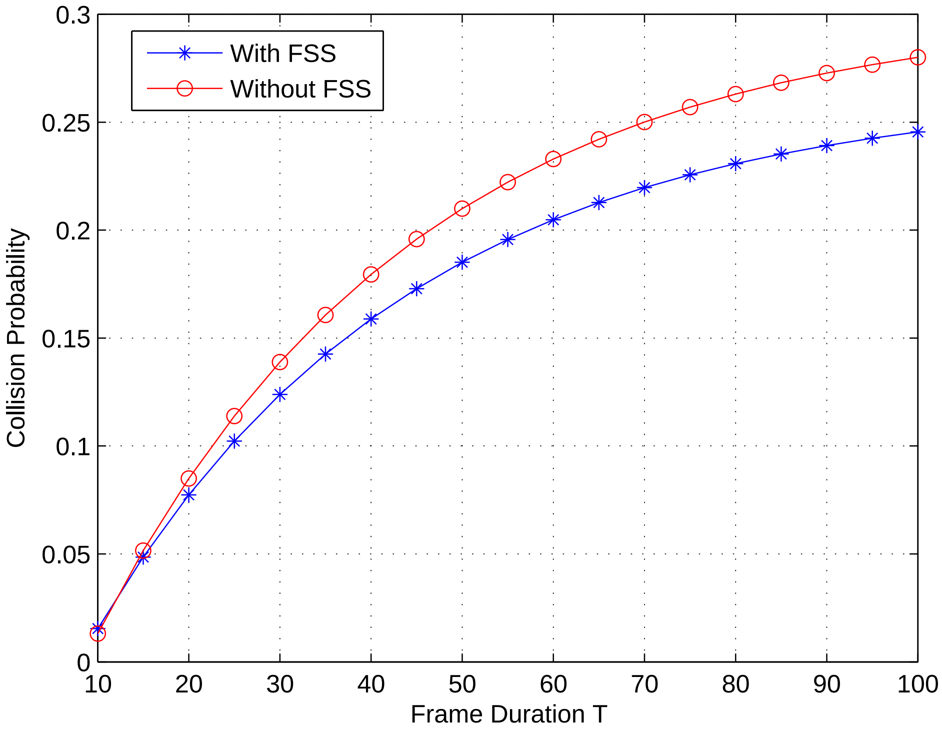

Figure 4.4: The collision probability for PU vs. frame duration with and without FSS for SNR=-10dB at a noise variance of $\sigma_u^2 = 1$.

4.4.1 Collision Probability

As shown in Figure 4.4, the collision probability under the MAC protocol with and without FSS is compared. It is not surprising that the collision probability increases as the frame duration increases. Since the PU arrives randomly and it has higher priority to utilize the channel, the longer the frame duration, the more chances that the PU will turn on, and the higher is the collision probability. The collision probability considered here is slightly higher than that in [36], since imperfect spectrum sensing will induce mis-detection, which further contributes to the collision at the beginning of a transmission. As illustrated in Figure 4.4, the collision probability of the SU for the protocol without FSS has a smaller value when the frame duration $T < 12ms$, after

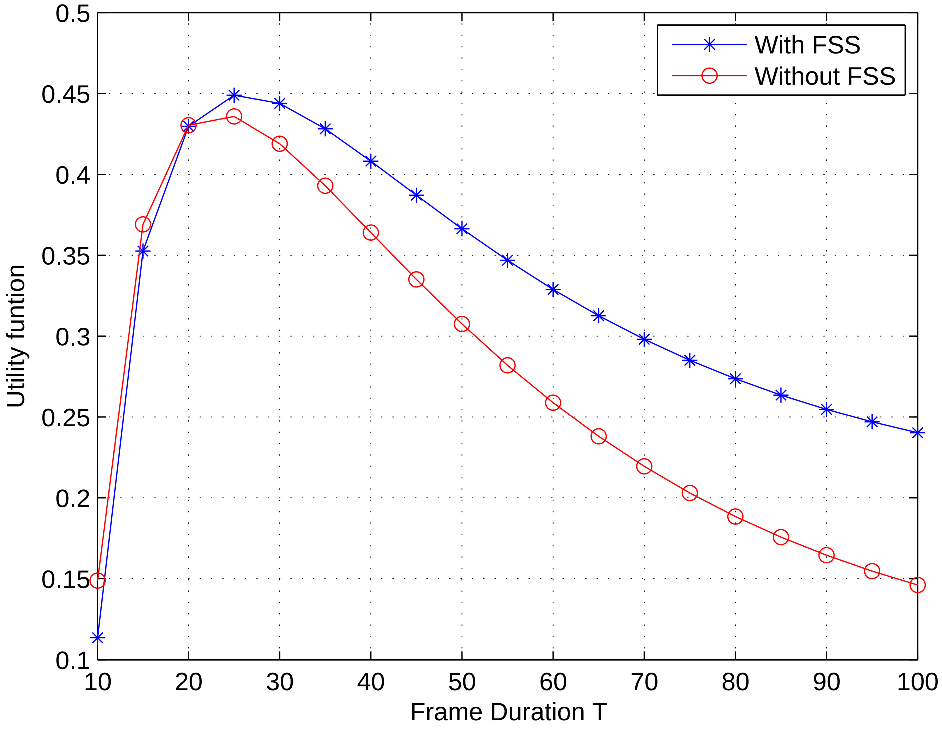

Figure 4.5: The utility function for SU vs. frame duration with and without FSS for SNR=-10dB at a noise variance of $\sigma_u^2 = 1$.

that, it becomes larger than the scheme with FSS. This is due to the fact that the probability that the channel is successfully detected idle for NSS and FSS are given by $P_{N,i} = (1 - P_{N,f})(1 - P_b)$ and $P_{F,i} = (1 - P_{F,f})(1 - P_b)$, respectively, which can almost be treated as the increasing rate of the collision probability. Since $P_{N,i} > P_{F,i}$, the collision probability for the protocol without FSS will increase faster when the frame duration becomes larger.

4.4.2 Utility of SU

In Figure 4.5, the results for the utility for SU under MAC protocol with and without FSS for $C_1 = 1$ (C_1 is the transmission reward) and $C_2 = 2$ (C_2 is the collision penalty)

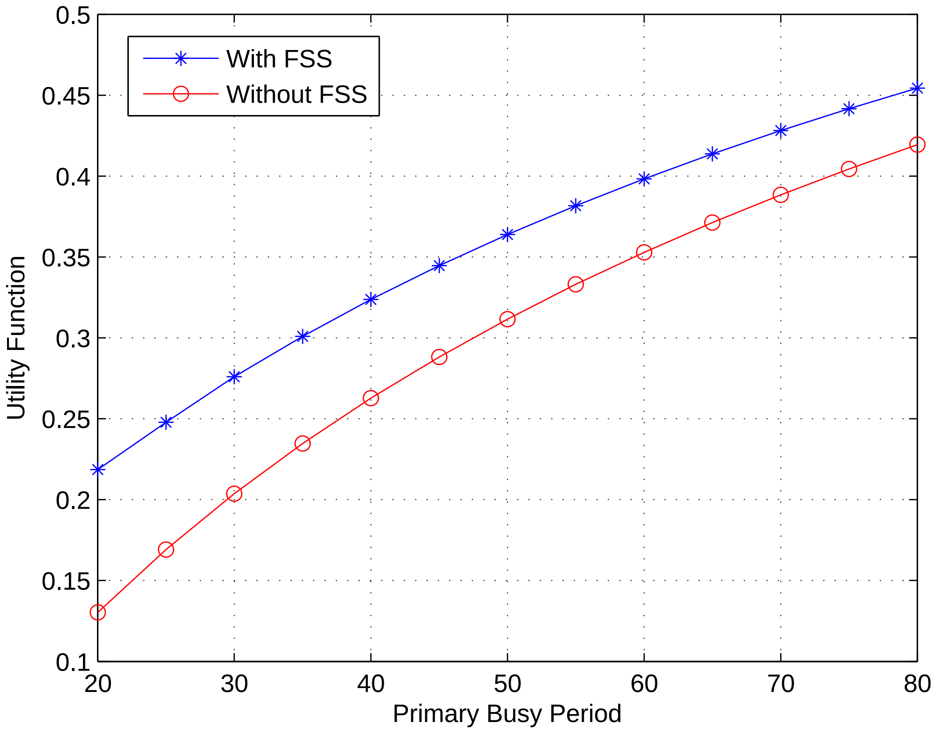

Figure 4.6: The utility function for SU vs. PU busy period with and without FSS for SNR=-10dB at a noise variance of $\sigma_u^2 = 1$.

are presented. Note that the two curves are very close to each other when the frame duration is less than $20ms$. After that the SU can achieve a higher utility with FSS, and this benefit becomes larger as the frame duration increases. This can be explained using the arguments in the collision probability above. It can be seen that there exists an optimal value of frame duration, such that the utility for the SU can be maximized, which illustrates the validity of Proposition 2. Figure 4.6 depicts the utility for SU $U(t_{on})$ as a function of the expected ON period t_{on}. From this figure, for a given t_{off}, as t_{on} increases, the utility for SU $U(t_{on})$ increases. It is easy to note that the MAC protocol with FSS always achieves a higher utility for the SU.

Furthermore, to provide better understanding of the performance of the proposed MAC protocol with FSS, the utility versus the penalty parameter (C_2) for a fixed

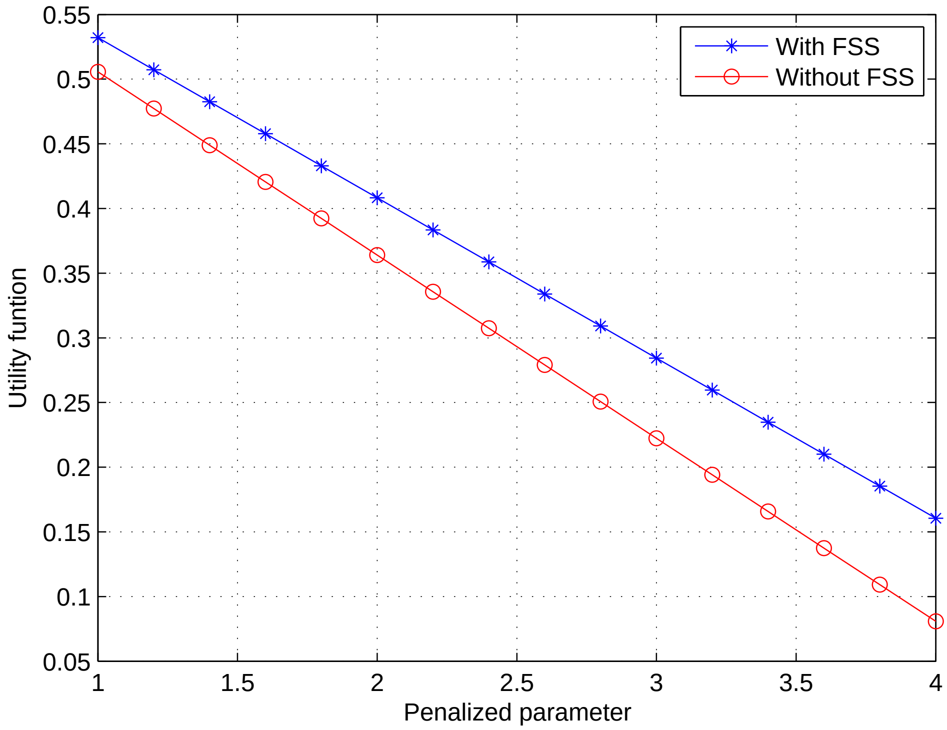

Figure 4.7: The utility function for SU vs. penalized parameter C_2 with and without FSS for SNR=-10dB at a noise variance of $\sigma_u^2 = 1$.

reward $C_1 = 1$ is plotted in Figure 4.7. From Figure 4.7, it should be recognized that the utility of the SU decreases as the collision penalty parameter C_2 increases. This is true since the utility function defined in Eqn. (4.38) is a linear monotonically decreasing function of C_2 for fixed C_1 and T. Moreover the utility for the SU without FSS has a sharper decreasing rate due to its larger collision probability. Therefore the system can adjust C_2 to provide the required protection to the PU. Figure 4.8 depicts the utility as a function of the benefit parameter C_1 for a fix C_2. From Figure 4.8, it can be seen that the utility increases as the benefit parameter C_1 increases. This is obvious since the utility function defined in Eqn. (4.38) is a linear increasing function of C_1 for fixed C_2 and T.

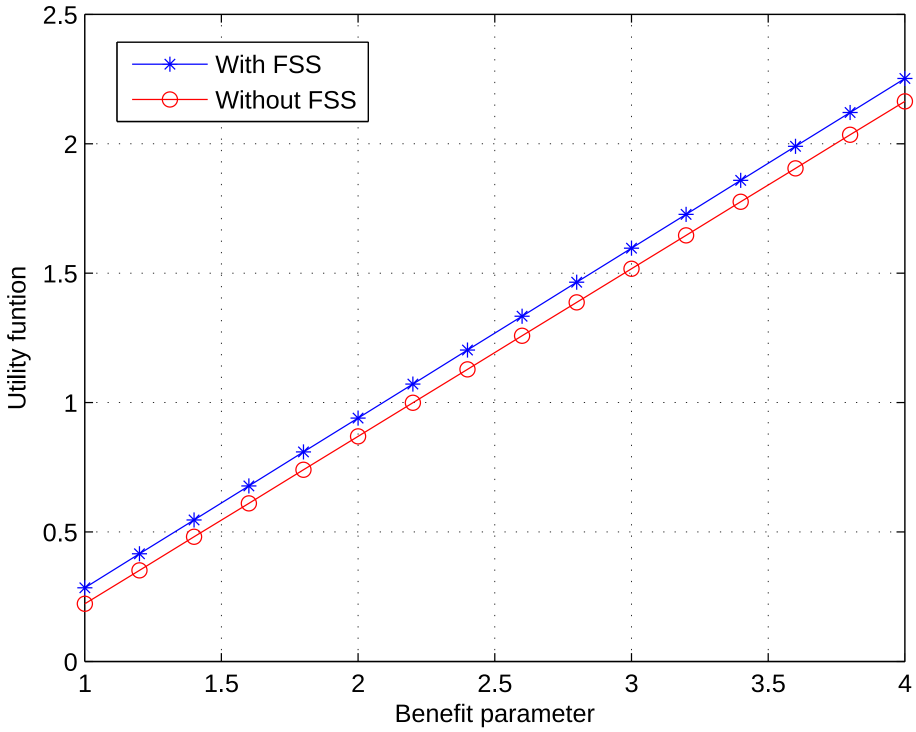

Figure 4.8: The utility function for SU vs. benefit parameter C_1 with and without FSS for SNR=-10dB at a noise variance of $\sigma_u^2 = 1$.

4.4.3 Normalized Throughput of PU

Figure 4.9 shows the performance comparison of MAC protocols with and without FSS in terms of the normalized throughput for the PU. It is not surprising to observe that the protocol with FSS achieves higher normalized throughput for the PU than that without FSS. This is because more protection is provided to the PU if FSS is carried out after the channel contention phase, which improves the throughput for the PU. It can also be seen that for small values of frame duration, the normalized throughput of the PU decreases as the frame duration increases. Throughput is defined as the time proportion for a successful transmission, thus for small frame duration (i.e. $T < t_{on} + t_{off}$), if no collision happens, the average effective time for successful

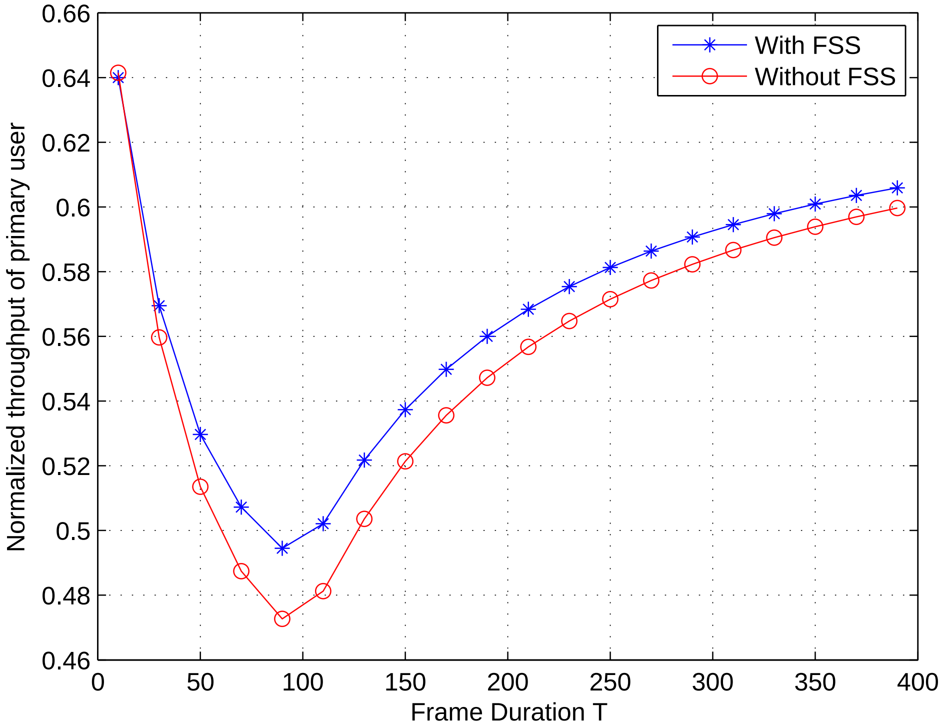

Figure 4.9: The normalized throughput for PU vs. frame duration with and without FSS for SNR=-10dB at a noise variance of $\sigma_u^2 = 1$.

transmission is t_{on}; otherwise if collision happens, the entire PU packets during the ON period will be considered lost and the average effective time for successful transmission is 0. Therefore, for smaller value of frame duration, the normalized throughput for the PU is determined by the collision probability which is an increasing function of frame duration. On the other hand, when $T > t_{on} + t_{off}$, the throughput increases as the frame duration. The reason is straightforward. As frame duration increases to a large value, each T may consist of several busy periods of the PU, thus increasing the normalized throughput.

Generally speaking, these analysis results show that the proposed MAC sensing-transmission protocol with FSS can improve the performance by reducing the collision probability and in the meanwhile increases the utility for the SU, and provides more protection to the PU.

4.4.4 Performance Comparison

Next the performance achieved by the proposed MAC sensing-transmission protocol with FSS and the Spectrum Access Policy (SAP) in [4] is compared. One should note that, in [4] both the number of collided PU packets and the SU throughput are normalized by the PU busy-idle cycle, while in this work, these two performance metrics are calculated based on each frame duration. For this reason, the author fixes the PU parameters used here as $t_{on} = 35ms$, $t_{off} = 65ms$, the number of primary packet in a busy period is set to $n_p = 1$, and the PU idle time is exponentially distributed. Therefore, the optimal spectrum access policy is $p^* = n_p\eta$, where η is the collision probability constraint. A set of analysis resulsts with $\eta = 0.1, 0.2, 0.3$ are conducted. The author varies the frame duration from $10ms$ to $100ms$ and examine two metrics: the throughput of the SU and the collision probability of the PU, both are normalized by the frame duration. The results are shown in Figure 4.10 and Figure 4.11.

It can be observed that, from Figure 4.10 the collision probability of both the proposed protocol and SAP [4] increases with the increase of the frame duration T. The collision probability P_c of SAP in [4] heavily depends on the choice of collision probability constraint η and P_c is an increasing functions of η. When $\eta = 0.1, 0.2$, the proposed sensing-transmission protocol with FSS can keep a lower collision probability for smaller frame duration, and when η increases to 0.3, the collision probability of the proposed protocol is much lower than that of SAP in [4], which means that the transmission of the PU is well protected.

Figure 4.11 depicts the normalized throughput of the SU as a function of frame duration T, obtained by the proposed method with FSS as well as SAP in [4]. It

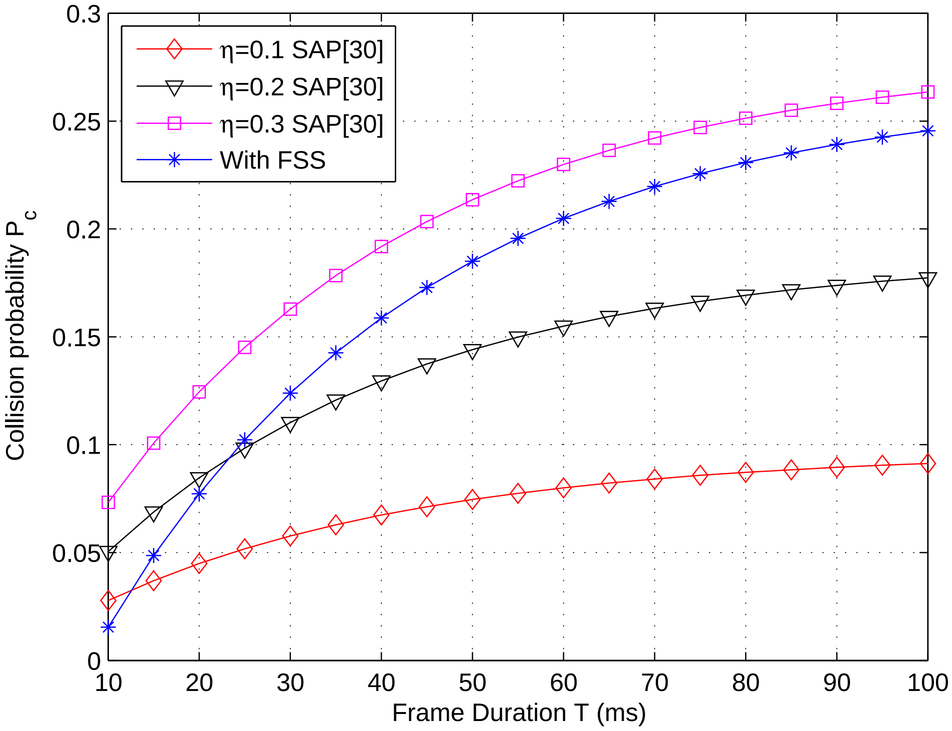

Figure 4.10: PU collision probability vs. frame duration for the proposed protocol with FSS and existing Spectrum Access Policy (SAP) in [30] for different collision probability constraint η.

can be seen that, the normalized throughput achieved by SAP increases with the increase of collision constraint η. By loosening the collision constraints, the SU has more opportunities of accessing the spectrum. As a result, the throughput is increased. It can be seen that the proposed protocol can obtain better throughput than SAP in [4], and notably in this case of $\eta = 0.3$, a smaller collision probability is always guaranteed as shown in Figure 4.10.

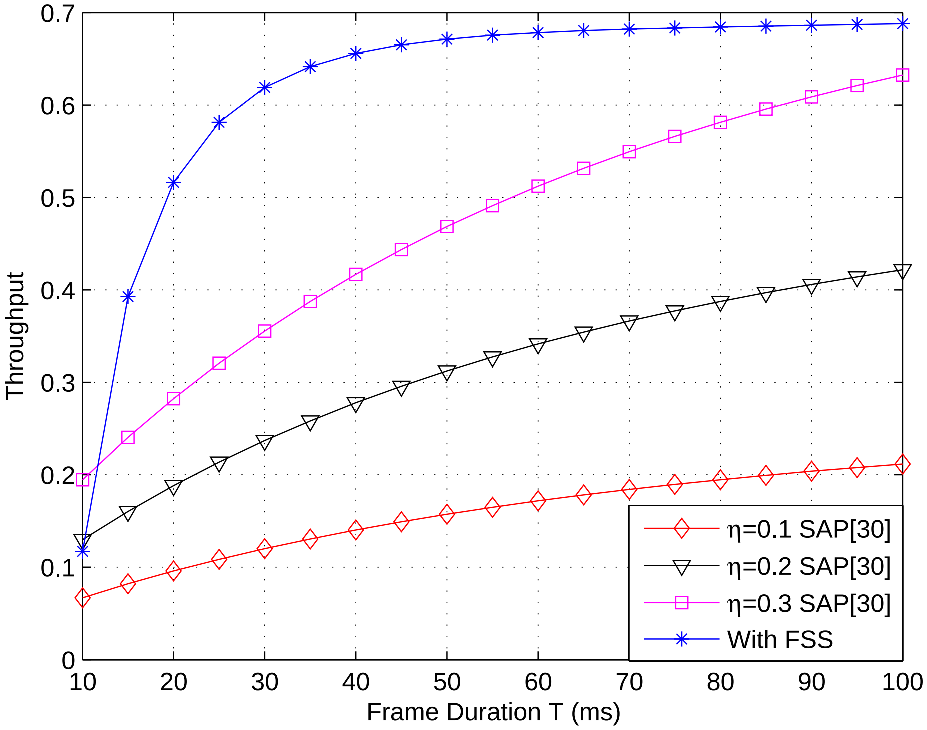

Figure 4.11: SU throughput vs. frame duration for the proposed protocol with FSS and existing Spectrum Access Policy (SAP) in [4] for different collision probability constraint η.

4.5 Conclusions

In this chapter, the author studies the design of MAC sensing-transmission protocol that inserts FSS after the channel contention phase, which has not been done by existing work. For a real environment, the PU packet may arrive at any time, and utilizes the channel without sensing and contention due to its higher priority. Thus the channel will become busy after the contention phase. Therefore, inserting Fast Spectrum Sensing into the MAC protocol design has significant impact in reducing the collision probability and improving the PU protection. Furthermore, it also overcomes the shortcoming of OSA-MAC by providing up-to-date sensing information. In this work, it does not assume perfect sensing, and treats the mis-detection as one part of collision probability, which is one improvement over [36] [37] with perfect sensing assumption.

To investigate the performance of the proposed MAC sensing-transmission protocol, theoretical formulae for the normalized achievable throughput-collision tradeoff and the utility-collision tradeoff for the SU are derived. Furthermore, quantitative method has been developed to obtain the optimal value of the frame duration, such that the utility of the SU can be maximized. The computed result of optimal frame duration through Eqn. (4.43) matches well with the simulated one, which confirms its validity.

Chapter 5

Sequential Sensing Based Spectrum Handoff

Spectrum handoff occurs when the PU appears in the licensed spectrum temporarily occupied by the SU, thus the SU is required to vacate the spectrum rapidly, and resume its transmission on a newly selected available channel. In this chapter, the author presents a sequential sensing based spectrum handoff policy for multiple-user CRNs which comprehensively considers spectrum sensing, target channel selection as well as spectrum estimation. In order to reduce the heavy complexity, the author selects the appropriate candidate channels for each SU. In case of spectrum handoff, the SU performs sequential sensing to determine the optimal sensing order together with the best target handoff channel over the selected candidate channels rather than all the channels based on Dynamic Programming (DP). Note that many spectrum handoff will occur during one SU transmission and the objective is to minimize the total number of spectrum handoff. The sequential sensing based spectrum handoff policy is evaluated through a comprehensive simulation study and the results reveal significant improvements in the system performance by reducing the number of spectrum handoff. Moreover, the proposed DP method can significantly lower the computational complexity compared to exhaustive search and common DP.

The rest of the chapter is organized as follows. The system model is introduced in Section 5.1. The key part: the detailed design of the proposed sequential sensing based spectrum handoff strategy is elaborated in Section 5.2, in which DP method is proposed to determine the optimal sensing order as well as the best target handoff channel with maximal residual idle time for each SU. The effect of error rate is evaluated in Section 5.3. Simulation results and evaluations are given in Section 5.4. Finally, Section 5.5 concludes the chapter.

5.1 System Model

The author considers a CRN consisting of M SUs and N channels/PUs, with channel indices $(1, 2, ..., N)$. The PUs are licensed holders and thus have absolute priority to interrupt the transmission of SUs. On the other hand, the SU can only utilize the channel opportunistically, and as soon as a PU is detected, the SU is forced to vacate the occupied channel. Thus spectrum handoff is initiated when the PU appears at its licensed channel, in this case the SU needs to determine a suitable target channel to resume its unfinished transmission. The target spectrum handoff channel is a key issue. Each SU has its own sensing order, i.e. $(i_1, i_2, ..., i_N)$ for SU i, which is a permutation of $(1, 2, ..., N)$. Whenever a spectrum handoff is required, the SU will perform sequential sensing according to its sensing order to determine the best target channel with maximal residual idle time, then resume its unfinished transmission on it, as shown in Figure 5.1. The residual idle time of the channel i_k, which is defined as the duration from the time instant that the channel is detected to be idle and is able to be utilized by the SU until the time instant that the interrupting event occurs and a

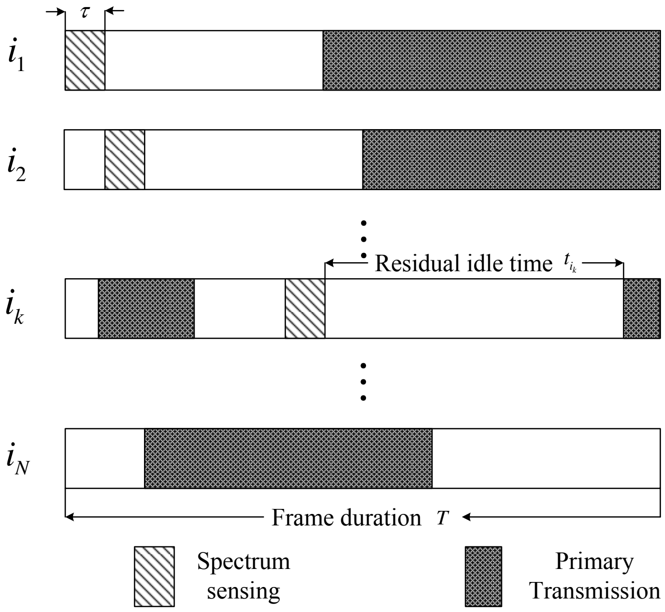

Figure 5.1: The sequential spectrum sensing to determine the optimal target handoff channel with largest residual idle time t_{i_k}

spectrum handoff is required, is denoted as t_{i_k} and is shown in Figure 5.1. Obviously, frequent channel handoff (small t_{i_k}) can degrade the system performance.

In this work, following the definition in [35], the primary-free probability of a channel indicates that the channel is not occupied by the PU, and the free probability of a channel indicates that the channel is occupied by neither the PU nor the SU. This is different from the previous two sets of work where the free probability of a channel only considers the PU activity. For each channel j, $1 \leq j \leq N$, the author models the time periods for ON and OFF states of the primary traffic using exponential distributions with expected value t_{on}^{j} and t_{off}^{j}, respectively [134] [135]. The PU's activity is independent of that in other channels, and the ON and OFF periods are independent of each other. Note that, there are only two possible states (ON/OFF) in the system, thus the theory of alternating renewal process [150] can be used to analyze the behavior of this process.

The intelligent cognitive technologies can allow the SUs to temporarily utilize the unused licensed spectrum. In order to enhance the utilization, the proposed approach requires three major capacities: spectrum estimation, sequential spectrum sensing and spectrum handoff. Spectrum estimation is to measure the residual idle time of the current transmitting channel and determine when to trigger a spectrum handoff; sequential spectrum sensing is to discover a new spectrum opportunity with largest residual idle time; spectrum handoff is to vacate the occupied licensed channel and resume the unfinished transmission on the best selected target channel. Thus, spectrum sensing is still a key element as it should be performed at the beginning of each period to detect the idle channel, and at the time when spectrum handoff is required. In the following the author takes the analysis of SU i as an example. The false alarm probability and detection probability are given by [14] [17].

$$P_{f,(i,j)} = Q((\frac{\lambda}{\sigma_{ij}^2} - 1)\sqrt{f_s\tau}) \tag{5.1}$$

$$P_{d,(i,j)} = Q((\frac{\lambda}{\sigma_{ij}^2} - 1 - \gamma_{ij})\sqrt{\frac{f_s\tau}{2\gamma_{ij}+1}}) \tag{5.2}$$

where λ is the energy detection threshold, τ is the sensing time, f_s is the sampling frequency, σ_{ij}^2 and γ_{ij} are the noise variance and the received SNR on channel j measured by SU i, respectively.

In a real cognitive system, the first design purpose is to protect the PU from interference by the SU, thus the detection probability should not be less than a predefined threshold, that is $P_{d,(ij)} \geq \alpha \geq 0.9$, for $\forall i, j$. The false alarm probability can be rewritten as a function of α, that is

$$P_{f,(i,j)} = Q(\sqrt{2\gamma_{ij}+1}Q^{-1}(\alpha) + \gamma_{ij}\sqrt{f_s\tau}) \tag{5.3}$$

More specifically, the proposed sequential sensing based spectrum handoff is illustrated as follows:

1. In the beginning, SU is transmitting at its default channel, the author assumes that SU will continue to estimate the residual idle time of current transmitting channel t_c, where c is the channel index especially of the channel currently being utilized by the SU, channel c is one of the handoff target channels $c \in \{i_1, i_2, ..., i_k, ...\}$.
2. Furthermore, when t_c is less than a predetermined threshold β, i.e., $t_c < \beta$, it indicates that the PU will appear at the current channel within β duration, then the SU has to prepare for spectrum handoff.
3. SU performs sequential sensing according to its own sensing order to find the best target channel with the maximum residual idle time.
4. SU then resumes its unfinished transmission on the selected target channel.
5. Finally, because a SU may be interrupted many times by the PU during its transmission period, steps (1)-(4) may be repeated.

5.2 The Design of The Proposed Policy

To find an optimal system configuration, two questions need to be answered first: 1) what is the optimal sensing order as well as the best target channel for each SU? and 2) what are the optimal candidate channels for each SU? The two questions are investigated as follows: the author will first determine the candidate channels that each SU will search for spectrum handoff. Then the author proposes sequential sensing to choose the best target channel among the candidate channels using Dynamic Programming (DP).

5.2.1 Selection of Candidate Channels

For sequential spectrum sensing, how many and which channels are selected as candidate channels will significantly affect the system performance, because the proposed strategy is aimed to determine the optimal sensing order where the computational complexity exponentially increases as the number of sensed channel increases. Moreover, a larger number of candidate channels can increase the total sensing time. However, to reduce the number of candidate channels, the probability of finding at least one idle channel decreases. In addition, since all the SUs contend for channel access, one channel may be selected by multiple SUs. Thus, collision may happen among SUs if they switch to the same channel. In this case, long handoff delay may induce. Therefore, the number of channels and which channels are selected as candidate channels should be decided with caution. In general, the principles of selecting candidate channels should meet the three requirements as much as possible: 1) keep a high probability to detect at least one idle channel; 2) reduce the sensing overhead and computational complexity as much as possible; 3) avoid collision with other SUs. Therefore the author proposes the following steps to construct the candidate channels for each SU.

Suppose the accepted channel condition thresholds for all the M SUs are $[\Gamma_1, \Gamma_2, ..., \Gamma_M]$, based on a SU selecting its own candidate channels. A threshold Γ_i is associated with each SU i, for $1 \leq i \leq M$. At each period, the SU first sequentially measures the condition parameters of all the channels. Let $\Upsilon = \{\rho_{ij}\}$, where ρ_{ij} captures the channel j's condition (e.g, channel gain) measured by SU i, $1 \leq j \leq N$. If ρ_{ij} is above the threshold Γ_i, channel j will become one candidate channel of SU i. That is

$$\forall j, \quad if \;\; \rho_{ij} \geq \Gamma_i, \quad then \quad j \Rightarrow C_i \tag{5.4}$$

where C_i is the set of candidate channels for SU i, and $|C_i| = N_i$.

Let P_i denote the probability that the SU i can successfully detect at least one primary free channel by sensing all the candidate channels in C_i. To determine P_i, it should be noted that a channel is called primary-free if this channel is not occupied by the PU and a false alarm does not happen. The following events are introduced:

A_i: at least one primary-free channel can be found after sensing all the candidate channels in C_i.

B_i: Exactly k channels are actually primary-free among all the candidate channels.

The probability that at least one primary-free channel is detected as idle can be obtained using the law of total probability, that is

$$\begin{aligned} P_i &= \sum_{k=1}^{N_i} Pr\{A_i|B_i\}Pr\{B_i\} \\ &= \sum_{k=1}^{N_i}(1-\prod_{j=1}^{k} P_{f,ij}) \sum_{\Lambda\subset C_i}[\prod_{\alpha\in C_i-\Lambda}(1-\theta^{(\delta)})\prod_{\delta\in\Lambda}\theta^{(\delta)}]] \end{aligned} \tag{5.5}$$

where Λ is the set of channels that are actually not occupied by the PUs, $|\Lambda| = k \leq N_i$ and $\theta^{(\delta)}$ is the primary-free probability of channel δ. The part inside the first parentheses represents the probability that at least one primary-free channel can be detected given that exactly k channels are actually primary-free $Pr\{A_i|B_i\}$, while the part inside the brackets denotes the probability that particular k channels are actually primary-free $Pr\{B_i\}$.

In order to maintain a high utilization of channel, choose $P_i \in [P_{min}, P_{max}]$. Here

P_{min} is a predefined positive value and P_{max} is the maximum value. Both are set by the system according to the QoS requirements. P_i should be no smaller than P_{min}, such that the SU i can detect primary-free channels to resume its unfinished transmission with a probability of at least P_{min}. On the other hand, P_i is constrained to be no larger than P_{max} in order to keep the sensing overhead low. This is because when P_i reaches P_{max}, the increasing trend of P_i achieved by adding more channels into its candidate channels set is small. However, the additional sensing overhead and computational complexity increase dramatically. Thus if $P_i < P_{min}$, the threshold Γ_i is reduced and the candidate channels C_i is re-selected; if $P_i > P_{max}$, the redundant channels with high overlapping probability $P_{over,j}$ are removed. Here $P_{over,j}$ is defined as

$$P_{over,j} = \frac{m_j}{M} \tag{5.6}$$

where m_j denotes the number of SUs who select channel j as its candidate channel. Since all the SUs contend for available channels for transmission, the lower $P_{over,j}$ is, the larger the probability that the channel is not occupied by other SU, thus causing less collision.

Intuitively, if the overlapping probability $P_{over,j} \leq \frac{1}{M}$, which means that channel j either only belongs to one SU's candidate channels or none of the SU selects it as a candidate channel, i.e. no other SUs will contend for access. From the view of this SU, the channel idle probability is the same as the primary-free probability, that is

$$\omega_j = \theta_j \tag{5.7}$$

However, if $P_{over,j} > \frac{1}{M}$, which means that more than one SUs may choose channel j as candidate channel, then channel j is idle for SU i only when there is no primary activity and no other SUs activity. In the following, the probability that a candidate channel is available for a particular SU will be determined. Suppose channel j is selected as candidate channel by SUs h_k, $1 \leq k \leq m_j$, then for SU h_1, channel j is considered as idle if it is not occupied by the PU and other SUs h_k, for $2 \leq k \leq m_j$. For simplicity of analysis, the author assumes that the SU transmits over all the candidate channels with equal chance, then the probability that channel j is not occupied by a SU equals to the probability that the SU is utilizing other channels belonging to its candidate channels. Hence, the probability that SU h_1 detects channel j as idle under the assumption that no PU is present is given by

$$P_{s,j} = \prod_{k=2}^{m_j} \frac{|C_k| - 1}{|C_k|} \tag{5.8}$$

The probability that channel j is detected as free of both the PU and other SUs can be expressed as

$$\omega_j = \begin{cases} \prod_{k=2}^{m_j} \frac{|C_k|-1}{|C_k|} \times \theta_j & m_j > 1 \\ \theta_j & m_j \leq 1 \end{cases} \tag{5.9}$$

5.2.2 Spectrum Estimation

While transmitting, the SU may decide to seek for better spectrum opportunity to switch. This typically happens when, for example, the SU judges that the quality of its current channel is no longer acceptable. This is done by continuously evaluating the quality of the current channel via some quality metrics, such as the residual idle time. That is, when the evaluated quality metric drops below a threshold, spectrum handoff is triggered.

Let t_{i_k} denote the residual idle time of channel i_k, then according to the alternating renewal theory [150], t_{i_k} has its probability density function as

$$f_{t_{i_k}}(t) = \frac{1 - F_{t_{off}^{i_k}}(t)}{t_{off}^{i_k}}, \quad where \quad t > 0 \tag{5.10}$$

$F_{t_{off}^{i_k}}(t)$ is the primary idle period cumulative distribution function and $t_{off}^{i_k}$ is the expected value.

Thus the expected residual idle time can be calculated as

$$t_{i_k} = \int_0^{t_{off}^{i_k}} t f_{t_k}(t) dt \tag{5.11}$$

Note that with a constant slot time, the actual residual idle time for data transmission changes with sensing order k. One goal of the proposed strategy is to determine whether the SU should carry out a spectrum handoff and then switch to a new channel with high quality. The policy that a SU should switch to a new channel is

$$t_c < \beta \tag{5.12}$$

where the index c denotes the current channel on which the SU is transmitting, and β is the residual idle time threshold below which the SU is required to perform sequential sensing to find the optimal target channel. Thus, the spectrum handoff can be initiated β duration before the arrival of the PU, which results in a short handoff delay.

5.2.3 Sequential Spectrum Sensing

In the following, the author proposes sequential sensing [35] [116] [117], in which spectrum is searched one by one until an idle channel with satisfied quality is detected. The question is when to stop sensing and carry out the spectrum handoff, and what is the optimal sensing order for each SU to discover a new transmission opportunity.

In this subsection, the author formulates the above sensing problem as a stochastic sequential decision-making problem [151]. The objective is to maximize the overall reward incurred over all stages for each SU. The sequential sensing process allows the problem to be terminated before the last stage as long as the optimal channel is detected. The basic components in the analysis of such problem are briefly described as follows.

System State: The system state is characterized by the knowledge of channel status $x_k \in \{0, 1\}$, indicating whether the channel is idle or not and the set of channels which have been sensed in stage k, Ω_k, i.e., $s_k = (x_k, \Omega_k)$. The author denotes the index of the channel sensed at stage k as i_k, thus $\Omega_k = \{i_1, i_2, ..., i_k\}$. Note that $\Omega_{N_i} = \{i_1, i_2, ..., i_{N_i}\}$, $\Omega_0 = \emptyset$, where $\{i_1, i_2, ..., i_{N_i}\}$ is a permutation of the elements of C_i and $\emptyset$ is an empty set. The author introduces an additional state $s_k = \mathcal{T}$ to denote that the process has been terminated, that is, sequential sensing has stopped.

Decision: At each stage k, after observing the system state s_k, a decision has to be made. To protect the PU and avoid collision with other SUs, spectrum handoff is not allowed when channel i_k is sensed busy. Hence, the only decision when $s_k = (1, \Omega_k)$ is $u_k = i_{k+1}$, which means continuing to sense the next channel i_{k+1}, where i_{k+1} is the best next sensed channel from the set of remaining channels $i_{k+1} \in C_i \backslash \Omega_k$. However, when channel i_k is sensed idle, the SU has to decide whether to give up the current channel and continue to sense the selected next channel, $u_k = i_{k+1}$ or $u_k = 1$ (which denotes that the SU stops sensing and carries out spectrum handoff on channel i_k). Note that once spectrum handoff starts, i.e., $u_k = 1$, the system enters the termination state and remains in it, i.e., $s_{k+1} = ... = s_{N_i} = \mathcal{T}$.

Cost Functions: If channel i_k is sensed busy, then the SU proceeds to sense channel

i_{k+1} ($u_k = i_{k+1}$) where it consumes a certain amount of time for sensing. When channel i_k is sensed idle, the SU will transmit at channel i_k as long as the expected reward of channel i_k is greater than that if the SU proceeds to sense the set of remaining channels. The reward associated with this decision is $\omega_{i_k} t_{i_k} - \tau - t_s$, where t_s is the switching time. Hence the expected reward function for stage k under decision u_k can be expressed as

$$U_k(s_k, u_k) = \begin{cases} \omega_{i_k} t_{i_k} - \tau - t_s & u_k = 1, s_k \neq \mathcal{T} \\ -\tau & otherwise \\ 0 & s_k = \mathcal{T} \end{cases} \tag{5.13}$$

The objective of the design is to find a sequence of decisions u_k, $k = 1, 2, ..., N_i$ mapping each state s_k into a control policy $u_k = u_k(s_k)$ to maximize the reward, which is defined as

$$J_{1,N_i} = E\{\sum_{k=1}^{N_i} U_k(s_k, u_k)\} \tag{5.14}$$

The sequence of decisions $\phi_{1,N_i} = \{u_1(s_1), u_2(s_2), ..., u_{N_i}(s_{N_i})\}$ is referred to as a policy starting from the initial stage 1 to the terminated stage N_i, which is the sensing-handoff strategy that specifies when to stop sensing and carry out spectrum handoff. Denoting the reward using policy ϕ_{1,N_i} as $J_{\phi_{1,N_i}}$, an optimal policy ϕ^*_{1,N_i} is then given by

$$\phi^*_{1,N_i} = arg \max_{\phi_{1,N_i}} J_{\phi_{1,N_i}} \tag{5.15}$$

The optimal policy from stage k to terminated stage N_i is defined as ϕ_{k,N_i} and its associated reward is given by $J_{\phi_{k,N_i}}$. Similar to [35], it refers to sensing the channels according to their descending order of primary-free probability θ_i as Intuitive Sensing Order. It is shown that the Intuitive Sensing Order is optimal for single user case in the following lemma. However, if multiple users are considered, Intuitive Sensing Order may not be optimal.

Lemma 1. *If the optimal sensing order is investigated for a single user case, the Intuitive Sensing Order is optimal. However, this optimality may not exist for multiple users case.*

Proof. Suppose an optimal sensing order is $\phi = (i_1, i_2, ..., i_{N_i})$, and there exists $k < N_i$ such that $\theta_{i_k} < \theta_{i_{k+1}}$, then the author will show the new sensing order resulting from switching the order of i_k and i_{k+1}, $\phi^{new} = (i_1, i_2, ..., i_{k+1}, i_k, ..., i_{N_i})$ is better than ϕ. The author proves this by classification.

Let i_j be the selected target handoff channel, when $j < k$ or $j > k+1$, from Eqns. (5.13) and (5.14). If SU senses channel i_j as idle and stops carrying out spectrum handoff, the reward is

$$J_\phi = J_{\phi^{new}} = -j\tau + \theta_{i_j} t_{i_j} - t_s, \quad j < k \ or\ j > k+1 \tag{5.16}$$

Otherwise, if the SU chooses to stop at channel i_k or i_{k+1}, the expected reward for sensing orders ϕ and ϕ^{new} can be compared as

$$J_{\phi^{new}} - J_\phi = \theta_{i_k}\theta_{i_{k+1}}(t_{i_{k+1}} - t_{i_k}) + (\theta_{i_{k+1}} - \theta_{i_k})[(k+1)\tau + t_s] \geq 0 \tag{5.17}$$

The last inequality holds due to the fact that the residual idle time is a monotonically increasing function of channel primary-free probability. Thus sensing the channels according to their descending order of channel primary-free probability is optimal for single user case. This result is also consistent with that in [34] if adaptive modulation is not used. However, if the optimal sensing order is explored for multiple SUs, the Intuitive Sensing Order may no longer be optimal. The author demonstrates this by the following examples:

Example 1: There are 2 SUs and 4 channels with primary-free probabilities as $(0.9, 0.8, 0.7, 0.6)$ and the candidate channels for users 1 and 2 are $(1, 2, 3)$ and $(1, 3, 4)$, respectively.

If multiple SUs are studied, the channel idle probabilities should include the contention among SUs. Thus the author recalculates the channel idle probabilities as $(0.57, 0.8, 0.37, 0.6)$ according to Eqn. (5.9). By searching, the author can obtain the optimal sensing order setting for these two SUs, which are $(2, 1, 3)$ and (4,1,3) respectively, which is not according to the descending order of primary-free probability.

Example 2: If the primary-free probabilities for the channels are $(0.9, 0.8, 0.7, 0.5)$, then the optimal sensing order for users 1 and 2 are $(2, 1, 3)$ and $(1, 4, 3)$ respectively, which is different from Example 1.

Therefore, from Examples 1 and 2, it can be seen that both the primary-free probability of the channels and the degree of the overlapping will jointly affect the optimal sensing order for multiple users case. $\square$

Since the objective function in Eqn. (5.14) is a summation operation, an optimal policy has the property that no matter what the initial state and decision is, the remaining decisions are also optimal. In particular, if the sensing order $\{i_1, i_2, ..., i_{N_i}\}$ is optimal, then for $\forall k \in (1, N_i)$, $\{i_k, i_{k+1}, ..., i_{N_i}\}$ is also an optimal sensing order of the remaining channels. Thus DP is applicable. Then the author formulates a DP solution for the optimal sequential sensing order for each SU with the basic idea of DP given as follows:

Stage N_i: Calculate the maximal expected reward value associated with the final channel in the sensing order. In the previous stage, a state is represented by the set of sensed channels $\Omega_{N_i-1} = \{i_1, i_2, ..., i_{N_i-1}\}$. Thus there exist $\binom{N_i}{N_i-1}$ possible states in stage N_i. If the observed system state is $s_{N_i} \neq \mathcal{T}$, then the maximum reward can be calculated as

$$J_{\phi_{N_i,N_i}}(s_{N_i}, u_{N_i}) = \begin{cases} -\tau & s_{N_i} = (1, \Omega_{N_i}) \\ -\tau - t_s + \max_{i_{N_i} \in C_i \backslash \Omega_{N_i-1}} \{\omega_{i_{N_i}} t_{i_{N_i}}\} & otherwise \end{cases} \tag{5.18}$$

The expectation value $E[J_{\phi_{N_i,N_i}}(s_{N_i}, u_{N_i})]$ can be calculated over s_{N_i}. Since the computational complexity of the calculation at a channel is $O(1)$, the computational complexity at this stage is $O(\binom{N_i}{N_i-1})$.

Stage k: DP problem can be stated in a recursive, step-by-step form by writing down the relationship between the reward function in one stage and the reward function in the adjacent stage. Here backward induction is used. For the problem starting from stage k and $s_k \neq \mathcal{T}$, the expected reward, for $k = 1, 2, ..., N_i - 1$, can be expressed as

$$J_{\phi_{k,N_i}}(s_k, u_k) = -\tau + \max_{i_{k+1} \in C_i \backslash \Omega_k} \{E[J_{\phi_{k+1,N_i}}(s_{k+1}, u_{k+1})]\} \tag{5.19}$$

when channel i_k is sensed busy and $\Omega_{k+1} = \Omega_k + i_{k+1}$. Otherwise,

$$J_{\phi_{k,N_i}}(s_k, u_k) = -\tau + \max\{\omega^*_{i_k} t^*_{i_k} - t_s, \max_{i_{k+1} \in C_i \backslash \Omega_k} \{E[J_{\phi_{k+1,N_i}}(s_{k+1}, u_{k+1})]\}\} \tag{5.20}$$

where $\omega^*_{i_k} t^*_{i_k}$ is given by

$$\omega^*_{i_k} t^*_{i_k} = \max_{i_k \in C_i \backslash \Omega_{k-1}} \{\omega_{i_k} t_{i_k}\} \tag{5.21}$$

The optimal decision at stage k is given by

$$u_k(s_k, \Omega_k) = arg \max_{i_{k+1} \in C_i \backslash \Omega_k} \{E[J_{\phi_{k+1,N_i}}(s_{k+1}, u_{k+1})]\} \tag{5.22}$$

when the channel is detected to be busy; and when channel i_k is sensed to be idle, there are two possible cases for the decision. In case 1,

$$\omega^*_{i_k} t^*_{i_k} - t_s > \max_{i_{k+1} \in C_i \backslash \Omega_k} \{E[J_{\phi_{k+1,N_i}}(s_{k+1}, u_{k+1})]\} \tag{5.23}$$

In this case, the SU prefers transmitting on channel i_k because it can produce maximal reward. Thus the SU will resume its unfinished transmission on the selected channel i_k until the next spectrum handoff, $u_k = i_k$; On the other hand, in case 2

$$\begin{aligned} &\exists\ i^*_{k+1} \\ &J_{\phi_{k+1,N_i}}(s^*_{k+1}, u^*_{k+1}) > \max\{\max_{i_{k+1} \in C_i \backslash \{\Omega_k + i^*_{k+1}\}} \{E[J_{\phi_{k+1,N_i}}(s_{k+1}, u_{k+1})]\}, \omega_{i_k} t_{i_k} - t_s\} \end{aligned} \tag{5.24}$$

In this case, the SU prefers continuing to sense the remaining channel $u_k = i^*_{k+1}$.

Note that the optimal sensing order strategy at stage k indicates transmission only occurs when the immediate reward on channel i_k is larger than the expected reward associated with continuing the process by sensing any of the remaining channels. The process can be repeated until stage 1. Then the optimal value that can be obtained by maximizing the objective function is given by

$$J_{\phi^*_{1,N_i}}(s_1, u_1) = \max_{i_1 \in C_i} E[J_{\phi_{1,N_i}}(s_1, u_1)] \tag{5.25}$$

Hence, at the beginning, the author should sense from the channel index given by

$$u_1(s_1, \Omega_1) = arg \max_{i_1 \in C_i} E[J_{\phi^*_{1,N_i}}(s_1, u_1)] \tag{5.26}$$

After the maximal reward value is obtained at stage 1, an optimal sensing order can be traced back according to the recorded optimal transition at each stage.

5.2.4 Spectrum Handoff

Spectrum handoff is the process of SU changing its operating channel when the PU appears on the current transmitting channel. A SU's communication may experience multiple interruptions from PUs during its transmission duration. These interruptions will result in a number of spectrum handoff. One should note that spectrum handoff has a significant effect on system performance. From the viewpoint of SUs, whenever spectrum handoff occurs, SU is required to perform sequential sensing to select a target channel, which consumes a lot of system resource. Moreover, spectrum handoff requires sensing time, switching time, handshaking time, all these will increase the SU data delivery time. Therefore spectrum handoff may degrade the performance of SU by incurring longer delay as well as temporary communication disruption since a new discovery of spectrum hole is required. From the perspective of the PU, spectrum handoff is initiated whenever the appearance of PU at the current licensed channel is detected. If the detection is imperfect or the SU cannot pause its transmission, collision with the PU will happen. Therefore, how to reduce the number of spectrum handoff in order to improve the system performance is one of the design goal of this research work.

As illustrated in Figure 5.2, when the PU appears in the current operating channel occupied by SU i, the transmission for SU i will switch to the first target channel i_1

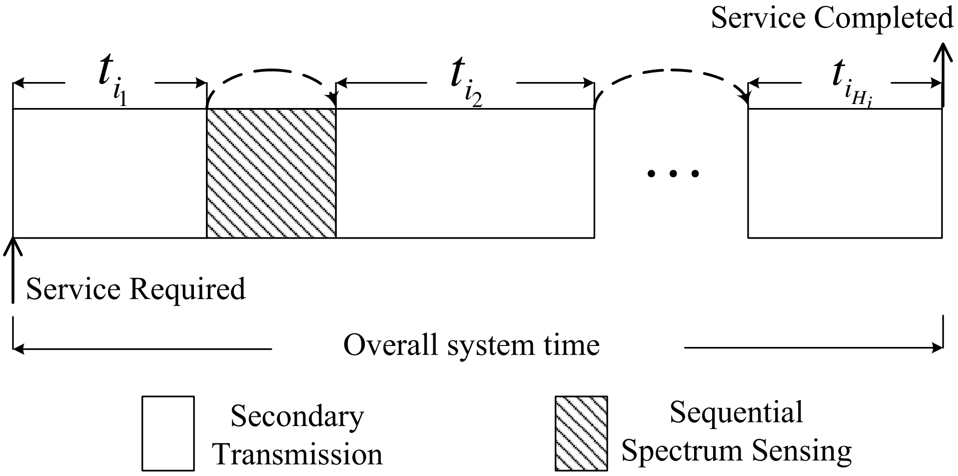

Figure 5.2: Example of overall system time of secondary transmission. The white areas indicate that SU resumes its unfinished transmission on the target channels. Furthermore the shaded areas indicate that sequential spectrum sensing is performed to determine the optimal handoff channel. As indicated in this figure, the target handoff channel sequence is $i_1, i_2, ..., i_{H_i}$ and the number of spectrum handoff is H_i for SU i within transmission duration l_s.

and transmit with duration t_{i_1}. When the residual idle time of the channel is below β, the SU will switch to channel i_2 and resume its transmission with duration t_{i_2}. This process will continue till the SU i finishes its transmission.

Let $\bar{H}_i$ denote the number of spectrum handoff for secondary user i from the beginning of its service to the end of the service. Then

$$\bar{H}_i = \min\{H_i | \sum_{k=1}^{H_i} t_{i_k} \geq l_s\} \tag{5.27}$$

where l_s denotes the required service time for the secondary user to finish its transmission. From (5.27), the number of spectrum handoff during secondary user's transmission period is dominated by the selected target channel. The objective is to minimize the number of spectrum handoff H_i, which is equivalent to maximizing the residual idle time t_{i_k} in each spectrum handoff. Thus, the problem can be separated into a number of subproblems with the aim of determining the target channel which has the maximum residual idle time for data transmission by sequential sensing. Then a series of target channels $(i_1, i_2, ..., i_{H_i})$ will be selected sequentially for multiple spectrum handoff.

5.3 The Effect of Sensing Error

Sensing error such as false alarm and missed detection will degrade the performance of SUs and PUs. Since the author already sets a target detection probability, the PUs will receive a satisfied protection. In the following, the effect of false alarm on the actual residual idle time of spectrum handoff will be investigated.

When a false alarm occurs in the sequential spectrum sensing, the idle channel will be declared as busy. The only decision at this stage is to sense the next selected channel. Hence, for sequential spectrum sensing with N_i channels, let $i_{j_1}, i_{j_2}, ..., i_{j_k}$ be the channels that false alarm happens, where $1 \leq j_1, j_2, ..., j_k \leq N_i$ and their associated residual idle times are $t_{i_{j_1}}, t_{i_{j_2}}, ..., t_{i_{j_k}}$. Let i_j be the selected handoff channel and its residual idle time is t_{i_j}. If false alarm happens, there is a probability that the selected handoff channel is not optimal, while one of the false alarm busy channel is optimal. Hence the actual transmission time will be reduced to $t_{i_j} - j\tau - t_s$ if and only if false alarm occurs in channels $i_{j_1}, i_{j_2}, ..., i_{j_k}$ and at least one of them has larger residual idle time.

One should note that although false alarm happens on channels $i_{j_1}, i_{j_2}, ..., i_{j_k}$, only the channel with maximum residual idle time will affect the transmission time. Thus, the expected effect on the transmission time can be calculated as

$$E[\Delta_t] = P_{f,ij^*} \max((t_{i_{j^*}} - t_{i_j}) + (j - j^*)\tau, 0) \tag{5.28}$$

where j^* indicates the index of false alarm busy channel which has maximum residual idle time.

Let $i_j^{(1)}, i_j^{(2)}, ..., i_j^{(H_i)}$ be the selected target handoff channels sequence during the SU transmission and their associated residual idle time are $t_{i_j}^{(1)}, t_{i_j}^{(2)}, ..., t_{i_j}^{(H_i)}$, where the superscript means the handoff number. If false alarm happens during SU transmission, the optimal selected target handoff channel sequence will change to $i_j^{(1)}, ..., i_{j_1}^{(j_1)}, ..., i_{j_m}^{(j_m)}, ..., i_j^{(H_i)}, i_j^{(H_{i1})}, ..., i_j^{(H_{in})}$. Note that $j_1, j_2, ..., j_m$ are the indices where false alarm happens and $H_{i1}, H_{i2}, ..., H_{in}$ are the extended number of handoff which represents the effect of sensing error in the spectrum handoff. Therefore, the total effected transmission time is given by

$$\Delta = \sum_{l=1}^{m} E[\Delta_t^{(l)}] = \sum_{l=1}^{m} \{P_{f,ij^*}^{(l)} \max((t_{i_{j^*}}^{(l)} - t_{i_j}^{(l)}) + (j - j^*)\tau, 0)\} \tag{5.29}$$

5.4 Simulation

In this section, the simulation results and discussions for the proposed sequential sensing based spectrum handoff strategy are presented. The parameters used in this system are as follows: the sampling frequency is fixed and set to $f_s = 6MHz$, the target detection probability $\alpha = 0.9$, the upper and lower bounds of idle probability are set as $P_{min} = 0.9$ and $P_{max} = 0.95$, respectively. The author assumes that there are $M = 4$ SUs in the network, while the number of channels varies between $2 \leq N \leq 10$.

5.4.1 Performance Comparisons

The conventional Sequential Spectrum Sensing SSS [3] scheme is used to compare with the proposed sequential sensing based spectrum handoff strategy. For SSS, the

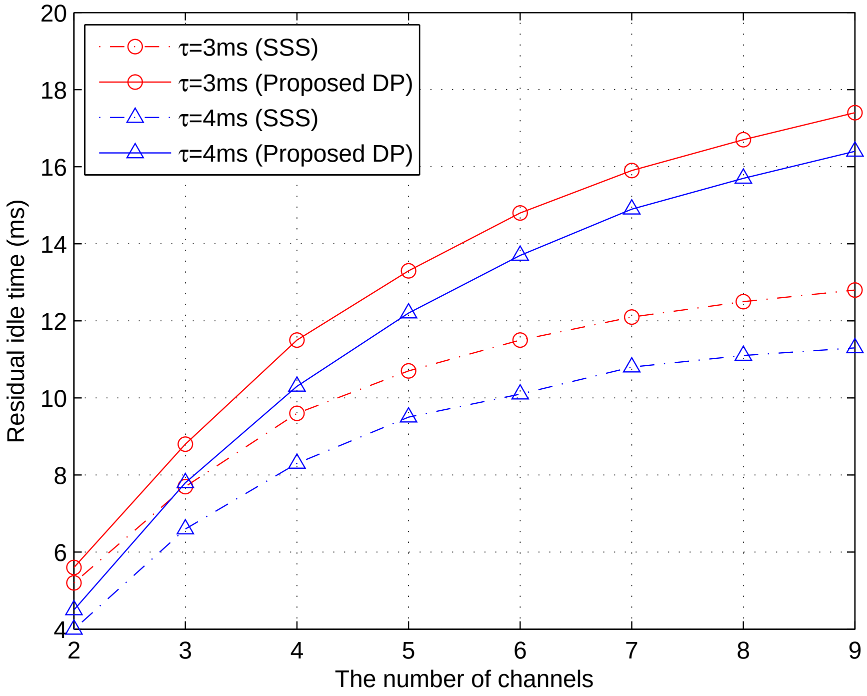

Figure 5.3: The number of sensed channels vs. the residual idle time of the selected handoff channel.

secondary transmission stops as the channels have to be sensed one by one until an idle channel is found whenever spectrum handoff is required. Figure 5.3 depicts the residual idle time as a function of the number of channels in the system, obtained by the proposed sequential sensing based spectrum handoff strategy as well as the SSS in [3]. It is evident from Figure 5.3 that the proposed strategy can achieve a much higher residual idle time than that achieved by SSS where the target channel is the first one detected to be idle. That is, the proposed method makes better use of sequential sensing by selecting the optimal channel with maximal residual idle time. Moreover, it is easy to note that the residual idle time decreases with an increase in the sensing time. This is reasonable due to the fact that a larger sensing time indicates that more fraction of the time is used for sequential sensing, which reduces the residual idle time.

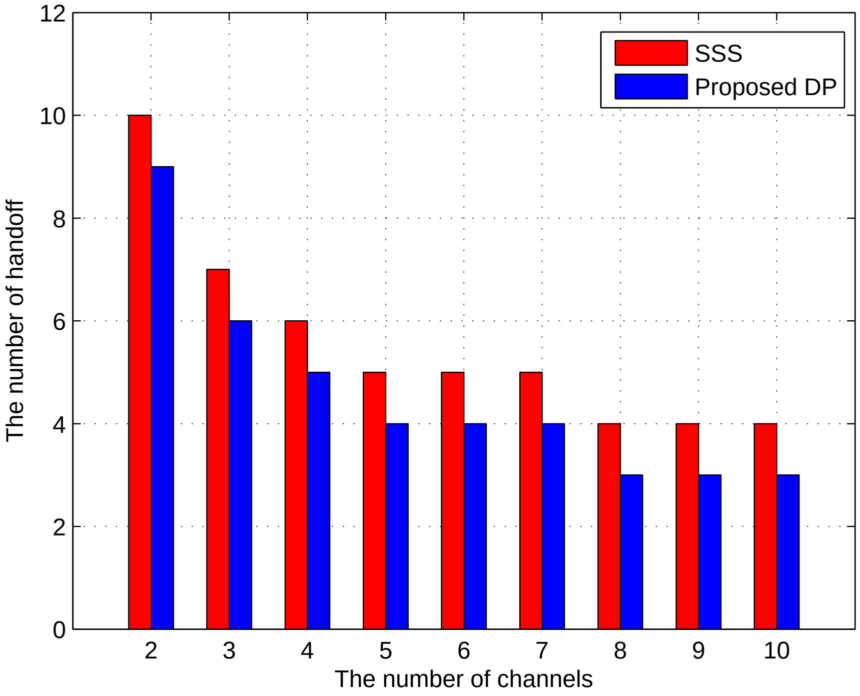

Figure 5.4: The number of sensed channels vs. the number of required handoff.

In Figure 5.4, the author plots the number of spectrum handoff for different number of sensed channels, obtained by the proposed sequential sensing based spectrum handoff strategy using DP as well as SSS [3]. Note that from the Figure 5.4 the proposed strategy can result in a lower number of spectrum handoff than that achieved by SSS. It is also worth observing that the larger the number of sensed channels, the lower the number of spectrum handoff that is required during SU's communication duration. This is because sequential sensing is performed to find the optimal channel with maximal residual idle time, the more the number of sensed channels, the better the selected target channel with longer residual idle time. Thus the residual idle time increases as the number of sensed channels increases. Moreover, the author determines the number of spectrum handoff based on Eq. (5.27), from which, it can be seen that the number

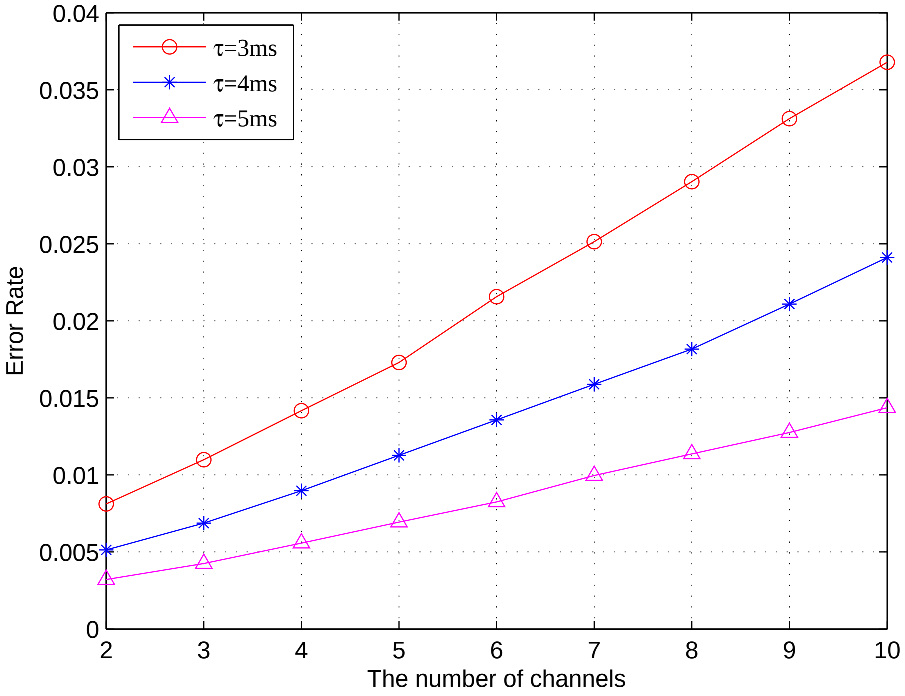

Figure 5.5: The effect of false alarm probability on the residual idle time vs. the number of channels.

of spectrum handoff reduces as the residual idle time of the target channel increases, which in turn indicates that the number of spectrum handoff reduces as the number of sensed channel increases.

5.4.2 The Effect of Error Rate

In the following, to provide a better understanding on how the proposed sequential sensing based spectrum handoff scheme behaves, the sensing performance is evaluated by plotting the error rate $E[\Delta_t]/t_{i_j}$ as a function of the number of channels for different sensing time $\tau \in \{3\text{ms},4\text{ms},5\text{ms}\}$. As shown in Figure 5.5, it is clear that the error rate is always below 0.1, which indicates that the error due to false alarm probability is small. As expected, the larger the sensing time, the lower the error rate is. This is true because the false alarm probability is a decreasing function of sensing time if both the SNR and target detection probability α are fixed. Moreover, the error rate increases as the number of sensed channels increases. As discussed in Section 5.3, although false alarm happens on channels $i_{j_1}, i_{j_2}, ..., i_{j_k}$, only the channel with maximum residual idle time will affect the transmission time. Thus, as the number of sensed channels increases, more channels will experience false alarm. Consequently, the maximum residual idle time of the false alarm channel defined by Eq.(5.28) representing the error will increase.

5.4.3 Complexity Evaluation

One way to find the optimal sensing order is to exhaustively search over all the possible sensing orders. The complexity is calculated by counting the number of times that the residual idle time at a specific channel is computed. Note that for each stage, the residual idle time is calculated once, hence, for each possible sensing order, the computational complexity is N. There exist $N!$ all possible sensing orders, therefore, the overall computational complexity of the exhaustive search for all the SUs is $O(MNN!)$.

For the sequential sensing based spectrum handoff approach proposed in this work, the author determines the optimal sensing order using DP, the computational complexity is analyzed as follows. At stage N, there exist $\binom{N}{N-1}$ states, the computational complexity is $O(\binom{N}{N-1})$. At stage k, $\Omega_k = \{i_1, i_2, ..., i_k\}$ has been sensed, thus there are $\binom{N}{k}$ states and each state $\Omega_k = \{i_1, i_2, ..., i_k\}$ has $N - k$ possible transitions to stage $k + 1$. The computation of each state is $O(k)$, so the total computational complexity at stage k is $O(k\binom{N}{N-k})$. Thus the computational complexity by performing sequential sensing over all the N channels in the system using DP (this method is referred to as

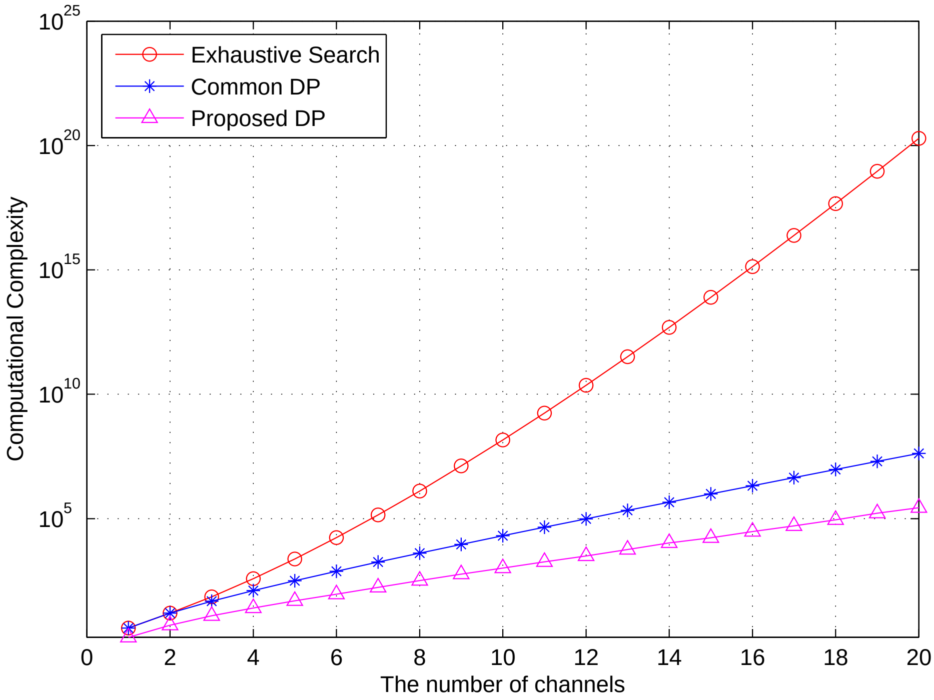

Figure 5.6: Computational complexity for the exhaustive search, common DP and the proposed DP method.

common DP) is

$$\mathcal{O}(M\sum_{k=0}^{N}k\binom{N}{N-k})=\mathcal{O}(MN2^{N-1}) \tag{5.30}$$

Moreover, in order to reduce the sensing overhead and computational complexity, for each SU, the sequential sensing is performed only over the candidate channels. Therefore, for the proposed method using DP, the computational complexity is further reduced to $\mathcal{O}(\sum_{i=1}^{M}N_i2^{N_i-1})$. As illustrated in Figure 5.6, the proposed DP approach is much simpler than the exhaustive search and the common DP approach.

5.5 Conclusions

In this chapter, the author has studied the design of sequential sensing based spectrum handoff strategy in multiple users CRNs. Most of the prior work on sequential sensing only considers single or two-SU scenario. The author proposes a sequential sensing which can determine the optimal sensing order for each SU as well as the best target channel for spectrum handoff by Dynamic Programming (DP). In addition, to reduce the heavy sensing complexity, candidate channels are selected for each SU, which jointly considers the following factors: 1) maintain the idle probability high; 2) keep the sensing overhead and computational complexity as low as possible; 3) avoid collision with other SUs. Through the comparison between the proposed sequential sensing based spectrum handoff scheme and conventional sequential sensing [3], it can be verified that the proposed scheme is more effective in improving the system performance by increasing the residual idle time which in turn reduces the number of spectrum handoff. Moreover, the proposed DP method can significantly lower the computational complexity compared with exhaustive search and common DP.

Chapter 6

Conclusions and Future Work

One major characteristic of CRN is that it enables the cognitive radio to sense the information from the radio environment in order to find out the idle spectrum at a specific time or location. Then the SUs can adjust its operating parameters so as to use the spectrum efficiently without causing harmful interference to the PUs. Thus, cognitive radio has to perform spectrum management which consists of four major parts: spectrum sensing, spectrum sharing, spectrum decision, and spectrum handoff. In this thesis, the author addresses some challenges of spectrum management in CRN in order to enhance the system performance in terms of the achievable throughput for SUs while maintaining a high protection to PUs. In this chapter, the author concludes the dissertation by summarizing the key contributions and proposing some possible directions for future research work.

6.1 Summary of Contributions

This dissertation presents novel ideas and models on the design and analysis of spectrum management in CRN that optimize the system performance by either maximizing the achievable throughput for the SUs or minimizing the cooperation overhead subject to protect the PUs. In Chapter 3, to reduce the cooperation overhead, a cluster-based adaptive sensing and access scheme is developed. In Chapter 4, a MAC protocol design with Fast Spectrum Sensing (FSS) is proposed to provide more protection to the PUs. While in Chapter 5, the author studies a sequential sensing based spectrum handoff strategy to determine the optimal sensing order as well as the optimal target channel. The major contributions addressing each of these issues are summarized as follows:

6.1.1 Cluster-Based Adaptive Multi-Spectrum Sensing and Access

In chapter 3, the author explores a cluster-based adaptive multi-spectrum sensing and access strategy for a CRN, in which the SUs seeking to access the channel can select a set of channels to sense and access with adaptive sensing time. The cooperation overhead is mainly dominated by the sensing time, number of SUs and the sensed channels. As the number of SUs and sensed channels increases, the overhead will increase dramatically. Thus, it is motivated to explore the number of sensed channels and the achievable system performance. To address this high cooperation overhead problem, the author proposes a cluster-based sensing and access scheme, in which synchronization and cooperation only happen among the SUs who belong to the same cluster and no FC is needed. By doing so, an adaptive sensing time scheme is used by each cluster. Consequentially, the sensing overhead will be significantly reduced.

The overall objective is to jointly design the sensing and access strategy to maximize the utility of the SUs so as to balance the twin requirements of keeping the sensing overhead minimal and achieving maximum throughput. The sensing strategy specifies the number of channels that should be sensed. The access strategy determines the expected number of channels that can be utilized and shared by the SUs under the interference power constraints to the PU and the transmitting SUs. Moreover the author explicitly calculates the expected number of channels that are detected to be idle, or being occupied by the PUs or being occupied by the transmitting SUs. Spectrum sharing with the PU and the transmitting SUs is accomplished by adapting the transmission power to keep the interference to an acceptable level.

The main insight of the cluster-based scheme is to derive an utility function which represents the tradeoff between the requirement to increase the achievable throughput and the desire to reduce the sensing overhead. The optimal number of channels that ought to be sensed is obtained numerically, such that the utility can be maximized. Simulation results illustrate that the proposed strategy outperforms ASA [2] and SSS [3].

6.1.2 MAC Spectrum Sensing Protocol Design

The author next looks into the MAC sensing-transmission protocol design with more protection to PUs in Chapter 4. Owing to the random arrival of the primary packet, and the PU will transmit without sensing and contention whenever it becomes active, severe interference may occur with the SU who is transmitting on the channel. Thus, how to incorporate the Fast Spectrum Sensing into the protocol design is the key point in enhancing the protection to the PU.

The author considers two kinds of spectrum sensing: NSS and FSS in the MAC sensing-transmission protocol design. NSS is performed before channel contention to provide up-to-date sensing information. FSS is carried out after channel contention to very quickly detect the return of the PU so as to avoid severe interference. Inserting FSS into the MAC protocol design has significant impact in reducing the collision probability and improving the PU protection. Furthermore, it also overcomes the shortcoming of OSA-MAC by providing up-to-date sensing information. In this work, it does not assume perfect sensing, and treats the mis-detection as one part of collision probability, which is one improvement over [36] [37] with perfect sensing assumption.

To realize the proposed design protocol, theoretical formulae for the normalized achievable throughput-collision tradeoff and the utility-collision tradeoff for the SU are derived. Furthermore, quantitative method has been developed to obtain the optimal value of the frame duration, such that the utility of the SU can be maximized.

6.1.3 Sequential Sensing Based Spectrum Handoff

In CRN, the SUs can opportunistically utilize the licensed channel if it is detected unoccupied by the PU. However, the SU is required to vacate the channel when the PU appears and determine a new suitable channel to resume its unfinished transmission. This process is called spectrum handoff. To implement spectrum handoff, the fundamental problems are required to be addressed: 1) How to select the optimal target handoff channel? 2) How to discover the new handoff channel as soon as possible?

In this work, the author has studied the design of sequential sensing based spectrum handoff strategy in multiple users CRNs. Dynamic Programming (DP) search can be used to find the optimal sensing order as well as the best target channel for each SU, such that the number of handoff during the SU communication is reduced. Most of the prior work on sequential sensing only considers single or two-SU scenario, in this work, multi-SU is considered. However, in the meantime, one should note that the complexity of DP search increases dramatically as the number of sensed channels increases. Thus, to reduce the heavy sensing complexity, a set of candidate channels is selected for each SU, which exploits the tradeoff between the spectrum opportunity, sensing overhead and computational complexity. The following three factors are jointly considered when selecting the candidate channels: 1) maintain the idle probability high; 2) keep the sensing overhead and computational complexity as low as possible; 3) avoid collision with other SUs. The results verified that the proposed scheme is more effective in improving the system performance by increasing the residual idle time which in turn reduces the number of spectrum handoff. Moreover, the proposed DP method can significantly lower the computational complexity compared with exhaustive search and common DP.

6.2 Future Research Directions

In this thesis, several main challenges of spectrum management in CRN are addressed. The following are recommended for future research directions.

6.2.1 Investigate the Heterogeneities of Channels and SUs

As discussed in Section 1.2.1, the characteristics of SUs are heterogeneous in terms of the noise power, received SNR, geographical location and the sensing quality. Moreover the PU channels are also heterogeneous in terms of channel idle probability and channel capacity. A CRN with multi channels and multi SUs should consider two stages while performing spectrum sensing: 1) How to assign the SUs to sense the most suitable channel; 2) How achievable is the optimal sensing performance? In all of the work illustrated in Chapters 3-5, the author only focuses on the second stage. Owing to the heterogeneous characteristics of both the PU channels and the SUs, different assignment policies will result in different sensing performance. Thus, one of the future direction may study the spectrum sensing and allocation problem under a more practical scenario where the heterogeneous characteristics of both SUs and the PUs channels are taken into consideration. Note that different channels have different characteristics e.g. channel idle probabilities, channel gains and channel capacity. Meanwhile, different SUs have different sensing qualities due to different energy detection thresholds and received SNR. Thus how to assign the available channels to the most suitable SUs, taking all the above factors into consideration, is a significant problem. One possible approach to study this problem is to develop an optimal matching between the available channels and the SUs. By defining weight value w_{ij} as the achievable throughput for the SU, the spectrum allocation and sensing problem can be formulated as a Maximum Weight Matching (MWM) problem, the objective of which is to maximize the achievable throughput for the SUs while satisfying the spectrum allocation constraints.

Given the CRN, let π^* denote the optimal spectrum allocation and sensing scheme such that the system weighted sum is maximized. Let $x(i)$ denote the channel that is assigned to SU i. Moreover, the binary variable x_{ij} indicates whether $x(i) = j$. Then the spectrum allocation problem with decision variable $\{x_{ij}\}$ can be formulated as follows:

Problem P1

$$\begin{aligned} \max \quad & \sum_i \sum_j x_{ij} w_{ij} && (6.1) \\ s.t. \quad & \sum_i x_{ij} \leq 1, \;\; for\; 1 \leq j \leq N \\ & \sum_j x_{ij} \leq 1, \;\; for\; 1 \leq i \leq M \\ & x_{ij} \in \{0,1\} \end{aligned}$$

where the first constraint specifies that one channel can only be assigned to one SU while the second constraint means that one SU only requires one channel for data transmission for each time. Note that it is also possible for a SU to simultaneously access two or more channels to transmit their data, however, this case is not considered in this model.

From the above MWM problem formulation, in order to obtain such optimal matching, all possible matchings between the primary channels and SUs have to be searched and compared, which introduces significant latency. As the number of primary channels or SUs increases, more complexity will be brought about simultaneously. Thus one of the main challenges of this problem is to develop an algorithm with lower complexity.

6.2.2 Cluster-Based Cooperative Spectrum Sensing

Cooperative spectrum sensing (CSS) is proposed to address the sensing performance degradation due to fading and shadowing. How to appropriately assign a set of SUs cooperatively in sensing a set of PU channels in order to enhance the performance of CSS while keeping the interference to the PUs at an acceptable level? This is the so called CSS problem. Thus to study CSS, the following problems have to be addressed: 1) How many SUs should cooperate in spectrum sensing? 2) How many PU channels should be sensed by a set of SUs? 3) How to model the heterogeneities of both the SUs and the PUs channels? Motivated by the future work (one-by-one case) in Section 6.2.1, another direction for future work is to exploit the CSS problem (multi-by-multi case) under a scenario where the heterogeneous characteristics of both SUs and PUs are considered.

The CRN can be partitioned into clusters and the members belonging to the same cluster will cooperate in sensing the same set of channels. The fundamental tradeoff in this proposed cluster-based CSS problem lies in the following: The more PU channels are sensed by the cluster, the more spectrum opportunity can be discovered. However, note that when less SUs participate in cooperative sensing, it will result in a small cluster size and low sensing accuracy. This is because that the PU signal only covers part of the whole CRN, not all the SUs can detect the channel status. Moreover, as more channels are sensed, less sensing time can be allocated to each channel, which further deteriorates the sensing quality. The target of the CSS is to tackle the tradeoff between sensing accuracy and the transmission opportunity. One possible approach for this cluster-based CSS problem is to develop a maximum weight one-sided biclique problem to obtain a proper assignment policy $a = \{a_1, a_2, ..., a_L\}$ and $\{b_1, b_2, ..., b_L\}$, where a_i is the number of members in cluster i, who cooperates in sensing b_i PU channels. Moreover, due to the heterogeneities of PUs channels and SUs being considered, a more detailed result that accurately indicates which SU should sense which channel can be achieved.

A bipartite graph $G(X \cup Y, \varepsilon)$ is a graph whose vertices can be divided into two disjoint sets, such that every edge in ε connects a vertex in X to one in Y; that is, X and Y are each independent sets [152]. In CRN, the topology of CRs and PUs channels can be represented as a bipartite graph $G(X \cup Y, \varepsilon)$. Vertex set X corresponds to the CRs in the network, and set Y contains the sensed PU channels. An edge exists between (x, y), $x \in X$ and $y \in Y$, if and only if the CR x is within the sensing range of the PU channel y. Thus CR x can correctly detect the PU channel y status. One example can be shown in Figure 6.1(a). The connectivity graph of a CRN is represented as a bipartile graph $G(X \cup Y, \varepsilon)$, with $X = \{CR_1, CR_2, CR_3, CR_4, CR_5, CR_6, CR_7\}$ and $Y = \{PU_1, PU_2, PU_3, PU_4, PU_5, PU_6\}$ as illustrated in Figure 6.1(a). A complete bipartite graph (biclique graph) $Q(S, B)$ is a bipartite graph such that for any two vertices $x \in S$ and $y \in B$, there has one edge in Q. For CRN, a biclique graph $Q(S, B)$ can be extracted from its bipartite graph $G(X \cup Y, \varepsilon)$. This biclique graph represents a cluster of nodes in S that cooperates in sensing all the channels in B. In Figure 6.1(b),

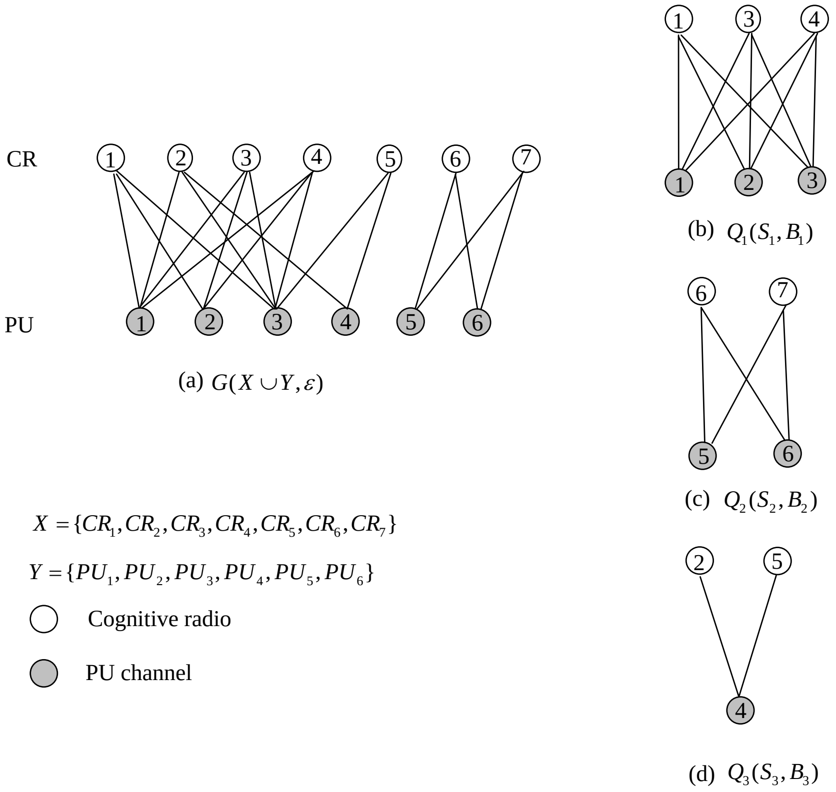

Figure 6.1: The connectivity graph represented by bipartile graph in (a), and (b)-(d) are the biclique graphs extracted from the bipartite graph in (a).

Figure 6.1(c) and Figure 6.1(d), three possible bicliques graphs extracted from Figure 6.1(a) are shown. The main design objective of CRN is to improve the performance of CRs in terms of achievable throughput without causing harmful interference to the PUs. Thus, in order to provide sufficient protection to the PUs, the cluster size cannot be too small. A lower bound on the number of cooperative CRs can be set while maximizing the throughput for the SUs. This is so called Maximum Weight One-Sided Biclique Problem for Cluster-Based CSS Assignment policy. In order to provide sufficient protection to the PUs, it is required to keep the detection probability above a given threshold Q_{th}, that is $Q_{d,j} \geq Q_{th}$. Hence

$$1 - \prod_{i=1}^{m} (1 - P_{d,(i,j)}) \geq Q_{th} \Longleftrightarrow m \geq \lceil \frac{\log(1 - Q_{th})}{\log(1 - P_{d,j}^{min})} \rceil = \bar{m}$$

where $\lceil z \rceil$ is the ceiling functions which returns the smallest integer not less than z. $P_{d,j}^{min}$ is the minimum detection probability among all the cooperative CRs. Observe that the detection probability is monotonically increasing with regards to the SNR γ_{ij} for a fixed sensing time, thus

$$P_{d,j}^{min} = \min\{P_{d,(i,j)} | \gamma_j^{min} = \min_{1 \le i \le m}\{\gamma_{ij}\}\} \tag{6.2}$$

$\bar{m}$ is the desired least number of cooperative CRs in order to provide sufficient protection to the PUs. Moreover, all the heterogeneous characteristics in both PU channels and CRs can be incorporated into the weight definition of the Maximum Weight One-Sided Biclique Problem, as

$$R_k(S_k, B_k) = \sum_{CH_j \in B_k} \frac{T-\tau}{T} P(\mathcal{H}_j) C_j (1 - Q_{f,j}^k(S_k, B_k)) \tag{6.3}$$

where $P(\mathcal{H}_j)$ denotes the idle probability for channel j, and C_j is the transmission capacity for channel j. S_k denotes the set of CRs in cluster k, $|S_k| = a_k$, and B_k is the set of sensed PUs channels in cluster k, $|B_k| = b_k$. Then $Q_{f,j}^k$ is given by

$$Q_{f,j}^k(S_k, B_k) = 1 - \prod_{CR_i \in S_k} (1 - P_{f,(i,j)}(\tau / b_k)) \tag{6.4}$$

Thus the total throughput which can be yielded for cluster k is

$$R_k(S_k, B_k) = \sum_{CH_j \in B_k} \frac{T-\tau}{T} P(\mathcal{H}_j) C_j (1 - Q_{f,j}^k(S_k, B_k)) \tag{6.5}$$

Based on above definition, to evaluate the cluster-based CSS assignment problem is the same as to extract some biclique graphs $Q(S_k, B_k)$ from the bipartite graph $G(X \cup Y, \varepsilon)$, while satisfying a lower bound on the number of cooperative CRs. Such a formulation is related to Maximum Weight One-Side Biclique Problem. In the problem, this corresponds to impose a lower bound on each $|S_k|$ and maximize the total throughput for all the clusters. Given the CRN, the aim is to determine the set of $a = \{a_1, a_2, ..., a_L\}$ and $\{b_1, b_2, ..., b_L\}$, where a_i is the number of SUs assign to sense b_i channels, such that the achievable throughput for SUs is maximized subject to provide sufficient protection to PUs.

Solving the Maximum Weight One-Side Biclique Problem is NP-hard. When the number of SUs and PU channels increases, the complexity to find the optimal solution will grows exponentially. Initially, $X_1 = X$ and $Y_1 = Y$. For k cluster, $X_k = X_{k-1}/S_{k-1}$ and $Y_k = Y_{k-1}/B_{k-1}$. The algorithm to yield the maximum weight biclique graph $Q_k(S_k, B_k)$ from the bipartite graph $G(X_k \cup Y_k, \varepsilon_k)$ is demonstrated as follows: Initially B_k is empty, and S_k is set to all the SUs, that is $S_k = X_k$. In l iteration, the channel y_l, $y_l \in Y_k/B_k$, that is able to be sensed by the largest number SUs in S_k, i.e., the channel with the highest connectivity degree $deg(y_l)$ in S_k, then add y_l to B_k and remove the SUs who cannot sense the channel y_l from S_k. If more than one channels have the same highest degree, the one that can bring more throughput increase will be chosen. Then calculate the update achievable throughput and record in vector Γ_k according to the following rules:

$$B_k \leftarrow B_k \cup y_l \qquad\qquad S_k \leftarrow S_k \cap \psi_{y_l}$$

$$R_k(S_k, B_k) = \sum_{CH_j \in B_k} \frac{T-\tau}{T} P(\mathcal{H}_j) C_j (1 - Q_{f,j}^k(S_k, B_k))$$

where ψ_{y_l} denotes the set of SUs that can sense PU channel y_l. Then repeat this process, until either one of the following conditions is satisfied 1) $|S_k| \leq m_k$, where m_k is the desired least number of cooperative SUs for cluster k; 2) the remaining channel in Y_k is empty. Thus detailed study and analysis of the Maximum Weight One-Side Biclique algorithm can be carried out in the future.

6.2.3 MAC Protocol Design for Multi-User and Multi-Channel

The analysis in Chapter 4 gives PU more protection under a CRN with 3 SUs and 1 PU. Future work in this direction may involve the extension of the system to more PUs and SUs. To investigate how the performance of the proposed protocol will be if different primary traffic models are considered is an interesting research direction.

Author's Publications

Journals

- **Wenjie Zhang**, Chai Kiat Yeo, Yifan Li, "MAC Sensing-Transmission Protocol Design with More Protection to Primary Users", IEEE Transactions on Mobile Computing, vol. 12, no. 4, pp. 621-632, Apr 2013.
- **Wenjie Zhang**, Chai Kiat Yeo, "Throughput and Delay Scaling Laws for Mobile Overlaid Wireless Networks", Elsevier Journal of Network and Computer Applications (JNCA)", vol. 35, issue 2, pp. 657-667, Mar 2012.
- **Wenjie Zhang**, Chai Kiat Yeo, "Joint Iterative Algorithm for Optimal Cooperative Spectrum Sensing in Cognitive Radio Networks", Elsevier Computer Communications, vol.36, issue 1, pp. 80-89, Dec 2012.
- **Wenjie Zhang**, Chai Kiat Yeo, "Cluster-Based Adaptive Multiple-Spectrum Sensing and Access in Cognitive Radio Networks", to appear in Wireless Communications and Mobile Computing, 2012.
- **Wenjie Zhang**, Chai Kiat Yeo, "Optimal Sequential Spectrum Sensing Based Spectrum Handoff in Cognitive Radio Networks", to appear in Elsevier Computer Networks, 2013.
- **Wenjie Zhang**, Chai Kiat Yeo, "Optimal Non-Identical Sensing Setting for Multi Channels in Cognitive Radio Networks", submitted to Elsevier Computer Communications (second revision), 2012.

Conferences

- **Wenjie Zhang**, Chai Kiat Yeo, "Throughput-Delay Scaling for Two Mobile Overlaid Networks", IEEE GlobeCom, Miami, USA, Dec 2010.
- **Wenjie Zhang**, Chai Kiat Yeo, "Optimal Non-Identical Sensing Setting for Multi-Channel Cooperative Sensing", IEEE International Conference on Communications (ICC), Tokyo, Japan, Jun 2011.
- **Wenjie Zhang**, Chai Kiat Yeo, Yifan Li, "Optimal Spectrum Allocation Considering the Heterogeneity of Channel and Secondary Users", IEEE Consumer Communications and Networking Conference (CCNC), Las Vegas, USA, Jan 2012.

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