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On spectrum allocation strategies in Cognitive Radio Networks

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On spectrum allocation strategies in Cognitive Radio Networks

by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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Ames, Iowa

2012

DEDICATION

To my beloved mother and father, my beloved wife, and all my family members.

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ACKNOWLEDGEMENTS

Finally, my deep thanks to my brother Thabet and my sister Zaynab who always support me with all possible means, especially during my graduate study.

My lovely mother, my father, and my wife: I love you more than you imagine ...

ABSTRACT

Due to the temporal and spatial underutilization of licensed spectrum bands, as well as the crowdedness of unlicensed bands, a new spectrum access paradigm has been recently proposed namely, Cognitive Radio (CR). CR enables users to adjust their transceivers' frequencies depending on the availability of licensed frequency bands which are otherwise unused by their licensees, called Primary Users (PUs). Thus, unlicensed wireless users, called Secondary Users (SUs) can dynamically and opportunistically access unused licensed bands in order to improve their throughput and service reliability. Whenever the licensed users, or the PUs, become active, SUs must vacate their bands. This dissertation is concerned with the operation of Cognitive Radio Networks (CRNs), and deals with four important problems.

First, a performance model to study heterogeneous channel access in CRNs is presented. In this model, there are two types of licensed channels, where one type has a larger bandwidth, and hence a higher service rate for SUs. Therefore, SUs prefer to use such channels, if available, over channels in the second type which have a lower service rate. SUs may also switch from the second to the first type of channels when they become available, even if their current channels are still available. We also model the SUs' sensing process, and derive several SUs' performance metrics including average waiting time. Numerical results show that our proposed operational model outperforms a baseline model that does not support prioritized access.

Second, we introduce a low overhead scheme for the uplink channel allocation within a single cell of CRNs operating as Wireless Mesh Networks (CR-WMNs). The scheme does not rely on using a Common Control Channel (CCC). The proposed mechanism is based on the use of Physical Layer Network Coding (PNC), in which two (or three) Secondary Users (SUs) who are requesting uplink channel allocation are allowed to transmit synchronously over a

randomly selected channel from a set of available channels, and without coordination. A Mesh Router (MR) which is listening to these transmissions, and is in charge of channel allocation, can detect up to 2 (or 3) requests, on the same channel due to the use of PNC, and replies back with a control packet which contains information about channel assignment. Our proposed mechanisms significantly outperform traditional schemes that rely on using one CCC, or do not use PNC, in terms of channel allocation overhead time.

Third, we also propose to enable SUs to recover their packets which collide with PUs' transmissions when a PU becomes active for two scenarios, based on the received phase shifts. When a collision occurs between an SU and a PU transmitters, the SU's receiver considers the PU's transmission as an interference, and hence, cancels its effect in order to recover its corresponding received packet's signals. Recovering collided packets, instead of retransmitting them saves transmitters' energy. Numerical results show that a high percentage of energy can be saved over the traditional scheme, in which our packets recovery mechanisms are not employed.

Finally, we propose a novel multicast resilient routing approach to select primary and backup paths from an SU source to SUs destinations. Our approach employs a multilayer hyper-graph, in order to model the network, e.g., channels. The primary paths to destination SUs are selected to minimize the end-to-end delay which takes into consideration channels switching latency and transmission delay. To protect the multicast session, we find a backup path for primary path, if feasible, such that these two paths are shared risk hyper-edge disjoint, in order to prevent a concurrent failure for these two paths, when the corresponding PU for this hyper-edge becomes active. Our simulation results show that increasing the number of available channels, increase the number of feasible primary and backup paths, and the maximum path delay decreases almost linearly.

CHAPTER 1   Introduction

In this chapter, we introduce Cognitive Radio Networks (CRNs), its importance to wireless networks communication, the required new protocols to improve its efficiency, and its research challenges.

1.1   Cognitive Radio Networks Technology

Recent statistical studies by FCC show that some frequency bands are crowded while others are underutilized [1], as shown in Figure 1.1. Also, the FCC study shows temporal and geographical variations in the utilization of the assigned spectrum which range from 15% to 85%. Therefore, researchers are motivated to propose new approaches which enable unlicensed spectrum users, known as Secondary users (SUs), to utilize the underutilized spectrum in both time and geographic dimensions, when licensed users, known as Primary Users (PUs), are idle.

As a result, due to temporal and spatial underutilization of licensed spectrum bands, as well as the crowdedness of unlicensed bands, a new spectrum access paradigm has been recently proposed namely, Cognitive Radio (CR) [42]. CR enables users adjust their transceivers' frequencies depending on the availability of licensed bands which are otherwise unused by their licensees [43], [44]. Thus, unlicensed wireless users, call them Secondary Users (SUs), can dynamically and opportunistically access unused licensed bands in order to improve their throughput and service reliability. SUs must vacate their bands, whenever licensed users, call them Primary Users (PUs), become active.

CR technology has many challenges, such as coexistence with legacy networks and existing network's protocols. Therefore, new novel protocols need to be developed, to empower CR users with smart and agile capabilities, where these protocols must be aware about CRNs
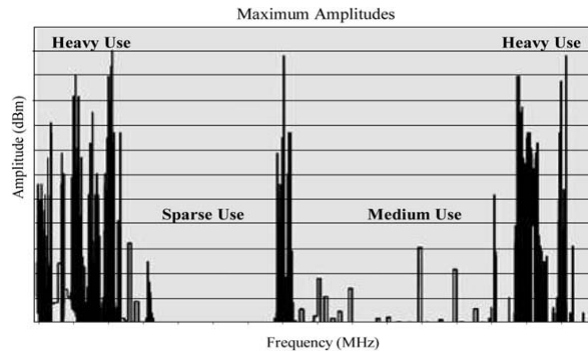
Figure 1.1: Spectrum Utilization [42].

challenges, as explained in the next section, Section 1.2.

1.2 Cognitive Radio Networks Challenges

CRNs have many challenges related to spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing. Some of these challenges are as follows:

- **Common Control Channel (CCC) problem**: spectrum allocation and SUs coordination require an assigned channel, which is only accessed by SUs to exchange control information in the network. Novel and scalable CCCs protocols are required to enhance SUs agility, neighbors discovery, information exchange, and routing decision. Some CCCs protocols are proposed for spectrum sharing in [2, 3, 4].

  Usually, networks such as CR-WMNs have heterogeneous channels availability. Therefore, the probability to find a single CCC such that it is available for a set of SUs is low [16]. A novel approach is proposed in [17], to allocate channels in CR-WMNs, without using CCCs. Their approach allocates spectrum bands for MCs such that the uplink and downlink connectivities are established with the network backbone, through their parent MRs. These connectivities must meet a predetermined SINR threshold and transmission power.

  On the other hand, the allocated CCC(s) may become unavailable when a PU return to access this channel. An efficient recovery control channel (ERCC) design is proposed [18] to address this problem. Their scheme is a heuristic and distributed approach,

in which each SU maintains a common available channels' list with its neighbors over network operation time. When a CCC with other node(s) becomes unavailable, due to PU activity, the SU can re-establish the CCC fast, by referring to maintained common available channels list.

- **Performance modeling**: A CRN is characterized by its dynamic operation and probabilistic resources availability. Hence, modeling the network users activity including PUs, SUs, and channels availability, requires sophisticated models. Modeling network performance is important to guarantee QoS requirements such as SUs throughput, SUs' maximum allowed interference level to PUs, SUs admission and blocking probabilities to the network [19, 20, 21].

- **Network connectivity:** in large scale wireless networks, network connectivity is an important performance metric. Neighbor nodes do not necessarily have the same available channels. Indeed, new novel protocols are required to keep the network connected during its operation [22, 23].

- **Cross layer design:** CR protocols design necessitates considering a set of network stack layers functionalities together. For example, spectrum management tasks such as spectrum sensing in physical layer and spectrum handoff require a cooperation between different network layers [42].

- **Channels heterogeneity**: due to heterogeneous available channels in CRNs. New schemes need to be developed, e.g., to construct network routing paths, and channels usage scheduling between SUs. For instance, multi-cast routing and channel allocation in CR-WMNs, require channel allocation algorithms which consider channels heterogeneity and switching latency [24].

- **Packets collision**: When a channel's licensed user, PU, becomes active, it transmits over its channel without sensing whether it is being used by an SU. As a result, the SU's transmission collides with that of the PU's, and packets are corrupted, and need to be retransmitted.

- **Multicast routing and protection**: CRNs routing is different from traditional networks [33, 34, 35], because selecting routes depends on the E2E delay which includes the transmission times and channels switching delay. It also requires sensing mechanism to detect available channels. Protecting a multicast session is crucial, especially in CRNs routes may fail due to fluctuations in channels availability besides the reasons in traditional wireless networks.

1.3   Wireless Mesh Networks

A Wireless Mesh Network (WMN) is a clustered topology which consist of a set of mesh clients, mesh routers, and gateway(s), as shown in Figure 1.2. Each cluster is a Mesh Router (MR), and a set of Mesh Clients (MCs). A MR is responsible for relaying their mesh clients' packets over multi-hops through other MRs to the gateway. MR is also responsible for intra-cluster communication. However, MCs can only communicate with their designated MR for either uplink or downlink communication.

Each mesh cluster may run a different MAC layer protocol such as IEEE 802.11 (for wireless local area networks), or IEEE 802.16/WiMAX (for wireless broadband communication). Therefore, WMNs play a crucial role in our today's life applications which require either long or short wireless communication ranges.

WMNs are able to support several applications which can not be solved using other known wireless networks, such as cellular networks, ad-hoc networks, wireless sensor networks, or even access points with an IEEE 802.11 protocol. Some of these applications, which are solvable by deploying WMNs, are as follows [5]:

- Broadband home networking: home broadband is an IEEE 802.11 WLAN. This network type has some problems such as Access Point (AP) localization, which aims to solve dead zones. MR can adjust its transmission power to cover dead zones. Also, MRs allow two nodes in neighboring clusters to communicate through their parents, instead of routing their packets to the network backbone.
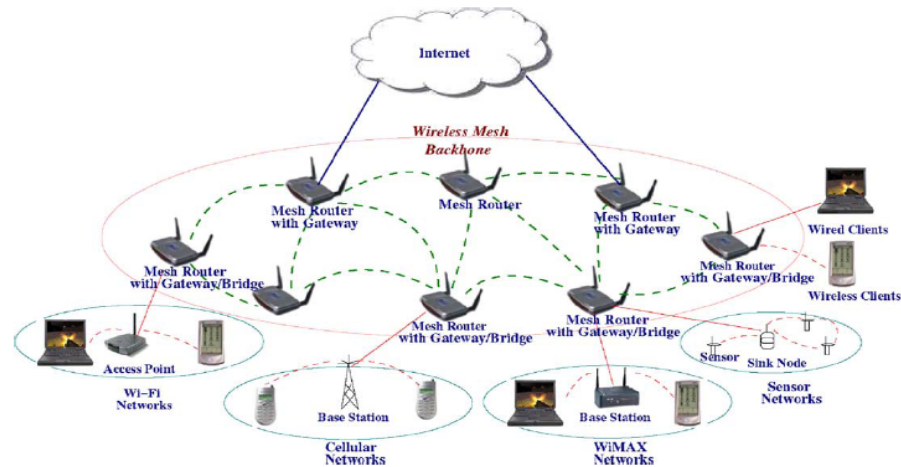
Figure 1.2: WMNs architecture [5].

- Enterprise networking: it may connect one building or multiple buildings such as hotels. If IEEE 802.11 APs are used in rooms, a wired Ethernet is used to connect these sub-networks. Therefore, the network is not protected against links failures, congestion, and transmission delay. Deploying WMNs solves these problems, since MRs which are spatially close to each others can communicate directly. Therefore the inter-cluster communication delay is decreased.

- Health and medical systems: used in medical centers, or health monitoring. Health applications require high transmission bandwidth, due to images and frequent reports from different rooms in a medical center. WMNs are an excellent solution for medical applications in terms of efficiency, cost, scalability, and because of the reasons which are explained above.

There are other applications for WMNs, such as disaster recovery to re-establish network connection in a city, security surveillance systems, and Building automation. It is worth mentioning that MAC layer protocols design for WMNs have some differences compared to the classical wireless networks. Because new design requirements must be considered, to have robust and scalable WMNs [5], such as supporting mobility for mesh clients such that the network can reconfigure itself accordingly and in a fast manner .

1.4   Cognitive Radio Wireless Mesh Networks (CR-WMNs)

We have mentioned in Section 1.3 that WMNs have emerged in many applications in our life. Therefore, integrating CR technology with WMNs, increases its opportunity to utilize unused spectrum bands in both time and geographic dimensions [15]. Traditional WMNs with one channel transmission are different from CR-WMNs which work over multiple available channels at the same time. Therefore, new protocols have been proposed recently, in order to facilitate the use of CR technology in WMNs, call it CR-WMNs. So, both MRs and MCs should be integrated with CR capabilities [12, 13, 14], which may increase their software and hardware complexities. This integration task is not trivial because many issues must be carefully considered to eliminate any possibility of degrading PUs performance in the same locality. For instance, some of these issues are spectrum sensing, spectrum management, transmission power adjustments by SUs, channels selection, transmission scheduling, routing management based on a single/multi interfaces transmission between MRs, end-to-end delay metric, and throughput.

In [6] a cognitive wireless mesh network concept, called CogMesh is introduced to implement seamless integration of CR capabilities on the top of ordinary WMNs, in which heterogeneous networks such as in WMAN, WPAN, and WLAN. CogMesh introduces self organizing, self optimizing, and self healing features for unlicensed users in wireless networks. Their protocol depends on a knowledge of the surrounding circumstances, e.g., spectrum usage, and interference range.

Multicast transmission in CR-WMNs, may have longer transmission delay than classic WMNs, due to a heterogeneous channels availability between the transmitter node, MR, and the receiver nodes, MR's clients. Therefore, an assisted multicast scheme is proposed [7] to reduce multicast time, and to increase the overall throughput. Their proposed method, allows receivers in a multicast group to forward the received data to other nodes of the multicast group(s), and allows transmission of digital coded packets. Therefore, receivers belonging to different multicast groups can decode and extract their data concurrently.

Increasing capacity for CR-WMNs is a challenge, especially with large number of MCs. A

concurrent transmission protocol has been proposed [8] to allow more than two SUs, say k, and a PU to transmit their packets simultaneously, based on employing dirty paper coding [9] and superposition coding. Their scheme, allows concurrent transmissions within a given interference region, based on the Interference Channel with Degraded Message Sets (IC-DMS) model, which is proposed earlier in [10].

As mentioned earlier, channels heterogeneity is a challenge, which makes routing packets from a source to destination(s) a difficult task. Routing decision needs to consider many factors, such as common channels along the route between relay nodes, end-to-end delay, network connectivity, interference to concurrent routing sessions, and transmission power management. One routing solution is proposed in [11], called SAMER, which opportunistically routes traffic across paths with higher bandwidth availability and quality. This scheme constructs routing paths in run-time, and balances between long and short term routes, to achieve routing stability.

1.5   Contribution of Our Research

In this dissertation, we study four research problems in cognitive radio networks. The First problem we study CRNs is performance modeling under heterogeneous channel access, while considering users activities and events. The goal of our model is to improve SUs performance by reducing their average waiting time in the system, which is required to transmit their packets. In the Second problem, we study uplink channel assignment in CR-WMNs using Physical Layer Network Coding (PNC). We propose three schemes, which employ PNC. The goal of these schemes is to reduce network setup time overhead, which is required to allocate channels for SUs operating as mesh clients in a WMN cluster by their parent MR. In the third problem, we propose to enable SUs to recover their packets which collide with PUs' transmissions when a PU becomes active for two scenarios, based on the received phase shifts. Recovering the collided packets, instead of retransmitting them saves SU's transmitters' energy. The proposed protocol goal is to save energy over the traditional scheme, in which our packets recovery mechanisms are not employed. In the fourth problem, we propose a novel multicast resilient routing approach to select primary and backup paths from an SU source to SUs

destinations. We use a multilayer hyper-graph to model the network, e.g., channels. The objective when selecting a path from SU source node to a destination SU node is to minimize the end-to-end delay, which includes channels switching latency and transmission delay. The selected primary and backup paths, if feasible, are Shared Risk Hyper-Edge[1] ($SRHE$) disjoint, in order to prevent both paths from failing together, when the corresponding PU's channel for the hyper-edge becomes active.

The main contributions of this research are as follows:

- Modeling SUs performance for heterogeneous channel access in CRNs. The model considers SUs switching channels with priority selection. SUs which are currently being served by channels with a lower service rate, switch to channels with a higher service rate, if available, although their current channels are still available.

- Modeling SUs sensing event, to study sensing rate effect on SUs performance such as waiting time in the system. Our results show, if sensing rate is increased after a certain level, it does not have a significant improvement on SUs performance.

- Solving the problem of CCC allocation: three schemes are proposed in order to allocate the set of available channels to SUs within MR cluster. Our proposed schemes employ PNC technique, which reduces the network setup time overhead significantly. Most importantly, our schemes do not require CCC(s), therefore, CCCs allocation challenges are solved in this study.

- Recovering SU's packets that collide with a PU's packet when becomes active, in order to reduce the consumed energy due to retransmitting the collided SU's packets. SU's receiver considers the PU's transmission as an interference, and therefore, cancels its effect in order to recover its corresponding received packet's signals.

- Developing a novel multicast resilient routing approach to select primary and backup paths from an SU source to SUs destinations (a subset of network's SUs), and minimizing

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[1]A Hyper-edge is used to represent a set of SUs in the same geographical locality that have a common channel.

the maximum path delay. The primary and backup paths do not fail together, since they are $SRHE$ disjoint.

1.6 Dissertation Organizations

The rest of this dissertation is organized as follows. We review related work in Chapter 2. Performance Modeling of Heterogeneous Channel Access in Cognitive Radio Networks presented in Chapter 3. In Chapter 4, we present our proposed schemes for Uplink Channel Assignment in Cognitive Radio WMNs Using Physical Layer Network Coding. Interference-Based Packet Recovery for Energy Saving in Cognitive Radio Networks is presented in Chapter 5. In Chapter 6, a Resilient Multicast Routing in CRNs using Multilayer Hyper-graph Approach is presented. We conclude this dissertation and layout our future work directions in Chapter 7

CHAPTER 2   Related Work

2.1   Introduction

In this chapter, the literature related to our work is reviewed. In Section 2.2, the literature on modeling CRNs is reviewed. In Section 2.3, Common Control Channel (CCC) challenges and some related protocols are explained. In section 2.4, Physical layer Network Coding (PNC) is introduced. Collided packets recovery is presented in section 2.5. Finally, section 2.6 presents the related work for multicast routing in CRNs.

2.2   Unlicensed Users Performance Modeling

CRNs have many challenges such as spectrum sensing, management, mobility, allocation and sharing [45], [46]. Usually, SUs in CRNs have QoS performance requirements, e.g., throughput and maximum transmission delay. Evaluating these metrics is not a trivial task, due to the CRNs dynamic nature, e.g., due to PUs fluctuating activities which may interrupt SUs, and hence may need to access the channel multiple times just to finish one communication session. To evaluate these performance metrics, a few models have been proposed in literature. In [47] and [48], a Markovian model is proposed to analyze spectrum access with and without buffering for new and interrupted SUs requests, which is used to evaluate SUs mean waiting time, and the probabilities of blocking, interruption, forced termination, and non-completion. Results from these papers show that buffering SUs requests reduces SUs' blocking and non-completion probabilities, with a very small increase of forced termination probability. However, all channels in the network are assumed symmetric, and SUs' sensing overhead is not considered in this model.

In reference [49], a quasi-birth and death Markov chain with continuous time and state space model is proposed to improve SUs performance by distributing their flows to multiple wireless networks. However, due to the high complexity for this model, since the size of the state space is large, they proposed an approximation solution for this model as well. They proposed two admission control schemes for SU flows: 1) priority, 2) and no priority schemes. Users in this model are classified as follows: 1) PUs of a network, 2) PUs with two types of traffic, PU and CR flows, to reduce their cost, 3) and unlicensed users, SUs, which sense all channels in networks looking for spectrum holes. In both admission control schemes, if an SU is admitted to a network, it will not leave it until finishing its transmission as long as it is not interrupted by a PU arrival. Moreover, when a PU is back, it is assigned to any channel. Also, a Markov model for spectrum sharing between PUs and SUs is proposed in [50], where if SUs are interrupted, they are suspended and wait to access another channel in a call level queue. During the period of SUs suspension the packets generated by SUs are either delayed or discarded, and therefore the queue becomes two sub-queues, delay and discard queues. In this model, three metrics are evaluated: packet loss ratio, packet delay, and spectrum utilization and throughput. Results show that by increasing the SU suspension queue length, both packet loss ratio and throughput increase and packet delay decreases. However, all channels are assumed symmetric in terms of service rates for either PUs or SUs, and PUs arrival rates are assumed to be the same on all channels as well.

A queuing network model for spectrum sharing between PUs and SUs was introduced in [51], where a closed form solution for equilibrium system state was derived in the form of a generating function. The model studies PUs QoS degradation due to unreliable SUs spectrum sensing where an SU keeps on using the channel, although a PU has arrived to the same channel. The paper assumes that channels are symmetric in terms of service rate for PUs and SUs. Besides, an SU moves from its channel to another only when it is interrupted by a PU arrival.

2.3 Protocols for Common Control Channel (CCC)

In CRNs, channel allocation to SUs and MAC protocol design become more challenging due to sporadic channel availability, potential lack of SUs cooperation, or hardware limitations. SUs need to communicate to exchange channels information availability and transmission scheduling. For example, if a pair of SUs need to communicate, both SUs must tune to the CCC, in order to agree on a transmission time and which common available channel to transmit their packets over. Also, this applies for multi-cast transmission session, such as in CR-WMN router and its clients in the cluster. Apparently, by increasing the network size, scalable and robust techniques are required to reduce the complexity of CCC problem. Moreover, to minimize the used channels as CCCs by SUs, in order to save network resources and operation cost.

Hence, some methods are proposed in order to simplify coordination between transmitters and receivers, usually a single CCC [61], a set of common channels to all SUs [62], or multiple local control channels for SUs groups [63] have been proposed as solutions. However, one CCC may be difficult to find, and CCC can not be used for data communication. If CCC fails, coordination is compromised. Therefore, coordination techniques without using CCC have been proposed. In [64] a new MAC protocol for multi-hop Cognitive Radio Networks (CRNs) is developed to avoid using a CCC by dividing the total time into a set of intervals where each interval represents one of the available channels. In [65] a swarm intelligence method is proposed to dynamically find and manage control channels, since the CCC may be unknown at the first deployment time. Moreover, a probabilistic and deterministic methods to allocate channels to SUs at network setup time are proposed in [25], without using a CCC. On the other hand, fixed CCC will increase the cost and vulnerability especially in licensed spectrum bands. Also, a survry in [29] provides a comprehensive study about CCC design and challenges.

2.4 Physical Layer Network Coding (PNC)

Recently, a promising technique called Network Coding (NC) [66] is used to increase network throughput, which allows nodes in a network to combine packets when they are transmitted, especially when multicast transmission is used.

Digital Network Coding (DNC) requires packet combining at layer 2 or above, i.e., both packets must be received correctly and independently before combining and transmitting process [26], as shown in Figure 2.1. However, PNC allows packets to be transmitted to the receiver simultaneously, because PNC employs the additive nature of simultaneously received electromagnetic waves to perform coding operation, with suitable modulation and demodulation schemes [67], as shown in Figure 2.2. Therefore, PNC increases the network throughput more than DNC. Since, Figures 2.1 and 2.2 show that nodes N_1 and N_2 need 3 time-slots to complete packets exchange through relay node R, rather than 4 time-slots as in the traditional packet transmission scheduling. However, if PNC is employed, only 2 time slots are required to finish the packets exchange process.

Generally, using NC in CRNs allows the exchange of control information robustly and expeditiously [68]. In this report, PNC is employed in CR-WMNs to improve the SUs performance such as robust channels assignment to SUs within clusters, which will be introduced in chapter 4.
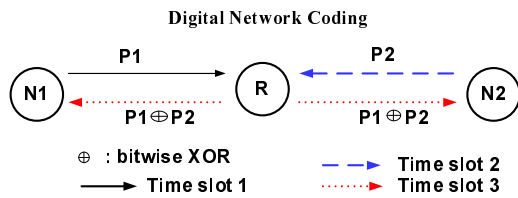
Figure 2.1: Digital Network Coding.
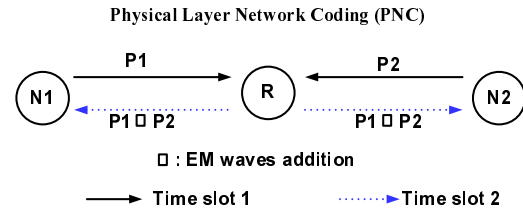
Figure 2.2: Physical layer Network Coding.

2.5 Collided Packets Recovery

Recovering collided packets in wireless networks has received attention recently. Many techniques are proposed in literature, in order to recover collided packets between transmitters. In [27], Analog Network Coding (ANC) is introduced to increase wireless network throughput, by encouraging specific transmitters' signals to interfere. Then, routers forward the interfered signals instead of individual packets, such that transmitters recover collided signals, in order to extract packets of interest. Results show that employing ANC increases throughput. Also in [28], a mechanism called MIXIT is proposed which is based on physical layer properties, in

order to improve WMNs throughput. It reduces packet forwarding overhead, because it allows to forward bits in a corrupted packet which are most likely can be decoded successfully.

A partial packets recovery for CDMA network is proposed in [30], in which a confidence values notion is employed, in order to decide which bits have been decoded with a low confidence, and hence, need to be retransmitted. As a result, the overall number of retransmission requests is reduced.

However in CRNs, there is few work in literature for recovering collided packets between primary users and secondary users. Since routing in CRNs is opportunistic over multiple channels or fading links, packets may be transmitted from one or multiple paths from a source to destination. A hybrid ARQ protocol which amplifies-and-forwards packets over multi-hop relays is proposed in [31], in order to control the E2E error. In their method, decoding process occurs at the destination node for the set of coded sub-packets which are transmitted by the source node.

In [32], an anti-jamming coding method is studied, in which jamming can be due to PU's activity and bad channel conditions. Two coding schemes are proposed, rateless coding and piecewise coding that increases SU throughput, due to increasing their transmission reliability.

In this dissertation, we propose packets recovery mechanisms for CRNs that are based on interference cancellation such that PU signal is considered as an interference by SU receiver. Our scheme recovers the collided packets between the unlicensed users and licensed users, when the licensed user becomes active while the unlicensed user is transmitting.

2.6   Multicast Routing in CRNs

Research for multicast routing in CRNs is limited literature. In this section, we review some of this research. In [37], a multicast routing protocol for CR ad-hoc networks is proposed, in order to find multicast routes using Minimal spanning tree-based routing algorithm, and its transmissions schedule such that channels are time slotted. Also for multi-hop CRNs, in [38] a multi-session multicast trees construction method is proposed, which minimizes the used network resources in polynomial time, e.g., bandwidth.

In [39], a multicast routing approach is proposed using a dynamic programming method, which allocates channel links and considers channels switching delay. Authors in [40], developed a layered graph model for constructing an efficient routing and channels allocation algorithms to reduce adjacent channels interference. However, authors have not consider switching time delay between channels over the selected routing path.

For one source and one destination, in [36] a protection method is proposed such that if the primary path to the destination fails due to a PU activity, a backup path is selected based on Bayesian decision.

CHAPTER 3 Performance Modeling of Secondary Users in CRNs with Heterogeneous Channels

3.1 Introduction

3.1.1 Background

Due to the temporal and spatial underutilization of licensed spectrum bands, as well as the crowdedness of unlicensed bands, a new spectrum access paradigm has been recently proposed namely, Cognitive Radio (CR) [42]. CR enables users to adjust their transceivers' frequencies depending on the availability of licensed frequency bands which are otherwise unused by their licensees [43]. Thus, unlicensed wireless users, called Secondary Users (SUs) can dynamically and opportunistically access unused licensed bands in order to improve their throughput and service reliability. In this case, whenever the licensed or the Primary Users (PUs) become active, SUs must vacate their bands.

CRNs have many challenges such as spectrum sensing, management, mobility, allocation and sharing [45], [46]. Usually, SUs have QoS performance requirements, e.g., throughput and maximum transmission delay. Evaluating these metrics is not a trivial task, due to the CRNs dynamic nature, e.g., due to PUs fluctuating activities which may interrupt SUs, and hence may need to access the channel multiple times just to finish one communication session. To evaluate these performance metrics, a few models have been proposed in literature. In [47, 48], a Markovian model is proposed to analyze spectrum access with and without buffering for new and interrupted SUs requests, which is used to evaluate SUs mean waiting time, and the probabilities of blocking, interruption, forced termination, and non-completion. Results show that buffering SUs requests reduces SUs' blocking and non-completion probabilities, with a

very small increase of forced termination probability. However, **in all other models** network channels are assumed symmetric in terms of channels bandwidth. In addition, SUs' sensing overhead is not considered in those models.

A quasi-birth and death Markov chain with continuous time and state space model is proposed in [49], to improve SUs performance by distributing their flows to multiple wireless networks. Due to the high complexity for this model, an approximation solution was proposed. They proposed two admission control schemes for SU flows priority, and no priority schemes. In both admission control schemes, if an SU is admitted to a network, it will not leave it until finishing its transmission as long as it is not interrupted by a PU arrival.

A Markov model for spectrum sharing between PUs and SUs is proposed in [50], when SUs are interrupted, they are suspended and wait to access another channel in a call level queue. During SUs' suspension, packets generated by SUs are either delayed or discarded, therefore the queue becomes two sub-queues, delay and discard queues. Three metrics are evaluated: packet loss ratio, packet delay, and throughput. Results show by increasing SU suspension queue length, both packet loss ratio and throughput increase and packet delay decreases. A queuing network model for spectrum sharing between PUs and SUs is introduced in [51], where a closed form solution for equilibrium system state was derived as a generating function. The model studies PUs QoS degradation due to unreliable SUs spectrum sensing where an SU keeps on using the channel, although a PU has arrived to the same channel. Besides, an SU moves from its channel to another only when it is interrupted by a PU arrival. Channels are assumed symmetric in terms of service rate for PUs and SUs in [50, 51].

3.1.2   Motivation

This work is motivated by:

- **First**, the fact that heterogeneous channels may be present in the same locality, e.g., TV channels, cellular telephone channels, wireless microphone channels, etc, which might be used by SUs, if available. The bandwidth availability in these channels is different. For instance, the licensed spectrum of Wireless Microphones has 200 KHz bandwidth, and

that of Digital TV (ATSC) has 6 MHz bandwidth. Therefore, this work is motivated
by the possibility of SUs switching channels opportunistically in order to improve their
performance.

- **Second**, the fact that some of the PUs of those channels characterized by long idle times,
  e.g., Digital TV channels, which may lead to a sustainable SU throughput, which also
  reduces channels switching overhead.

- **Third**, this work is also motivated by the need to consider sensing time and its effect on
  channel utilization and transmission delay. There are different technologies for spectrum
  sensing such as energy and feature detection. Energy detection sensing is frequent, and
  its typical sensing time is less than 1 ms, while feature detection, such as cyclostationary
  detection, is less frequent and sensing time is around 24.2 ms for Digital TV [55].

We are therefore motivated to develop a modeling approach that considers these three
important issues and allows one to evaluate the performance of SUs under these realistic
conditions.

3.1.3 Chapter Contributions

The contributions of this chapter are as follows:

1. We introduce a performance model for CRNs that models heterogeneous channels, as
   well as the sensing process in a manner that is dependent on the load. That is, the
   sensing time increases if fewer channels become available, and if fewer SUs are available
   to sense channels.

2. We introduce a strategy that gives preference to access channels with potentially larger
   idle times and higher bandwidth.

3. Through numerical results, we show that our proposed strategy outperforms a baseline
   model that does not allow switching between channels. In particular, our proposed
   strategy reduces the mean waiting time for SUs in the system.

4. Also, our numerical results show if sensing time is very small (≤ 1 ms), its effect on SUs performance is insignificant.

3.1.4 Chapter Organization

The rest of this chapter is organized as follows. The model and assumptions are explained in Section 3.2. In Section 3.3, our proposed Continuous Time Markov Chains ($CTMC$) model is presented. Performance metrics are derived in Section 3.4. The baseline model is described in Section 3.5, which is used for comparison to our proposed model. Numerical results and discussions are presented in Section 3.6. We conclude the chapter in Section 3.7.

3.2 Model and Assumptions

We use a mixed queuing network to model the CRN system where PUs are modeled as a closed chain of customers, while SUs are modeled as an open chain. Table 3.1 shows the notation and their description. Our proposed model contains two types of channels, C_1 and C_2, and a Virtual Queue (VQ), which is used to accommodate SUs. It is assumed that channels in C_1 have a higher bandwidth than channels in C_2, and SUs, therefore, prefer to use channels in C_1. SUs may move from the VQ to a channel in C_1, if available, as their first preference. Otherwise, they move to a channel in C_2, if available. In this model, whenever an SU detects an available channel in C_1, the SU starts using this channel, although the SU may have been using a channel in C_2. The purpose for doing so is to improve the SUs performance. SUs detect out-of-band channels availability by exchanging control information over Common Control Channel (CCC) [52]. The maximum number of SUs which can be in the system equals the VQ buffer size, β. Therefore, if an SU is interrupted during its service by the channel's PU, the SU moves to the VQ, and starts to sense for available channels in order to finish its own transmission, and then leaves the system. Our work in this chapter is accepted in [41].

Table 3.1: Table of Notations, where $i = \{1, 2\}$.

Notation	Description
C_i	Number of channels in type i.
v	Number of SUs in the system: VQ, C1, and C2.
β	The maximum size of the VQ buffer.
s	A binary variable for sensing state, where 0 means no sensing is being conducted. 1, otherwise.
p_i	Number of busy PUs in type i channels.
η	SUs sensing rate.
$\Psi_{(p_1+p_2,v)}$	SUs sensing rate function.
p_f	Probability of false alarm.
λ_s	SUs arrival rate.
λ_{p_i}	PUs arrival rate in type i channels.
μ_{s_i}	SUs service rate in type i channels.
μ_{p_i}	PUs service rate in type i channels.
$\{v, p_1, p_2, s\}$	A system state where v, p_1, p_2, and s are the number of SUs in system, busy PUs in C_1, busy PUs in C_2, and sensing state.
$\pi_{v,p_1,p_2,s}$	The probability of a steady state $\{v, p_1, p_2, s\}$.
p_b	Probability of SUs blocking, for C_1 and C_2 overall.
p_a	Probability of SUs admission, for C_1 and C_2 overall.
$\overline{L}$	Average number of SUs in the system: VQ, C_1, and C_2.
$\overline{W}$	SUs average waiting time in the system: VQ, C_1, and C_2, until finishing their packet transmission.

3.2.1   Assumptions

- SUs exchange channels' information, such as channel's availability using a CCC [53], which is assumed to be always available.

- Each channel has its own PU assigned to it.

- The number of SUs in the network is unlimited, but a maximum of β can be in the system, either occupying channels, or waiting for channels to become available.

- Each channel is modeled as a server with no buffer.

- There are two types of channels, type 1 and type 2.

- SUs assign a higher priority for using type 1 channels over type 2, due to the higher throughput of type 1 channels.

- Assume each SU has two transceivers, one for data transmission, and the other for exchanging control packets with other SUs over the CCC, and for conducting in band and out-of-band sensing.

- The Virtual Queue (VQ) is a concept to hold the newly arrived and interrupted SUs, as well as SUs being served.

- When an SU finishes its transmission, the SU leaves the network. However, if an SU is interrupted, the SU moves to the VQ and waits for an available channel in order to complete its transmission.

- When a PU or an SU finishes its transmission on a type 1 channel, e.g., channel k, then an SU being served on a type 2 channel, if any, moves to channel k, in order to improve the SUs throughput.

- SUs sensing time[1] is exponentially distributed with a rate that is dependent on v, p_1, and p_2. Let $\Psi_{(p_1+p_2,v)}$ be this sensing rate function, and it will be defined in the numerical

---

[1]In this chapter, it is assumed that what we refer to as the sensing time, includes both the channel sensing, and channel switching times.

results Section, Section 3.6, equation (3.13). Practically, $\Psi_{(p_1+p_2,v)} >> \lambda_s, \lambda_{p_1}, \lambda_{p_2}, \mu_{s_1}$, μ_{s_2}, μ_{p_1}, and μ_{p_2}.

- Sensing is triggered when an SU arrives, given there is an idle channel. Or, when a PU or an SU finishes transmission and there is at least one SU waiting in the VQ.

- We only model good sensing which results in finding an idle channel that the SU can use. Modeling sensing which does not result in accessing a channel, either because all channels are busy, or because there are no waiting SUs, will have no bearing on the system operation, and does not change the model.

- The probability of misdetection under sensing is assumed to be very small, and is therefore negligible, in order to reduce the model complexity. Misdetection is defined as detecting the channel as idle, while the channel is occupied by a PU's transmission.

- The probability of false alarm, p_f, is considered in this model, since it has much higher effect than the probability of misdetection in our system model, and it is usually less than 0.1, e.g., as in IEEE 802.22 CRNs standard [54]. False alarm is defined as detecting the channel as busy by a PU's transmission, while in reality it is idle.

3.2.2 Parameters

- C_1 and C_2 are the number of channels of types 1 and 2, respectively, and are also the number of PUs assigned to these channels.

- PUs assigned to type 1 and type 2 channels, have exponentially distributed inter-arrival times with rates of λ_{p_1} and λ_{p_2}, respectively, when they are idle.

- PUs using type 1 and type 2 channels have service rates of μ_{p_1} and μ_{p_2}, respectively, with exponential distributions, when they are active.

- β is the maximum size of the VQ[2].

- SUs arrival rates to the VQ is λ_s with Poisson distributions.

---

[2]In our numerical results, β is set to a large value such that SUs $p_a \approx 1$.

- On type 1 and type 2 channels, the SUs service rates are μ_{s_1} and μ_{s_2}, respectively, with an exponential distributions.

3.2.3 Variables

- s is a binary variable, $\{0,1\}$, for sensing state, where 0 means no sensing is being conducted. While 1, otherwise.

- v is the total number of SUs in the VQ, including those being served by types 1 and 2 channels, while in this model v is taken as finite, the virtual queue size, β, can also be set to a very large number, hence approximating the infinite number of SUs case, as will be shown in Section 3.6.

- p_1 and p_2 are the numbers of PUs being served by type 1 and type 2 channels, respectively.

- For our model, we define the state space, call it ζ, as (v, p_1, p_2, s), where: $0 \le v \le \beta$, $0 \le p_1 \le C_1$, $0 \le p_2 \le C_2$, and s is a binary variable, such that v must be ≥ 1, if $s = 1$, which means at least one SU must exist to conduct sensing.

- let $\pi_{\hat{v}, \hat{p_1}, \hat{p_2}, s}$ be the stationary probability vector where $v = \hat{v}$, $p_1 = \hat{p_1}$, $p_2 = \hat{p_2}$, and s is a binary variable such that if $s = 1$, sensing is being conducted by SU(s). Otherwise; no sensing.

It is to be noted that the assumption of memoryless distributions, i.e., exponential distributions, has been made in order to make the model mathematically tractable. This is a standard assumption that is made in such complicated models. It is to be also noted that the queuing network is ergodic, because it is irreducible and has a finite state space. The queueing network therefore has a unique steady state (S.S.) distribution, $\overrightarrow{\pi}$.

3.3 Model Formulation

There are 5 cases of the global balance equations. Since sensing is inconsequential when no channels are available, it is assumed that sensing is terminated when a PU arrives to occupy

its channel and no other channels are available. It is also assumed that at most one decision can be made based on sensing at the same time.

In order to model the system exactly, a greater number of state variables need to be included, which will significantly increase the system complexity. Therefore, we introduce two relaxations which result on bounds on system performance. These are an optimistic bound and a pessimistic bound. The definition of these two models are as follows:

- For the **optimistic bound analysis**, if sensing is conducted, then we assume it is on a channel in type 2 (lower SUs service rate), i.e., all available channels in type 1 are being used.

- For the **pessimistic bound analysis**, if sensing is conducted, then we assume it is on a channel in type 1 (higher SUs service rate), i.e., all available channels in type 2 are being used.

Throughout this section, we consider the optimistic bound performance, while formulating the global balance equations. With minor modifications of these global balance equations, we can also model the pessimistic bound performance.

Case 1: If $v < (C_1 - p_1)$, then all active SUs are using channels in C_1. Hence, the global balance equations are equations (3.1) and (3.2).

$$
\pi_{v,p_1,p_2,1}[\lambda_s + v\mu_{s_1} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2} + \Psi_{(p1+p_2,v)}(1 - p_f)]
$$

$$
= \pi_{v-1,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{v\geq 1} + \pi_{v-1,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{v\geq 2} + \pi_{v+1,p_1,p_2,1}\left[(v+1)\mu_{s_1}\right] + \pi_{v,p_1+1,p_2,1}
$$

$$
\left[(p_1+1)\mu_{p_1}\right]\mathbb{1}_{v\geq 1} + \pi_{v,p_1,p_2+1,1}\left[(p_2+1)\mu_{p_2}\right]\mathbb{1}_{v\geq 1} + \pi_{v,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{v\geq 1} \quad (3.1)
$$

$$
+ \frac{v}{C_1 - p_1 + 1}\pi_{v,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]
$$

$$
+ \frac{C_1 - p_1 + 1 - v}{C_1 - p_1 + 1}\pi_{v,p_1-1,p_2,1}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{v\geq 1}.
$$

Sensing is considered for all channels, with channels in C_1 given a higher priority when sensed by SUs. In equation (3.1), $\mathbb{1}_{v\geq x}$ is an indicator function which equals 1 if the condition, $v \geq x$, holds. Otherwise, it is 0. The LHS of equation (3.1), is the probability flux of leaving state $(v, p_1, p_2, 1)$ due to: an SU arrival with rate λ_s, an SU in C_1 finishes its transmission with

rate $v\mu_{s_1}$, a PU in C_1 or C_2 finishing its transmission with rates $p_1\mu_{p_1}$ and $p_2\mu_{p_2}$, respectively, a PU arrived to C_1 or C_2 with rates $(C_1 - p_1)\lambda_{p_1}$ or $(C_2 - p_2)\lambda_{p_2}$, respectively, and end of sensing with rate of $\Psi_{(p1+p_2,v)}(1 - p_f)$.

The RHS of equation 3.1, is probability flux of entering state $(v, p_1, p_2, 1)$. This is due to: an SU arrived while the system in states $(v - 1, p_1, p_2, 0)$ and $(v - 1, p_1, p_2, 1)$. An SU finishing its transmission while the system in state $(v + 1, p_1, p_2, 1)$ with rate $(v + 1)\mu_{s_1}$, a PU completing service while the system is in state $(v, p_1 + 1, p_2, 1)$ or $(v, p_1, p_2 + 1, 1)$, with rates $(p_1 + 1)\mu_{p_1}$ or $(p_2 + 1)\mu_{p_2}$, respectively, a PU arriving to C_2 with rate $(C_2 - p_2 + 1)\lambda_{p_2}$, while the system in state in state $(v, p_1, p_2 - 1, 1)$, a PU arriving to C_1 while in state $(v, p_1 - 1, p_2, 0)$, and interrupting an SU which is using its channel, thus sensing by the SU is triggered with probability $\frac{v}{C_1 - p_1 + 1}$, and a PU arriving to its channel which is not being used by an SU, with probability $\frac{C_1 - p_1 + 1 - v}{C_1 - p_1 + 1}$, while the system is in state $(v, p_1 - 1, p_2, 1)$, given there has been sensing. In the rest of the chapter, only the new transition states will be explained, due to space limitation.

In equation (3.2), the LHS is similar to that in equation (3.1), but there is no sensing. In the RHS, the second term to the last, the system transits from state $(v, p_1 - 1, p_2, 0)$ to state $(v, p_1, p_2, 0)$, due to a PU arrival to its channel in C_1 where no SU exits, with a probability of $\frac{C_1 - p_1 + 1 - v}{C_1 - p_1 + 1}$, given there was no sensing.

$$
\pi_{v,p_1,p_2,0}[\lambda_s + v\mu_{s_1} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2}]
$$

$$
= \pi_{v,p_1,p_2,1}\left[\Psi_{(p1+p_2,v)}(1 - p_f)\right]\mathbb{1}_{v\geq 1} + \pi_{v+1,p_1,p_2,0}\left[(v + 1)\mu_{s_1}\right] + \pi_{v,p_1+1,p_2,0}\left[(p_1 + 1)\mu_{p_1}\right]
$$

$$
+ \pi_{v,p_1,p_2+1,0}\left[(p_2 + 1)\mu_{p_2}\right] + \frac{C_1 - p_1 + 1 - v}{C_1 - p_1 + 1}\pi_{v,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right] \tag{3.2}
$$

$$
+ \pi_{v,p_1,p_2-1,0}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right].
$$

Case 2: If $(C_1 - p_1) \leq v < (C_1 - p_1) + (C_2 - p_2)$, then the global balance equations are (3.3) and (3.4). In this case, if PU being served within C_1 finishes its transmission, SUs sensing is triggered. Also, these equations implicitly model the SUs preference to be served by C_1 channels rather than C_2 channels. Thus, when a PU in C_1 finishes its transmission, say at channel k, sensing is triggered, and then an SU moves to channel k.

In equation (3.3) in the last term on the RHS, a PU arrives to its channel in C_2, where no SU is using it, with probability $\frac{C_2 - p_2 + 1 - (v - C_1 - p_1)}{C_2 - p_2 + 1}$, given sensing was not being conducted. Thus, system transits to state $(v, p_1, p_2, 0)$ (LHS). In equation (3.4), the system transits to state $(v, p_1, p_2, 1)$ in LHS, from different states, for example: from state $(v, p_1, p_2 - 1, 0)$ with a probability of $\frac{v - C_1 - p_1}{C_2 - p_2 + 1}$, when a PU arrives to C_2 and interrupts an SU that is using its channel. Thus, the PU arrival causes sensing to start. The same thing occurs in the second term to last, in state $(v, p_1, p_2 - 1, 1)$ with the same probability. However, in this case an SU which was already engaged in sensing will just continue to sense. However, in the last term a PU arrives to its channel in C_2, where no SU is using it, with probability $\frac{C_2 - p_2 + 1 - (v - C_1 - p_1)}{C_2 - p_2 + 1}$, given sensing was being conducted.

$$\pi_{v,p_1,p_2,0}[\lambda_s + (C_1 - p_1)\mu_{s_1} + (v - C_2 + p_2)\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2}]$$

$$= \pi_{v,p_1,p_2,1}\left[\Psi_{(p1+p_2,v)}(1 - p_f)\right]\mathbb{1}_{v\geq 1} + \pi_{v+1,p_1,p_2,0}\left[(v + 1 - C_1 + p_1)\mu_{s_2}\right] + \pi_{v,p_1,p_2+1,0}$$

$$\left[(p_2 + 1)\mu_{p_2}\right] + \frac{C_2 - p_2 + 1 - (v - C_1 + p_1)}{C_2 - p_2 + 1}\pi_{v,p_1,p_2-1,0}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right].$$

$$(3.3)$$

$$\pi_{v,p_1,p_2,1}[\lambda_s + (C_1 - p_1)\mu_{s_1} + (v - C_1 + p_1 - 1\mathbb{1}_{(v-C_1+p_1)\geq 1})\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} +$$

$$(C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2} + \Psi_{(p1+p_2,v)}(1 - p_f)]$$

$$= \pi_{v-1,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{v\geq 1} + \pi_{v-1,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{v\geq 2} + \pi_{v+1,p_1,p_2,0}\left[(C_1 - p_1)\mu_{s_1}\right]$$

$$+ \pi_{v+1,p_1,p_2,1}\left[(C_1 - p_1)\mu_{s_1}\right] + \pi_{v+1,p_1,p_2,1}\left[(v + 1 - C_1 + p_1 - 1)\mu_{s_2}\right]$$

$$+ \pi_{v,p_1+1,p_2,0}[(p_1 + 1)\mu_{p_1}] + \pi_{v,p_1+1,p_2,1}\left[(p_1 + 1)\mu_{p_1}\right]\mathbb{1}_{v\geq 1} + \pi_{v,p_1,p_2+1,1}$$

$$\left[(p_2 + 1)\mu_{p_2}\right]\mathbb{1}_{v\geq 1} + \pi_{v,p_1-1,p_2,1}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{v\geq 1}$$

$$+ \pi_{v,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right] + \frac{v - C_1 + p_1}{C_2 - p_2 + 1}\pi_{v,p_1,p_2-1,0}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]$$

$$+ \frac{v - C_1 + p_1}{C_2 - p_2 + 1}\pi_{v,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{v\geq 1}$$

$$+ \frac{C_2 - p_2 + 1 - (v - C_1 + p_1)}{C_2 - p_2 + 1}\pi_{v,p_1,p_2-1,1}[(C_2 - p_2 + 1)\lambda_{p_2}]\mathbb{1}_{v\geq 1}.$$

$$(3.4)$$

Case 3: If $v = (C_1 - p_1) + (C_2 - p_2)$, then the global balance equations are equations (3.5) and (3.6). In equation (3.5) the last term in RHS, shows sensing is triggered by a PU interruption

of an SU which was served by the PU's channel, with probability $\frac{C_2-p_2}{C_2-p_2+1}$, given there is still one free channel in C_2. However, in equation (3.6), the last term on the RHS corresponds to a PU arriving to a channel where no SU was being served, with probability of $\frac{1}{C_2-p_2+1}$, and hence, sensing is not triggered.

$$\pi_{v,p_1,p_2,1}[\lambda_s + (C_1-p_1)\mu_{s_1} + (C_2-p_2-1)\mu_{s_2}\mathbb{1}_{C_2-p_2\neq0} + p_1\mu_{p_1} + p_2\mu_{p_2}$$
$$+ (C_1-p_1)\lambda_{p_1} + (C_2-p_2)\lambda_{p_2} + \Psi_{(p1+p_2,v)}(1-p_f)]$$
$$= \pi_{v-1,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{v\geq1} + \pi_{v-1,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{v\geq2} + \pi_{v+1,p_1,p_2,0}\left[(C_1-p_1)\mu_{s_1}\right]$$
$$+ \pi_{v+1,p_1,p_2,0}\left[(C_2-p_2)\mu_{s_2}\right] + \pi_{v+1,p_1,p_2,1}\left[(C_1-p_1)\mu_{s_1}\right]$$
$$+ \pi_{v+1,p_1,p_2,1}\left[(C_2-p_2-1\mathbb{1}_{(C_2-p_2)\geq1})\mu_{s_2}\right] + \pi_{v,p_1+1,p_2,0}\left[(p_1+1)\mu_{p_1}\right] \tag{3.5}$$
$$+ \pi_{v,p_1,p_2+1,0}\left[(p_2+1)\mu_{p_2}\right] + \pi_{v,p_1+1,p_2,1}\left[(p_1+1)\mu_{p_1}\right]\mathbb{1}_{v\geq1}$$
$$+ \pi_{v,p_1,p_2+1,1}\left[(p_2+1)\mu_{p_2}\right]\mathbb{1}_{v\geq1} + \pi_{v,p_1-1,p_2,0}\left[(C_1-p_1+1)\lambda_{p_1}\right]$$
$$+ \pi_{v,p_1-1,p_2,1}\left[(C_1-p_1+1)\lambda_{p_1}\right]\mathbb{1}_{v\geq1} + \pi_{v,p_1,p_2-1,1}\left[(C_2-p_2+1)\lambda_{p_2}\right]\mathbb{1}_{v\geq1}$$
$$+ \frac{C_2-p_2}{C_2-p_2+1}\pi_{v,p_1,p_2-1,0}\left[(C_2-p_2+1)\lambda_{p_2}\right].$$

$$\pi_{v,p_1,p_2,0}[\lambda_s + (C_1-p_1)\mu_{s_1} + (C_2-p_2)\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1-p_1)\lambda_{p_1} + (C_2-p_2)\lambda_{p_2}]$$
$$= \pi_{v,p_1,p_2,1}\left[\Psi_{(p1+p_2,v)}(1-p_f)\right]\mathbb{1}_{v\geq1} + \frac{1}{C_2-p_2+1}\pi_{v,p_1,p_2-1,0}\left[(C_2-p_2+1)\lambda_{p_2}\right]. \tag{3.6}$$

Case 4: If $(C_1-p_1) + (C_2-p_2) < v < \beta$, then, equations (3.7) and (3.8) are the global balance equations. Recall that for the optimistic bound analysis, if sensing is conducted, then it is at a channel in C_2, i.e., all available channels in C_1 are being used.

In equations (3.7) and (3.9), the last term in RHS corresponds to a PU arriving to a channel where an SU is sensing it, which occurs with probability of $\frac{1}{C_2-p_2+1}$, hence sensing is terminated. However, in Equation (3.8) the last term in RHS, shows that the sensing has not been terminated , since the PU arrives to a channel where sensing is not being conducted, with probability of $\frac{C_2-p_2}{C_2-p_2+1}$. However, the PU arrival causes an SU interruption, where the SU goes back to the VQ, and waits for a channel to become available. Recall that we assume

sensing is always conducted at a channel in type 2.

$$
\pi_{v,p_1,p_2,0}[\lambda_s + (C_1 - p_1)\mu_{s_1} + (C_2 - p_2)\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2}]
$$
$$
= \pi_{v,p_1,p_2,1}\left[\Psi_{(p1+p_2,v)}(1 - p_f)\right]\mathbb{1}_{v\geq 1} + \pi_{v-1,p_1,p_2,0}\left[\lambda_s\right] + \pi_{v,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]
$$
$$
+ \pi_{v,p_1,p_2-1,0}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right] + \frac{1}{C_2 - p_2 + 1}\pi_{v,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{v\geq 1}.
$$
$$
(3.7)
$$

$$
\pi_{v,p_1,p_2,1}[\lambda_s + (C_1 - p_1)\mu_{s_1} + (C_2 - p_2 - 1\mathbb{1}_{(C_2-p_2)\neq 0})\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1}
$$
$$
+ (C_2 - p_2)\lambda_{p_2} + \Psi_{(p1+p_2,v)}(1 - p_f)]
$$
$$
= \pi_{v-1,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{v\geq 2} + \pi_{v+1,p_1,p_2,1}\left[(C_1 - p_1)\mu_{s_1}\right] + \pi_{v+1,p_1,p_2,1}\left[(C_2 - p_2 - 1\mathbb{1}_{(C_2-p_2)\geq 1}))\mu_{s_2}\right]
$$
$$
+ \pi_{v+1,p_1,p_2,0}\left[(C_1 - p_1)\mu_{s_1}\right] + \pi_{v+1,p_1,p_2,0}\left[(C_2 - p_2)\mu_{s_2}\right] + \pi_{v,p_1+1,p_2,1}\left[(p_1 + 1)\mu_{p_1}\right]\mathbb{1}_{v\geq 1}
$$
$$
+ \pi_{v,p_1,p_2+1,1}\left[(p_2 + 1)\mu_{p_2}\right]\mathbb{1}_{v\geq 1} + \pi_{v,p_1+1,p_2,0}\left[(p_1 + 1)\mu_{p_1}\right] + \pi_{v,p_1,p_2+1,0}\left[(p_2 + 1)\mu_{p_2}\right]
$$
$$
+ \pi_{v,p_1-1,p_2,1}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{v\geq 1} + \frac{C_2 - p_2}{C_2 - p_2 + 1}\pi_{v,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{v\geq 1}.
$$
$$
(3.8)
$$

Case 5: In this case $v = \beta$. As a result, equations (3.9) and (3.10) are the global balance equations.

$$
\pi_{\beta,p_1,p_2,0}[(C_1 - p_1)\mu_{s_1} + (C_2 - p_2)\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2}]
$$
$$
= \pi_{\beta-1,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{\beta\geq 1} + \pi_{\beta,p_1,p_2,1}\left[\Psi_{(p1+p_2,v)}(1 - p_f)\right]\mathbb{1}_{\beta\geq 1} + \pi_{\beta,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]
$$
$$
+ \pi_{\beta,p_1,p_2-1,0}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right] + \frac{1}{C_2 - p_2 + 1}\pi_{\beta,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{\beta\geq 1}.
$$
$$
(3.9)
$$

$$\pi_{\beta,p_1,p_2,1}[(C_1-p_1)\mu_{s_1}+(C_2-p_2-1\mathbb{1}_{(C_2-p_2)\neq0})\mu_{s_2}+p_1\mu_{p_1}+p_2\mu_{p_2}+(C_1-p_1)\lambda_{p_1}+$$

$$(C_2-p_2)\lambda_{p_2}+\Psi_{(p1+p_2,v)}(1-p_f)]$$

$$=\pi_{\beta-1,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{\beta\geq2}+\pi_{\beta,p_1+1,p_2,1}\left[(p_1+1)\mu_{p_1}\right]\mathbb{1}_{\beta\geq1}+\pi_{\beta,p_1,p_2+1,1}\left[(p_2+1)\mu_{p_2}\right]\mathbb{1}_{\beta\geq1}$$

$$+\pi_{\beta,p_1+1,p_2,0}\left[(p_1+1)\mu_{p_1}\right]+\pi_{\beta,p_1,p_2+1,0}\left[(p_2+1)\mu_{p_2}\right]+\pi_{\beta,p_1-1,p_2,1}\left[(C_1-p_1+1)\lambda_{p_1}\right]\mathbb{1}_{\beta\geq1}$$

$$+\frac{C_2-p_2}{C_2-p_2+1}\pi_{\beta,p_1,p_2-1,1}\left[(C_2-p_2+1)\lambda_{p_2}\right]\mathbb{1}_{\beta\geq1}.$$

$$(3.10)$$

3.4 Performance Metrics

In this section, we introduce several performance metrics which can be used to evaluate CRN performance. These include the probabilities of admission and blocking of SUs, average number of SUs in the system during the network operation, and average waiting time for SUs in the system until completing service. We solved the steady state probability distribution, $\overrightarrow{\pi}$, by solving the equation $\overrightarrow{\pi}Q=0$, where Q is the transition rate matrix that can be constructed using the global balance equations $(3.1)-(3.10)$.

However, the number of linearly independent global balance equation is $(m-1)$. Therefore, use the fact that the summation of all probabilities in the steady state distribution equals 1. As a results, we have m linearly independent solvable equations.

Let us introduce the following definitions:

Definition 3.4.1 *Probability of blocking of SUs (p_b): It is the probability that a new SU request for transmission is blocked due to the lack of space in the VQ.*

Definition 3.4.2 *Probability of admission for SUs (p_a): It is the probability that a new SU request for transmission is admitted.*

Definition 3.4.3 *The average number of SUs in the system ($\overline{L}$), which includes those being served by channels of types 1 and 2, and also those waiting for a channel to become available.*

Definition 3.4.4 *Average waiting time* $(\overline{W})$ *of SUs, which is measured from the instant of arrival, until finishing its transmission.*

The following equations are used to evaluate the performance metrics of our proposed model.

1. The probability of blocking for SUs (p_b) is given by equation (3.11).

$$p_b = \sum_{p_1=0}^{C_1} \sum_{p_2=0}^{C_2} \sum_{s=0}^{1} \Bigg[\sum_{\substack{\{v=\beta\}, \\ (v,p_1,p_2,s)\in\zeta}} \pi_{v,p_1,p_2,s} \Bigg]. \tag{3.11}$$

2. The probability of SU admission, (p_a), equals to $1 - p_b$.

3. The average number of SUs in the system $(\overline{L})$, is given by equation (3.12).

$$\overline{L} = \sum_{p_1=0}^{C_1} \sum_{p_2=0}^{C_2} \sum_{s=0}^{1} \Bigg[\sum_{\substack{v=1, \\ (v,p_1,p_2,s)\in\zeta}}^{\beta} v \times \pi_{v,p_1,p_2,s} \Bigg]. \tag{3.12}$$

4. To find the average waiting time $\overline{W}$, we appeal to Little's Theorem, where $\overline{L}$ is given by equation (3.12), and $\overline{W}$ is expressed as $\overline{W} = \frac{\overline{L}}{p_a \times \lambda_s}$.

3.5 Baseline Model

In this section, we introduce and model another system. This is a system similar to our proposed model, but with no channel switching to type 1 channels (if available) by SUs which are being served in type 2 channels, unless there are no longer available channels on type 2. We developed this system and use it as a baseline model to establish the advantages of our proposed approach. For example, if an SU arrives and selects a channel, say from set C_2, the SU keeps using this channel, until finishing its transmission, as long as this channel is available. However, if the SU is interrupted, and sense there are no available channels on type 2 to use it, and there is an available channel on type 1, therefore the SU switches to this channel. Otherwise, when no channel is available in both types 1 and 2, the SU is buffered in the VQ, until a channel becomes available. Appendix A presents the global balance equations for the baseline model, where we consider the Optimistic Bound (OB) performance in global balance

equation formulation. However, with a minor modification of these equations the Pessimistic Bound (PB) performance can be expressed. The performance metrics for the baseline model are similar to our model, in Section 3.4. Similarly, those equations with minor modifications are used to evaluate the baseline model performance metrics.

3.6 Numerical Results

This section presents the numerical results for SUs average waiting time, with respect to SUs arrival rate to the system, λ_s. Also, we study the effect of SUs sensing rate on the system performance.

The sensing rate is dependent on both the number of unused channels, and on the number of SUs performing the sensing process. It was proven in [56] that the expected time to detect an unused channel is inversely proportional to the number of unused channels, which means that the sensing rate is proportional to this number. Moreover, if the total number of channels is very large, and is evenly divided among the SUs sensing for available channels (out-of-band sensing), then the rate of detecting an empty channel is the sum of the individual SUs sensing rates. We therefore express the sensing rate, as a function of p_1, p_2, and v, $\Psi_{(p_1+p_2,v)}$, as shown in equation (3.13), where η is the sensing rate when there is only a single SU sensing, and there is only one available channel.

$$\Psi_{(p_1+p_2,v)} = \eta \hat{N} \hat{I}. \tag{3.13}$$

$\hat{N}$ is the number of SUs in the system which are not being served by channels (waiting/interrupted) or want to improve their performance by switching to a channel in type 1, and therefore conduct out-of-band sensing. $\hat{I}$ is number of idle channels in type 1 and 2 channels which are not being used by SUs or PUs. Based on the global balance equations $(3.1)-(3.10)$, if $v \leq (C_1 - p_1)$, $\hat{N} = 0$ (No SUs are interested in sensing, since all current SUs are being served by type 1 channels). If $(C_1 - p_1) < v \leq (C_1 - p_1 + C_2 - p_2)$, then $\hat{N} = v - (C_1 - p_1)$. Otherwise, $\hat{N} = v - (C_1 - p_1 + C_2 - p_2)$. If $v \leq (C_1 - p_1 + C_2 - p_2)$, then $\hat{I} = (C_1 - p_1 + C_2 - p_2) - v$.

Otherwise, $\hat{I} = 1$. According to equation (3.13) the sensing rate increases (the sensing time decreases) when more SUs are active and sensing the channels. The sensing rate decreases (the sensing time increases) when more PUs are active, and therefore there are fewer available channels, and it takes longer to search for and sense those channels.

In order to evaluate our proposed model, we consider two different scenarios as follows, it is worth mentioning that in both scenarios, SUs service rates in type 1 and 2 channels are different.

- **Scenario** 1 parameters, $\mu_{s_1} = 60$, $\mu_{s_2} = 15$, $\lambda_{p_1} = \lambda_{p_2} = 5$, $\mu_{p_1} = \mu_{p_2} = 10$, $\eta = 250$, $C_1 = C_2 = 4$, $p_f = 0.09$, and $\beta = 40$.

- **Scenario** 2 parameters, $\mu_{s_1} = 80$, $\mu_{s_2} = 20$, $\lambda_{p_1} = 5$, $\lambda_{p_2} = 25$, $\mu_{p_1} = 15$, $\mu_{p_2} = 80$, $\eta = 380$, $C_1 = C_2 = 3$, $p_f = 0.05$, and $\beta = 50$. This scenario, is different from the first one, where PUs arrival and service rates are not equal in both channel types. Also, PUs service time in type 1 channels is greater than those in type 2, to capture the heterogeneity nature, such as in TV channels and cellular phones channels.

3.6.1 Average waiting time of SUs:

We show how the SUs' average waiting time, $\overline{W}$, changes with respect to SUs arrival rate, λ_s. **It is worth mentioning the probability of SUs admission, p_a, in our model and the baseline model for all numerical results in this section is almost 1. In our results, β is set to a value, e.g., in scenario 2 $\beta = 50$, such that p_a is almost 1. We have varied β size up to 100 in both Scenarios studies, however, this do not change the numerical results, e.g., $\overline{W}$. Therefore, we approximate the infinite number of SUs case in our results.** Figure 3.1 which corresponds to scenario 1, shows that $\overline{W}$ increases by increasing SUs arrival rate, λ_s. Our model outperforms the baseline model in both the Optimistic Bound (OB) and Pessimistic Bound (PB) analysis, because our model reduces $\overline{W}$ for SUs in the system. For example, for the OB analysis, and when $\lambda_s = 20, 100$, and 150, our model reduces $\overline{W}$ by up to 12.44%, 20.68%, and 11.99%, respectively, with respect to the baseline model. One observation, when $\lambda_s = 100$, $\overline{W}$ reduction is higher than when

$\lambda_s = 150$. Therefore, our model $\overline{W}$ reduction percentage over the baseline model reaches its maximum value, when λ_s increased to some value, and then this percentage decreases.

Also, Figure 3.2, which corresponds to scenario 2 system parameters, shows that $\overline{W}$ increases by increasing λ_s. This figure, shows although the PUs behavior is different between the two types of channels, our model outperforms the baseline model in the OB and PB analysis. For example, for the PB analysis, and when $\lambda_s = 50$, our model reduces $\overline{W}$ by up to 16.23% with respect to the baseline model. Please notice that sensing rate, equation (3.13), is higher than the SUs and PUs arrival and service rates in these cases studies.

3.6.2 Sensing Rate:

We consider the Pessimistic and the Optimistic bounds analysis for scenarios 1 and 2, respectively, in our model to study the effect of sensing rate, η, on SUs performance. The system parameters correspond to scenarios 1 and 2 parameters, except that in both scenarios λ_s is fixed and is set to 100, while the sensing rate is varied on the X axis. Figure 3.3 shows that the SUs' average waiting time, $\overline{W}$, decreases by increasing η. The smallest value for sensing rate in this figure is 50, i.e., an average sensing time of 20 ms, which is about the sensing time using feature detection [55]. However, for the energy detection method, the sensing time is ≤ 1 ms [55], or $\eta \geq 1000$. Clearly, when the energy detection method is used instead of feature detection, the SUs performance is better and $\overline{W}$ decreases. This figure also shows that if η is increased beyond 1000, its effect on SUs performance is insignificant for both cases studies scenarios, e.g., in scenario 1 for the PB, when η is increased from 50 to 1000, $\overline{W}$ is reduced by up to 34.56%, however, when η is increased from 1000 to 2000, $\overline{W}$ is only reduced by up to 3.42%. Since our model discards SU arrivals occurring while channels are being sensed, $\overline{W}$ in Figure 3.3 is underestimated.

3.7 Chapter Summary

In this chapter we proposed a model for heterogeneous channel access in Cognitive Radio Networks (CRNs). In this model, there are two types of licensed channels, where one type has
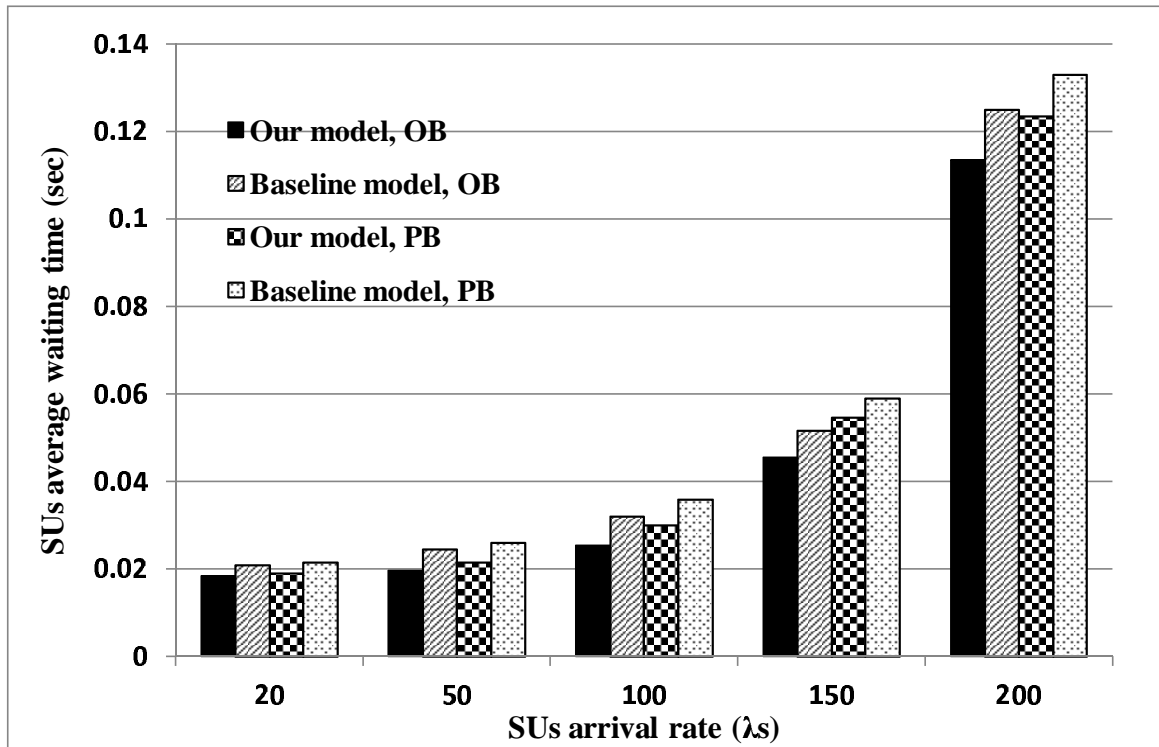
Figure 3.1: Scenario 1, SUs $\overline{W}$ time with respect to their arrival rate, λ_s.
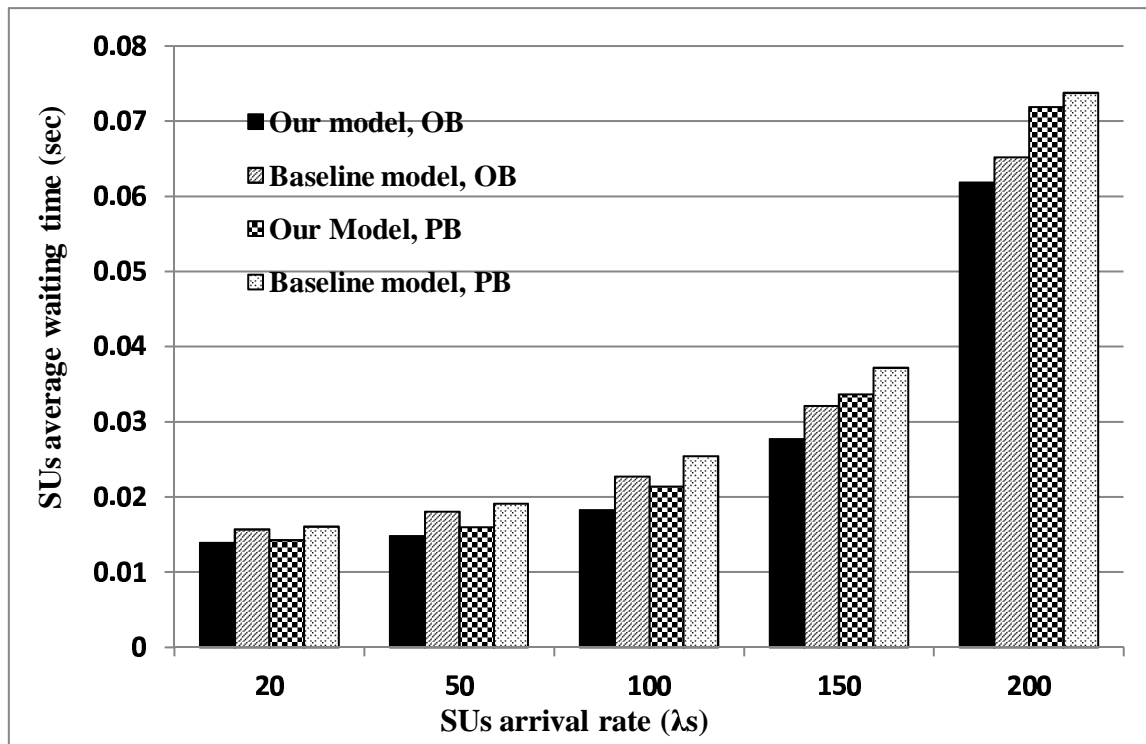
Figure 3.2: Scenario 2, SUs $\overline{W}$ time with respect to their arrival rate, λ_s.

p
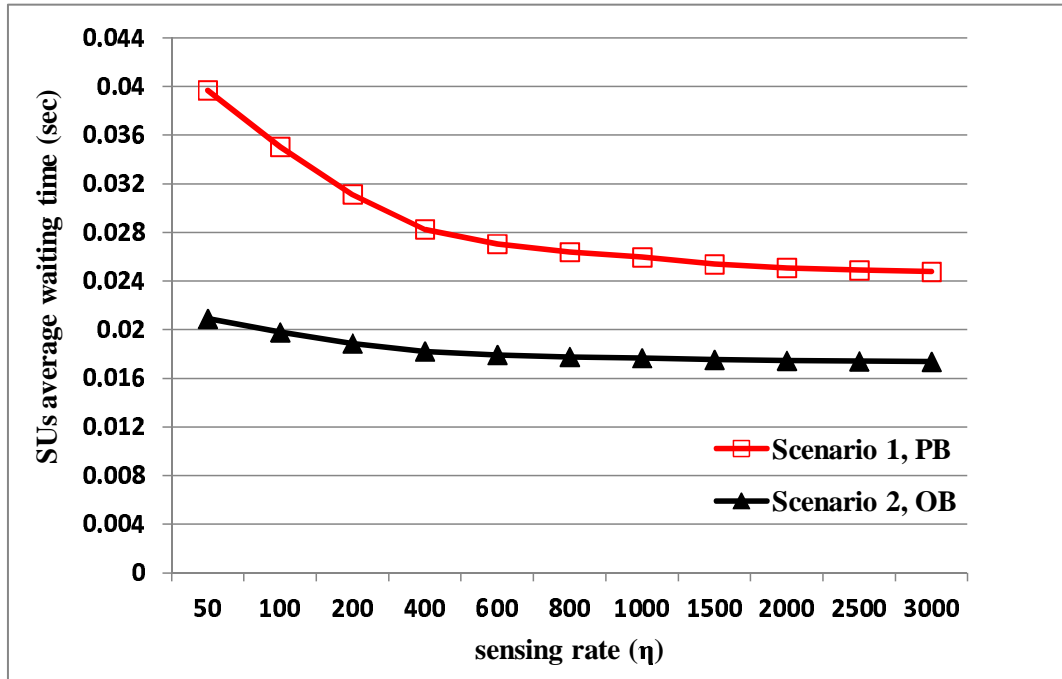
Figure 3.3: SUs $\overline{W}$ time, with respect to their sensing rate, η, for scenarios 1 and 2 for PB and OB, respectively, where λ_s is fixed and set to 100.

a larger bandwidth. SUs may use the first type if it is available, or if it becomes available. We also model the SUs' sensing process and study its effect on performance, such that sensing rate is dependent on both the number of unused channels, and on the number of SUs performing the sensing process. We used a mixed queuing network model to model the CRN system, and developed the global balance equations for a $CTMC$. We derived SUs' performance metrics, such as SUs admission and blocking probabilities, and their average waiting time in the system. We compare our proposed system to a baseline model, which is the same as our proposed model, except that SUs in type 2 channel can not improve their throughput by switching to channels in type 1, if available, unless they are interrupted at their current type 2 channels.

Numerical results show that our proposed model outperforms the baseline model. We also found that if sensing time is very small (≤ 1 ms), its effect on SUs performance is insignificant.

CHAPTER 4   Uplink Channel Assignment in Cognitive Radio WMNs Using Physical Layer Network Coding

4.1   Introduction

4.1.1   Background

Although CR networking is a promising technique, it has many challenges that need to be dealt with, such as spectrum sensing, management, mobility, allocation and sharing [57, 58, 59, 60]. Consequently, channel allocation and MAC protocol design becomes more challenging due to sporadic channel availability, potential lack of SUs cooperation, or hardware limitations. In order to simplify coordination between transmitters and receivers, usually a single common control channel (CCC) [61], a set of common channels to all SUs [62], or multiple local control channels for groups of SUs [63] have been proposed as solutions. However, one CCC may be difficult to find, and a CCC can not be used for data communication. If the CCC fails, coordination is compromised. In generally, fixed CCC will increase the cost and vulnerability especially in licensed spectrum bands. Therefore, coordination techniques without using CCC have been proposed. In [64] a new MAC protocol for multi-hop Cognitive Radio Networks (CRNs) is developed to avoid using a CCC by dividing the total time into a set of intervals where each interval represents one of the available channels. In [65] a swarm intelligence method is proposed to dynamically find and manage control channels, since the CCC may be unknown at the first deployment time.

Recently, the use of network coding [66] was proposed in order to allow the exchange of control information robustly and expeditiously in [68]. In this chapter, we propose to use physical layer Network coding (PNC), which allows multiple packets to combine in air and

through interference [67], for requesting channel assignment by multiple users.

4.1.2 Motivation

A CR network (CRN) usually employs a CCC that is used to allow exchange of control information among users in the network. This results in a wastage of network resources when there is no control data to exchange between SUs. Also, the CCC can be a source of delay, especially if SUs do not listen to the same CCC simultaneously. This motivated us to develop a coordination strategy between SUs in a CR Wireless Mesh Network (WMN) which includes the clients in a WMN and the Mesh Router (MR) without using a CCC. We propose to employ PNC in order to reduce the channel allocation overhead.

In our proposed schemes, SUs which act as mesh clients are allowed to combine their transmissions over the same channel using PNC, for requesting the MR to allocate uplink channels. If one, two, or three SUs send channel requests on the same channel, PNC allows the MR to extract such requests, hence increasing the probability of success (p_s) for request transmissions. The only restriction is that PNC requires a strict synchronization between transmissions of SUs to MR. However, the issue of synchronization and how to achieve it has been addressed and resolved in [69], [70], [71].

In this chapter, we propose three PNC schemes, namely, PNC_{w1m}, PNC_{w2m}, and PNC_{w3m}. PNC_{w1m} and PNC_{w2m} schemes allow up to 2 requests to be detected by the MR, while in PNC_{w3m} a MR can detect up to 3 SUs channel requests packets. Decoding the received signals in PNC_{w1m} depends on the received energy, while decoding the received signals in PNC_{w2m} and PNC_{w3m} depends on the received phase shifts. Our contribution in this chapter is the introduction of a channel request strategy that does not require a CCC, and which results in a reduced time overhead for channel allocation to client SUs. Two PNC schemes of our work in this chapter, PNC_{w1m} and PNC_{w2m}, are published in [73].

4.1.3 Organization

The rest of this chapter is organized as follows. The system model is introduced in Section 4.2. In Section 4.3, we present the physical layer network coding model which is employed in our proposed strategy. Then, we introduce our three proposed schemes, PNC_{w1m}, PNC_{w2m} and PNC_{w3m}. Section 4.4 describes the communication protocol between SUs and the MR in the uplink direction for our proposed three schemes. In Section 4.5, we conduct a simulation study of the proposed PNC_{w1m}, PNC_{w2m} and PNC_{w3m} protocols in order to assess their performance. Finally, we conclude the chapter in Section 4.6.

4.2 System Model

A WMN consists of a set of cells where each cell is managed by an MR. Each of the clients and the MR in the cluster are within transmission range of each other. We concentrate on uplink (from client SUs to MR) channel allocation. Let the number of client SUs in a cluster and the available channels at the MR be M and N, respectively. The assumptions are as follows:

- The MR has N transceivers for its N available channels.[1]

- Each SU has one transceiver.

- There is no coordination among SUs while selecting or accessing channels. This means that an SU does not know if it is transmitting on a certain channel simultaneously with other SUs or not.

- The proposed model is receiver based, where the receiver is the MR in the uplink direction from the SUs in the WMN cluster.

- The SUs' transmissions are synchronized, which is a requirement of PNC, in terms of time, frequency and phase. Simple and effective synchronization techniques for a group of transmitters to a receiver have been proposed in [69], [70], [71]. Those techniques are

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[1]In case the MR has fewer than N transceivers, e.g., L, the protocol described in this chapter can be applied to L channels at a time, while using $\lceil \frac{N}{L} \rceil$ rounds.

used periodically by SUs to ensure synchronization in a WMN cluster and to adjust any time, frequency or phase drifts.

- Transmission power management is used, we assume that in the deployment phase SUs cooperate with MR to adjust their transmission power levels such that their received signal power levels at MR have the same or very close power levels.

4.3   Physical Layer Network Coding Model

Physical layer Network Coding (PNC) is utilized in packet recovery to allow multiple access over the same channel and at the same time. PNC has been applied to the physical layer to increase the network capacity [67]. PNC is different from Digital Network Coding (DNC) where the coding arithmetic in the latter scheme is applied on individually received digital bit streams. However, in PNC concurrent and synchronously received electromagnetic waves are utilized in coding operation.

The goal of our protocol is to reduce the CRN setup time which refers to the overhead time required to assign the available channels at the MR to SUs. A complete setup communication protocol is described later in Section 4.4. In our proposed protocol, PNC is used only for network setup where the control packets are too short and only contain the SU's ID to enable the MR to assign channels properly to SUs.

Under the proposed schemes, the assignment of IDs to M SUs such that they can be unambiguously decoded requires an ID field length of $M + 1$ bits such that the ID's bits corresponding to SU_i are all set to zeros except bit number i which is set to 1. For instance, for SU_1 the ID is "0000010" if $M = 6$ and for SU_2 the ID is "0100" for $M = 3$. Table 4.1 shows an example of selected IDs when $M = 5$. It is worth noting that in one cluster of WMNs the number of SUs usually is not large, and only a short ID field is required. The reason for this choice of ID will become clear when we discuss our strategies.

We propose that SUs in a CR-WMN cluster adopt one of the following three modulation schemes, PNC_{w2m}, PNC_{w1m} or PNC_{w3m} (which are explained in detail in Subsections 4.3.1, 4.3.2 and 4.3.3, respectively), in the network operation to transmit their IDs concurrently

where the ID coding proposed earlier is used in these modulation schemes. Let us introduce the following defintions:

Definition 4.3.1 *Time Slot: is a period of time which includes: First, a MR broadcasts at the beginning of this period of time, over all its available channels, N, a pull signal which contains the ID numbers of its available channels. Second, each SU selects a channel out of N, and sends its ID number to the MR. Third, the MR assigns channels for successfully received SUs packets, and broadcasts an allocation packet to corresponding SUs, which contains their channels assignment. Fourth, SUs send positive acknowledgment packets to the MR, to confirm their channels assignment.*

Definition 4.3.2 p_s: *is the probability that an SU successfully transmits a channel request packet and is therefore assigned a data channel, if available, by the MR.*

Definition 4.3.3 *Setup time overhead: is the required time to allocate the available channels at the MR to the SUs in the WMN cluster by the MR itself.*

The received signals are decoded to extract the stations' IDs, or to detect collisions efficiently. Selecting one strategy over others has a trad-off for the p_s and the setup time overhead as illustrated in Section 4.5, e.g., PNC_{w1m} has lower setup time than PNC_{w2m} and PNC_{w3m}.

4.3.1 PNC_{w2m} (PNC with Two Modulation Schemes):

Let there be two transmitters (SUs), say A and B, and one receiver (MR) where the SUs send their IDs to the MR. A and B use one channel at the same time to transmit requests (for uplink channels) to the MR. A transmitter can employ standard Binary phase-shift keying (BPSK) modulation, call it M_1, in which the symbol can take antipodal values A_1 or A_0, while the other transmitter can employ another BPSK that is orthogonal to the first, call it M_2 which corresponds to B_1 and B_0 as shown in Figure 5.2. In this scheme, the two modulation schemes, $M1$ and $M2$ are used, and an SU randomly decides to use either $M1$ or $M2$ as its modulation scheme. If the two SUs use orthogonal BPSK schemes, then this is sufficient to decode the received signals as the combinations of the bits are uniquely decodable, as shown in
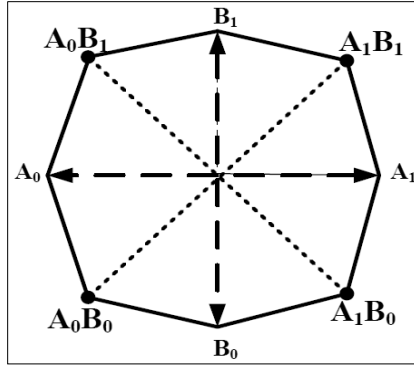
Figure 4.1: Constellation diagram for two transmitters A and B.

Figure 5.2 and Table 5.1, e.g., when 2 SUs transmit simultaneously symbols A_1 and B_1 at the same time slot, the received phase shift at the MR is $\frac{\pi}{4}$. Signals transmitted by A and B SUs are shown in dashed lines in Figure 5.2. In this case, these two transmitters can be regarded as transmitting orthogonally to each other. The BER in this scheme is similar to orthogonal QPSK if both A and B transmit simultaneously, and orthogonally.

The BPSK signal with orthogonal signalling is used by the MR to decode the signals from the SUs transmitters, A and B, by using the resultant phases and the energy of the received signals as shown in Table 5.1. In PNC_{w2m} scheme, each SU chooses one of the two modulation schemes, M_1 and M_2, randomly and independently. Therefore, two or more SUs may choose the same modulation scheme, and this can result in a collision.

Definition 4.3.4 PNC_{w2m} collision (PNC_{w2mC}): the collision on a channel is due to either a transmission where more than 2 SUs access the channel simultaneously or 2 SUs access the channel simultaneously, but both have selected the same modulation technique.

To detect PNC_{w2mC} in this scenario, assume some SUs use modulation technique M_1 and the others use modulation technique M_2. The phase shifts for the received signals are used to detect collisions. If the phase shifts do not match the values in Table 5.1, then this indicates a collision. When more than two SUs use the same channel, then none of the detected phase shifts will correspond to A_1B_0 or A_0B_1 (due to using the SUs' IDs coding shown in Table 4.1). For example, assume there are two SUs, say SU_i and SU_j, where SU_i has selected M_1 and SU_j has selected M_2 as their modulation techniques. If the received symbol is A_0B_1, that means

SU_i and SU_j have transmitted bits 0 and 1, respectively. However, when more than two SUs access the channel in the same time slot, the received signal phase shift does not match A_1B_0 or A_0B_1. Thus, in PNC_{w2m} decoding the received signals mainly depend on their received phase shifts.

If both SUs employ the same modulation scheme, e.g., M_1, corruption happens when one of the transmitters transmits '1' bit and the other transmits '0' bit, given both SU transmitters have the same transmission energy. In this case, the received signal can not be used for decoding because its energy level is zero. We call this signal 'X'. Actually for this reason, we preferred to introduce PNC_{w2m} scheme before PNC_{w1m} scheme, since PNC_{w1m} considers this problem. PNC_{w1m} decodes the received signal for a pair of SU transmitters although there are some received bits' signals have zero energy, 'X'.

4.3.2 PNC_{w1m} (PNC with One Modulation Scheme):

In this scheme, all SUs use one modulation scheme, e.g., $M1$. Thus, the decoding process shown in Table 5.1 does not work. When any pair of SUs transmit their IDs using the same BPSK modulation scheme M_1, the bits of SUs' IDs are Mixed using PNC, call it $PMIX$, which is shown in Table 4.3. For example for 2 SUs, if both SUs transmit 0's or 1's, then, the received phase shifts correspond to bits 0 or 1 bits, respectively. However, their received signals have higher energy than either transmitted signals by SUs. Another scenario for 2 SUs, if one SU transmitted A_0, and the other SU transmitted A_1. Hence, the received signal at MR has no energy, call it 'X'. As a result, the SUs' IDs must be chosen such that two conditions hold: (a) PMIX of any pair of SUs' IDs is unique, and (b) PMIX of more than two SUs' IDs is distinguishable from PMIX of any pair of SUs' IDs.

When the SUs' IDs are selected as indicated above, then they satisfy the above two conditions (a and b), and the received signals can be decoded correctly. For example, if $M = 2$, the IDs for SU_0 and SU_1 are "001" and "010", respectively, and their received code word at MR is "0XX" if both SUs use the same channel. This can be decoded uniquely, since each ID has exactly one bit equal to '1'. It should be noted that when SU_i and SU_j transmit their IDs

using the same modulation scheme, bits i and j will both have no energy (X), and the rest of the bits will be zeroes. Notice that if only M bits are used for the ID packet, e.g., $M = 2$, the IDs will be "01" and "10" for SU_0 and SU_1, respectively. Thus, if those SUs use the same channel, the received code word at MR is "XX" which contains no energy and will not be detected. Therefore, the extra '0' bit to the left is necessary to detect the SUs transmissions at the MR. Condition (b) is satisfied, given the proposed SUs' IDs selection strategy is employed, because when the received bits stream at MR has no bits with zero energy, 'X', this indicates that more than 2 SUs have transmitted their packets at the same time slot, which means that collision occurred.

Definition 4.3.5 PNC_{w1m} *collision* (PNC_{w1mC}): *A transmission on a channel where more than 2 SUs have accessed the channel simultaneously.*

If PNC_{w1mC} occurs, the received signal values for k (k is the number of SUs out of M, which transmitted their packets on the same channel and in the same time slot) bits are all '0's with the same energy level (given the k SUs received energy levels are the same, $k \geq 3$). The rest of $(M - k + 1)$ bits are '0's and their energies are equal and have a higher energy level than the k bits, recall M is the total number of SUs in WMN cluster. Thus, no 'X' bits are received. Therefore, the collision is detectable by the MR because the received codeword bits are all zeros with π as their phase shifts (if M_1 is employed by SUs). Thus, decoding the received signals mainly depends on their received power levels. The BER is similar to BPSK if both A and B transmit individually or simultaneously.

4.3.3 PNC_{w3m} (PNC with Three Modulation Schemes):

This scheme allows a successful coding and decoding, when three SUs transmit their packets concurrently. This scheme also uses physical layer network coding (PNC), but allows up to 3 SUs packets' IDs to be decoded successfully by the MR. Figure 4.2 shows the Constellation diagram for three transmitters A, B, and C. We define the following modulation (M) techniques: M_1 (A_1, A_0), M_2 (B_1,B_0), and M_3 (C_1, C_0). M_1, M_2, and M_3 are the basic
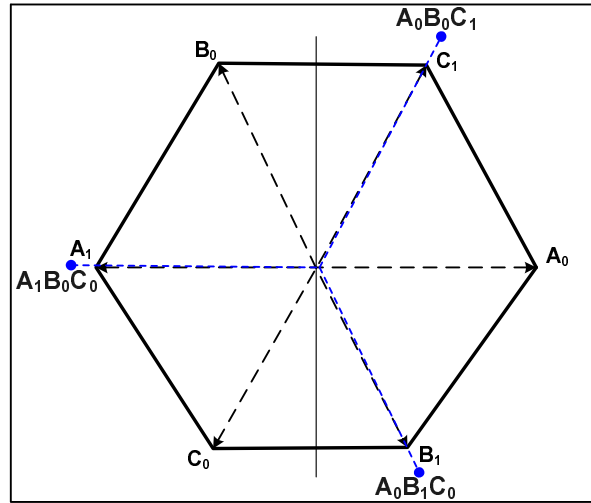
Figure 4.2: Constellation diagram for three transmitters A, B, and C.

Binary Phase-Shift keying (BPSK), a 120 degree phase shifted, and a 240 degree phase shifted versions, respectively.

We are only interested in the phase shifts for signals where the 3 SUs send at most one bit as '1' or all bits '0's, because we use the ID coding method as in Table 4.1. For example, the following cases never occur: $A_1B_1C_0$, $A_1B_0C_1$, $A_0B_1C_1$, and $A_1B_1C_1$, due to using this ID selection method.

Table 4.4 explains coded signals for 3 SUs transmitters, and how to decode them, e.g., when 3 SUs transmit simultaneously A_0, B_0, and C_1 symbols, respectively, the received phase shift for these symbols is $\frac{\pi}{3}$.

However, Tables 4.5, 4.6, and 4.7 show the coded and decoded signals for all possible combinations of 2 transmitters out of 3 (A, B and C) when PNC_{w3m} is employed by SUs in the network. Tables 4.5 show the possible combination when only 2 SUs transmit, under PNC_{w3m}, where one SU employs M_1 and the other SU employs M_2 as their modulation schemes, e.g., when A_0 and B_1 are transmitted, the received phase shift at the MR is $\frac{-\pi}{6}$. Table 4.6 show the possible combination when only 2 SUs transmit, under PNC_{w3m}, where one SU employs M_1 and the other SU employs M_3 as their modulation schemes, e.g., when A_0 and C_0 are transmitted, the received phase shift at the MR is $\frac{-\pi}{3}$. Table 4.7 show the possible combination when only 2 SUs transmit, under PNC_{w3m}, where one SU employs M_2 and the

other SU employs M_3 as their modulation schemes, e.g., when B_1 and C_0 are transmitted, the received phase shift at the MR is $\frac{-\pi}{2}$.

Therefore, as shown in these tables all cases and combinations of 2 or 3 SUs phase differences are distinguishable from each others. Thus, collisions can be detected.

Definition 4.3.6 *Successful transmission under PNC_{w3m} includes three cases, as follows:*

1. *When one SU selects a channel and any modulation technique M1, M2, or M3.*

2. *When 2 SUs select a channel and choose different modulation techniques.*

3. *When 3 SUs select a channel and they choose different modulation techniques.*

Other than that, SUs transmissions are considered to result in a collision, in which the received signal at the MR cannot be decoded, e.g., when 3 SUs transmit and two of them employ the same modulation scheme, say M_1. Or, more than 3 SUs transmit simultaneously and at the same channel. As a result, the associated SUs, when they do not receive channel allocation indication due to collision, try to send their requests again in the following time slot(s).

4.4 Communication Protocol

The communication and control signals exchange protocol is explained in this section. Mainly, we are interested in setup time reduction in CR-WMNs using PNC. SUs at deployment phase, tune to available channels at MR. However, whenever channels availability at MR changes, the MR advertises its available N channels to SUs by broadcasting the available channels information over all N channels. If an SU is tuned to a channel which becomes no longer available at MR, therefore, the SU is no longer receiving packets from MR. In this case, the SU waits for few time slots, e.g., 2 time slots, in which no packets are received. Therefore, the SU starts scanning the spectrum until finding an available channel, and tunes its transceiver to this channel.

Initially, the SUs adopt either PNC_{w1m}, PNC_{w2m}, or PNC_{w3m} through its operation. The communication protocol for PNC_{w1m}, PNC_{w2m}, or PNC_{w3m} is as follows:
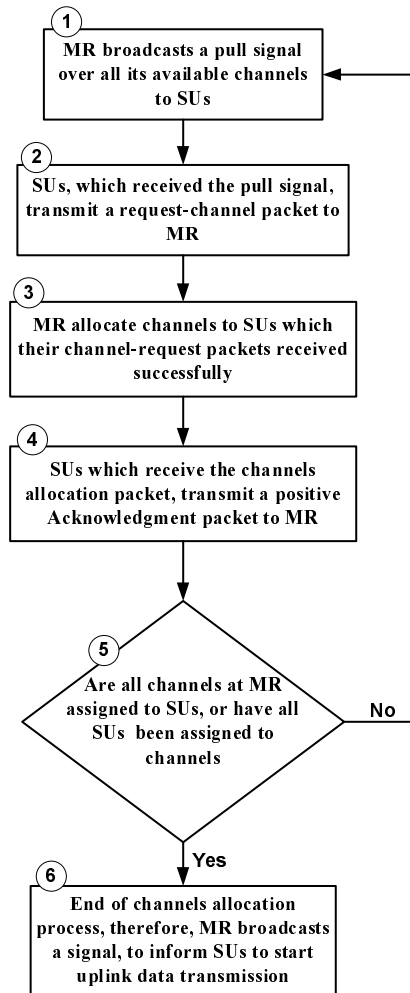
Figure 4.3: Communication protocol for channels allocation by MR, where the number in the small circle denotes the step number in the communication protocol.

The communication protocol steps, as shown in Figure 4.3, are as follows:

1. The MR sends a pull signal over all its N channels, which also includes the list of all free channels and their spectrum information such as their location on the spectrum band and their bandwidths. Each SU therefore becomes aware of all free channels.

2. When an SU receives the pull signal, the SU selects one channel randomly out of N, and sends a channel request packet containing its ID to the MR on that channel. Transmissions by SUs need to be synchronized for PNC implementation.

3. The MR receives a set of channel requests from SUs over some/all of its channels. At

this stage, the MR concludes that the received packet over a channel is due to either 1 or 2 SU transmissions (no collision), or more than two SU transmissions (collision), e.g., if PNC_{w2m} is employed by SUs, as explained above. The MR processes the successfully received channel requests and assigns channels to SUs. Then, the MR broadcasts the channel allocation over each channel on which a request was received. For instance, if two SUs requests are received, the MR broadcasts one packet which contains the channel assignment information for both SUs. But when a collision occurs, the MR does not broadcast a channel assignment packet, hence the SUs (e.g., if PNC_{w2m} is employed by SUs, the number of SUs ≥ 3) will try to send their channel requests in the next time slot, and on a channel which is selected randomly from among the remaining channels.

4. The SUs, which sent requests in step 2, stay tuned to the same channel in order to receive the channel allocation packet sent by the MR. At this stage, there are two possibilities: first, the SU does not receive a reply from the MR due to either packets colliding at step 2, or lack of available channels. Second, the SU receives channel allocation packet, in which the SU finds that it has been assigned a channel, or it is not assigned a channel due to lack of available channels. Each SU which receives a channel allocation packet sends a positive ACK signal to the MR, containing its ID, over the channel that was assigned by the MR, and in this case there will be no collision, and PNC is not needed, since the MR assigns at most one SU to a channel, for data transmission after the channels allocation process is finished at Step 6.

5. Go to Step 6, in two cases: first, the number of SUs is at least equal to N, and all channels at the MR have been assigned to SUs. Second, the number of SUs does not exceed N, and all SUs have been assigned to channels. Otherwise, go to Step 1 in order to repeat Steps form 1 to 5.

6. In this Step, the MR broadcasts a signal over the available channels to inform the SUs to start their uplink data transmissions where these data packets will be relayed by the MR to the gateway of the CR-WMN.
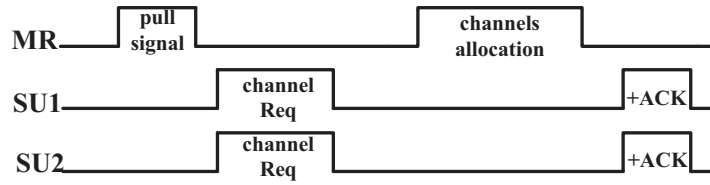
Figure 4.4: Control Signals for one time slot in PNC for 2 SUs, e.g., $PNCw2m$ and $PNCw1m$.

For example, Figure 4.4 shows a time line for exchanging the control signals and executing the communication protocol between MR and 2 SUs in one time slot, assuming the SUs transmissions are synchronized.

4.5   Results and Discussion

In this section, five different schemes are considered and compared using simulation, as follows:

- **The First scheme** is the classical scheme where one channel is used as a CCC for channel allocation to SUs by MR in the WMN cluster. We refer to this scheme as the CCC scheme. The SUs' access channel protocol is CSMA/CA with the RTS/CTS used in IEEE 802.11 networks. We used the OPNET simulation tool to implement the CCC scheme.

- **The Second scheme** is a time slotted scheme where PNC is not used, and we refer to it as (No PNC). For an SU's packet request to be successful, it must be the only packet on the channel in a time slot.

- **The Third scheme** is a time slotted with PNC_{w1m}, call it PNC_{w1m}.

- **The Fourth scheme** is a time slotted with PNC_{w2m}, call it PNC_{w2m}.

- **The Fifth scheme** is a time slotted with PNC_{w3m}, call it PNC_{w3m}.

At the beginning of each time slot, all SUs which have not been assigned channels yet, compete for the N channels such that each SU selects a channel randomly to send a channel

Request (Req) packet to the MR without coordination among them. In these four schemes (the second, third, fourth, and the fifth schemes) there are no RTS/CTS handshakes. In the second scheme, if more than one SU accesses a channel, a collision occurs. However, in the third and fourth schemes, if more than two SUs access a channel, a collision occurs. In the fifth scheme, if more than three SUs access a channel, a collision occurs.

When a collision occurs on a channel the MR will not be able to decode the received SUs' IDs correctly. Subsequently, those SUs will try in the following time slots until channels are assigned to them by the MR (if there are still available channels). We assume that the communication is synchronized. For simplicity, we assume that the propagation and processing delays are included in a time slot which is shown in Figure 4.4. To measure the overall delay for the time slot, we used the OPNET simulation tool. In our simulation study, we used the default channel model in OPNET which is the Additive White Gaussian Noise (AWGN) model [72]. OPNET consists a set of pipeline stages at the radio transceiver to calculate the corresponding BER. We used the default model for background noise that considers a constant ambient noise level and a constant thermal noise at the receiver, to calculate the Signal-to-Noise Ratio in the SNR model stage of the radio transceiver pipeline. The BER is found by evaluating the SNR in the pipeline stages, and find its corresponding BER value in a pre-calculated lookup table that resides in OPNET libraries. It is worth mentioning that the BERs for PNC_{w1m} and PNC_{w2m} are similar to BPSK and orthogonal QPSK, respectively, with no collisions.

4.5.1 Probability of Success:

Recall that the probability of success, p_s, is the probability that an SU successfully transmits a channel request packet and is therefore assigned a data channel, if available at MR. Figures 4.5, 4.6, 4.7, and 4.8 show the p_s for the second scheme where PNC is not used, (No PNC), the third scheme (PNC_{w1m}), the fourth scheme (PNC_{w2m}), and the fifth scheme (PNC_{w3m}) when the number of channels, N, is 4, 6, 8 and 10, respectively, and for different numbers of SUs.

Clearly, the results show that using PNC_{w1m}, PNC_{w2m}, or PNC_{w3m} schemes increases

p_s for channel requests compared to (No PNC) scheme where PNC is not employed. It also decreases the channel assignment time delay, as will be shown next. Also, these Figures show that PNC_{w1m} outperforms both PNC_{w2m} and PNC_{w3m} in terms of p_s for different N and M when it is employed by SUs. However, PNC_{w3m} outperforms PNC_{w2m} in terms of p_s. Recall, decoding the received signals in PNC_{w2m} and PNC_{w3m} depends on the received phase shifts, while in PNC_{w1m} it depends on the received energy. Thus, it is better to use PNC_{w2m} or PNC_{w3m} scheme over PNC_{w1m}, when the environment conditions are worse such as noise.

For example, in Figure 4.8 the number of channels, N, is equal to 10 and when the number of SUs, M, is equal to 8, the p_s is 0.47 for the Second scheme when PNC is not employed by SUs, however, p_s increases to 0.85, 0.66, or 0.75, if PNC_{w1m}, PNC_{w2m}, or PNC_{w3m} is employed by SUs, respectively. Recall, one scheme can be employed by SUs in a CR-WMN cluster at a time, e.g., PNC_{w1m}.

4.5.2   Setup Time Overhead:

Figures 4.9, 4.10, 4.11, and 4.12 show the setup time overhead for the five schemes explained earlier when the number of channels, N, is 4, 6, 8 and 10, respectively, and different numbers of SUs, M, in a CR-WMN cluster.

Clearly, our proposed schemes (PNC_{w1m}, PNC_{w2m}, or PNC_{w3m}) which use PNC technique outperform both the first and the second schemes, namely, the CCC and the time slotted without PNC schemes (No PNC), respectively. The results show PNC_{w3m} has less setup time overhead than PNC_{w2m}. On the other hand, PNC_{w1m} outperforms both PNC_{w2m} and PNC_{w3m} in terms of setup time overhead.

Table 4.8 shows the setup time overhead reduction percentages for the third, the fourth, and the fifth schemes compared to the first scheme for different values of N and M. The results show that PNC_{w1m} scheme outperforms both PNC_{w2m} and PNC_{w3m} schemes, because the setup time overhead is less when PNC_{w1m} scheme is employed by SUs rather than PNC_{w2m} or PNC_{w3m}. Also, Table 4.8 shows the reduction in setup time overhead for PNC_{w1m} scheme is higher than PNC_{w2m} and PNC_{w3m} for different values of N and M. On the other hand,
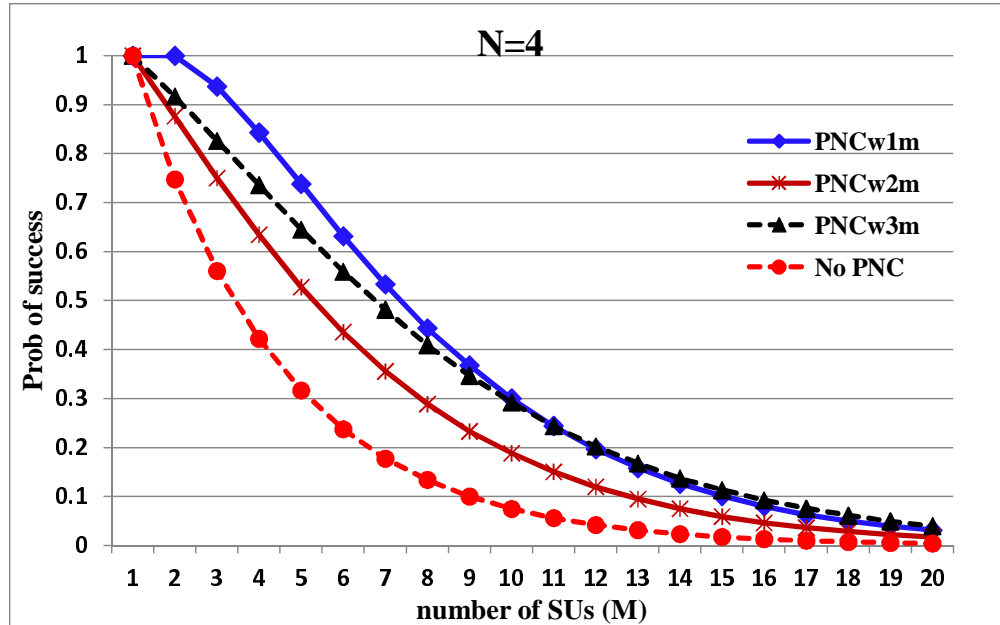
Figure 4.5: Prob of success, p_s, when $N = 4$.
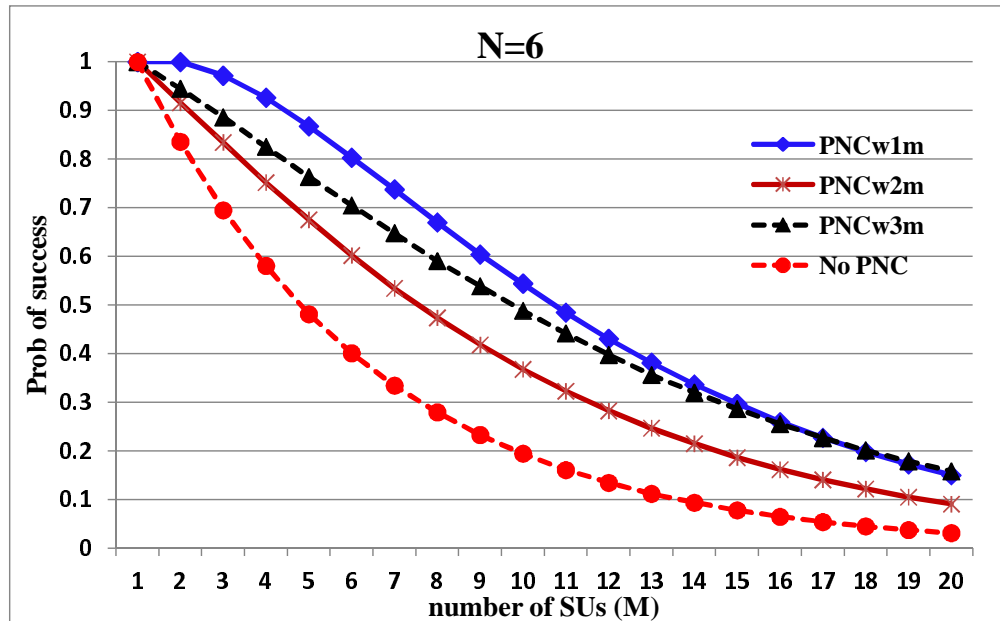
Figure 4.6: Prob of success, p_s, when $N = 6$.
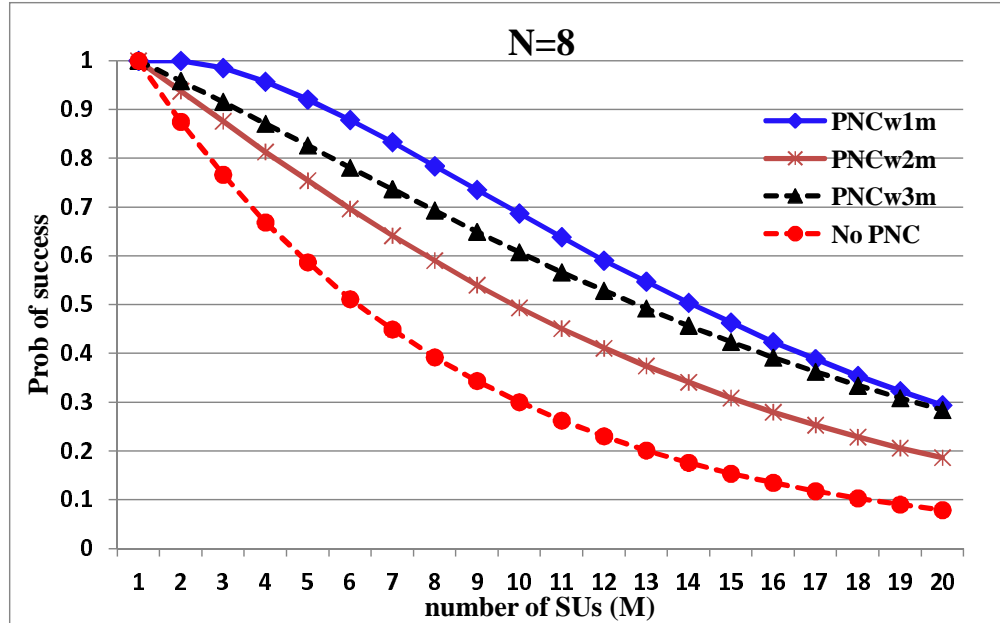
Figure 4.7: Prob of success, p_s, when $N = 8$.
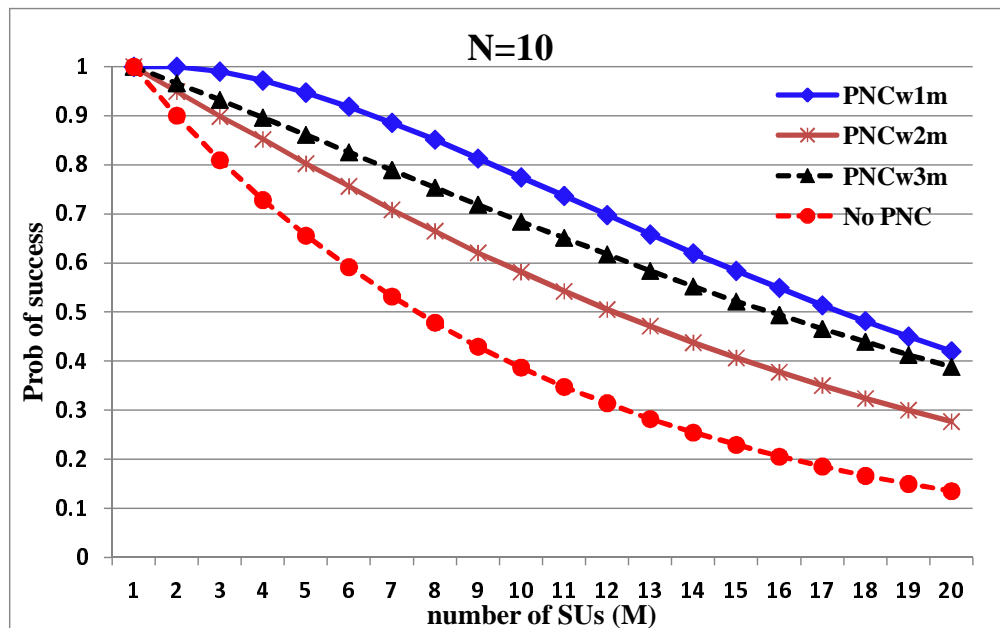
Figure 4.8: Prob of success, p_s, when $N = 10$.
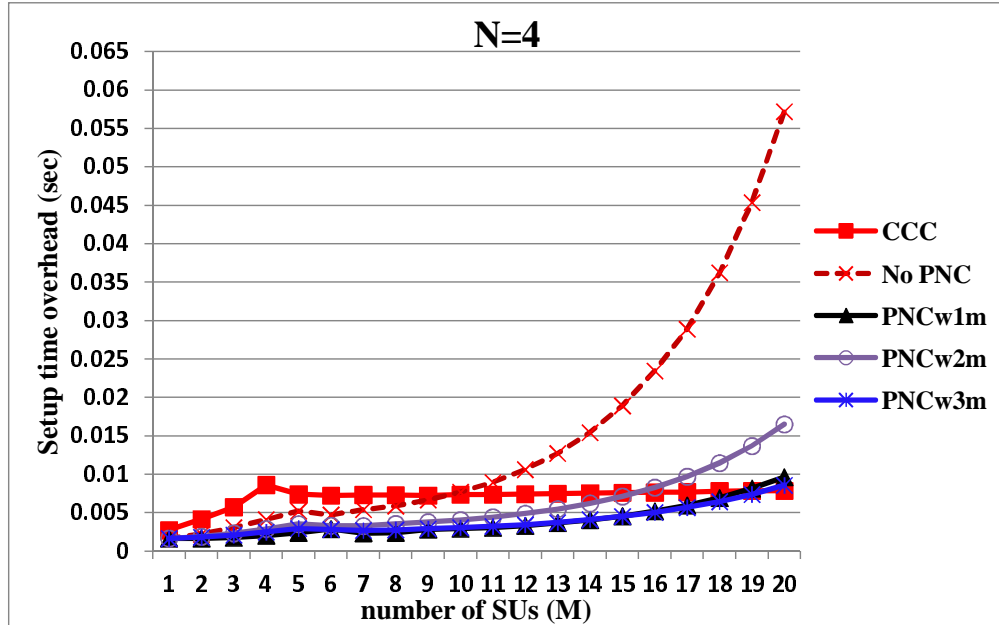
Figure 4.9: CR network setup time overhead, when N=4.
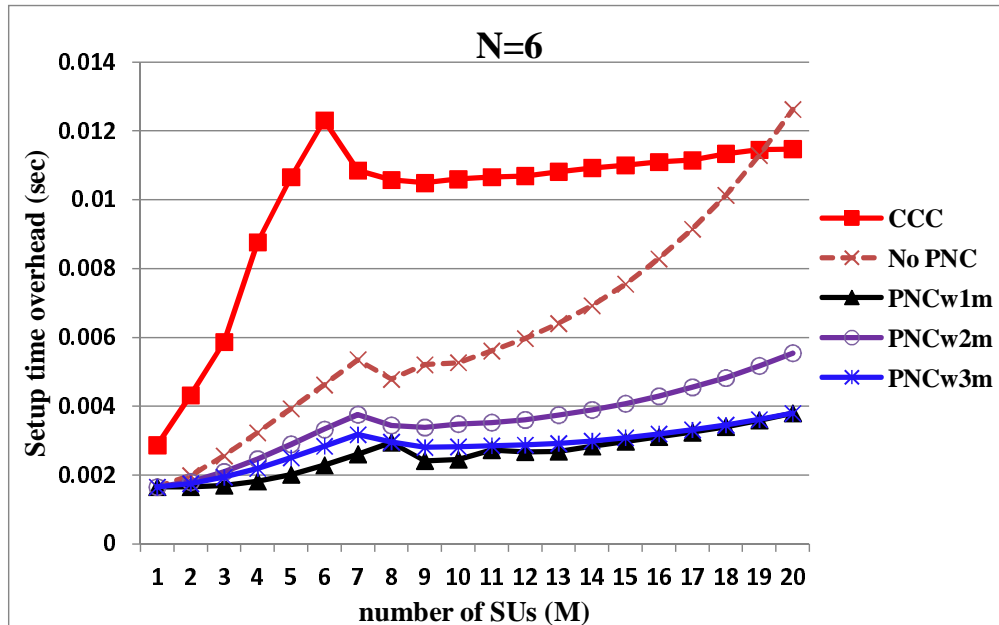
Figure 4.10: CR network setup time overhead, when N=6.
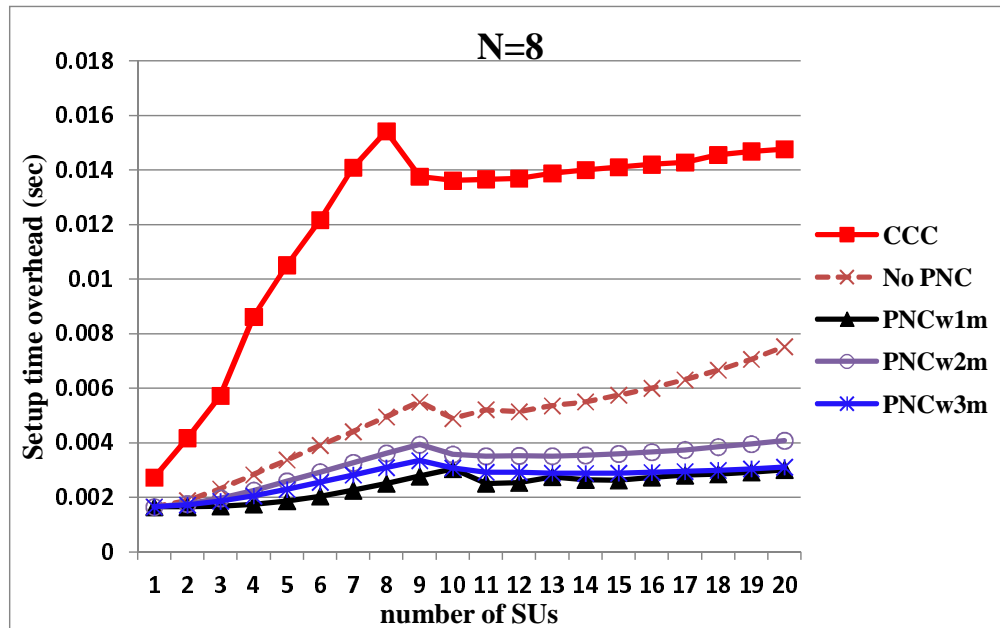
Figure 4.11: CR network setup time overhead, when N=8.
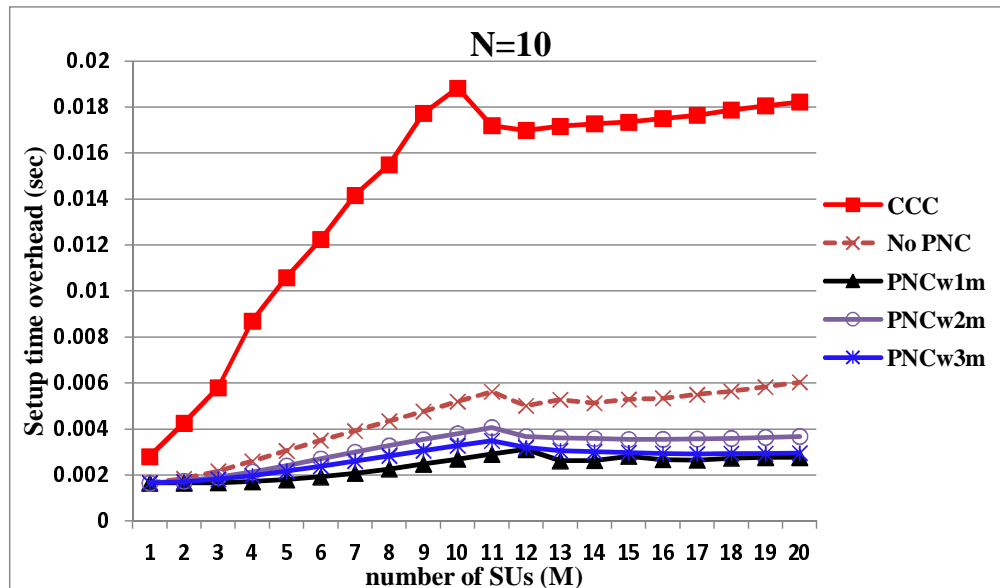
Figure 4.12: CR network setup time overhead, when N=10.

PNC_{w3m} outperforms PNC_{w2m}, since the reduction in setup time overhead for PNC_{w3m} is higher than PNC_{w2m}.

An interesting observation is that the setup time overhead increases almost linearly if the number of SUs is $\leq N$. However, if the number of SUs is $> N$, then the overhead starts to decrease before increasing again. Actually, the peak is always at N, N+1, N+1, N+1, and N+2 for CCC, (No PNC), PNC_{w2m}, PNC_{w3m}, and PNC_{w1m} schemes, respectively.

4.6 Chapter Summary

In this chapter, we propose three new schemes for channel request and assignment in CR-WMNs. Our schemes are based on employing Physical layer Network Coding (PNC). In the first and second modulation schemes, namely PNC_{w1m} and PNC_{w2m}, up to 2 SUs may select the same channel to send channel request packets to the MR, simultaneously. However, in our third scheme, namely PNC_{w3m}, up to 3 SUs may select the same channel to send channel request packets to the MR, concurrently.

In the proposed PNC schemes, PNC_{w1m}, coding and decoding the received signals depends on the energy received at MR. However, in PNC_{w2m} and PNC_{w3m}, coding and decoding the received signals at MR depends on their received phases shifts.

Simulation results show that our three proposed schemes outperform the CCC scheme and the scheme in which time is slotted and an SU selects randomly one channel out of N channels to send the channel request packet to MR without using PNC. The new schemes have much lower setup time overhead, which is required to allocate N channels to the set of SUs in the CR-WMN cluster. Also, the probability of success (p_s) for packet delivery by SUs is higher when PNC is employed in the slotted time scheme. Also, the simulation results show PNC_{w1m} scheme outperforms both PNC_{w2m} and PNC_{w3m} schemes in terms of p_s and setup time overhead, if it is employed by SUs. Also, PNC_{w3m} scheme outperforms PNC_{w2m}, since PNC_{w3m} has a higher p_s and a lower setup time overhead.

Table 4.1: The set of valid IDs for five SUs in a WMN cluster.

SU	SU's ID
0	000001
1	000010
2	000100
3	001000
4	010000

Table 4.2: Signals coding and decoding for two transmitter nodes and one receiver node in PNC_{w2m} scheme.

A	B	PNC Signal	Decoded Signals
0	0	signal with the phase difference $e^{j(-\frac{3\pi}{4})}$	A_0,B_0
0	1	signal with the phase difference $e^{j(\frac{3\pi}{4})}$	A_0,B_1
1	0	signal with the phase difference $e^{j(-\frac{\pi}{4})}$	A_1,B_0
1	1	signal with the phase difference $e^{j(\frac{\pi}{4})}$	A_1,B_1

Table 4.3: The PMIX operation for transmitted bits in PNC_{w1m} scheme.

A	B	PMIX
0	0	0
0	1	X
1	0	X
1	1	1

Table 4.4: Signals coding and decoding for three transmitter nodes and one receiver node in PNC_{w3m} scheme.

A	B	C	PNC Signal	Decoded Signals
0	0	0	Signal with zero energy at the origin	A_0,B_0,C_0
0	0	1	signal with the phase difference $e^{j(\frac{\pi}{3})}$	A_0,B_0,C_1
0	1	0	signal with the phase difference $e^{j(-\frac{\pi}{3})}$	A_0,B_1,C_0
1	0	0	signal with the phase difference $e^{j(\pi)}$	A_1,B_0,C_0

Table 4.5: Signals coding and decoding for two transmitter nodes, A and B, and one receiver node in PNC_{w3m} scheme.

A	B	PNC Signal	Decoded Signals
0	0	signal with the phase difference $e^{j(\frac{\pi}{3})}$	A_0,B_0
0	1	signal with the phase difference $e^{j(\frac{-\pi}{6})}$	A_0,B_1
1	0	signal with the phase difference $e^{j(\frac{5\pi}{6})}$	A_1,B_0

Table 4.6: Signals coding and decoding for two transmitter nodes, A and C, and one receiver node in PNC_{w3m} scheme.

A	C	PNC Signal	Decoded Signals
0	0	signal with the phase difference $e^{j(\frac{-\pi}{3})}$	A_0,C_0
0	1	signal with the phase difference $e^{j(\frac{\pi}{6})}$	A_0,C_1
1	0	signal with the phase difference $e^{j(\frac{7\pi}{6})}$	A_1,C_0

Table 4.7: Signals coding and decoding for two transmitter nodes, B and C, and one receiver node in PNC_{w3m} scheme.

B	C	PNC Signal	Decoded Signals
0	0	signal with the phase difference $e^{j\pi}$	B_0,C_0
0	1	signal with the phase difference $e^{j(\frac{\pi}{2})}$	B_0,C_1
1	0	signal with the phase difference $e^{j(\frac{-\pi}{2})}$	B_1,C_0

Table 4.8: A sample for setup time overhead reduction percentages for the third, fourth, and fifth schemes compared to the first scheme (CCC).

Scheme	N=4, M=6	N=4, M=10	N=10, M=6	N=10, M=10
PNC_{w1m}	60%	60%	84%	85%
PNC_{w2m}	54%	45%	77%	79%
PNC_{w3m}	60%	58.3%	80.5%	82.5%

CHAPTER 5   Interference-Based Packet Recovery for Energy Saving in Cognitive Radio Networks

5.1   Introduction

In CRNs, PUs and SUs packets may collide when a PU becomes active while an SU is transmitting its packet. Recovering SUs collided packets can lead to performance improvement such as energy saving in some wireless networking environments, e.g., WiMAX wireless networks, cellular networks, and licensed wireless microphones. In this chapter, we propose two recovery mechanisms, which we refer to as graceful hand-off mechanisms 1 and 2. These recovery mechanisms are based on canceling the effect of interference that is caused by colliding signals. We assume PUs and SUs to be in the same locality in a wireless network, which employ BPSK or QPSK as their modulation techniques. BPSK and QPSK modulations are used in many wireless communication networks, such as a high-speed wireless access standards, e.g., WiMAX wireless networks, in which the spectrum bands range from 2 GHz to 66 GHz, and include both licensed and unlicensed bands, according to IEEE $802.16-2009$ Standard [75]. A WiMAX user or subscriber (who pays for channel access) may change its modulation scheme based on the channel quality. For example, when channel's conditions are bad, a user employs low complexity modulation such as BPSK/QPSK, to increase data transmission reliability. However, when channel's conditions are good, higher complexity and higher bit rate modulation techniques are employed such as $16-QAM$ or $64-QAM$ in order to increase throughput. In this chapter, we are interested in cases when a PU (WiMAX subscriber or BS) employs BPSK while transmitting over its licensed channel bands, and SUs modulation technique is QPSK, or vice versa. Or, both PUs and SUs employ BPSK. If an SU is transmitting over a

channel, and the channel's PU becomes active, then a collision occurs between the SU and the PU packets. Our goal in this chapter is to recover these collided packets of SUs.

Besides WiMAX networks, recent research has considered using licensed channels of cellular network to increase the capacity of SUs in CRNs [76, 77]. SUs opportunistically access cellular network channels, while its PUs are protected. CDMA2000, which is a 3G mobile standard networks that uses Code/Time Division Multiple Access multiplexing techniques for data and voice transmission in cellular networks, employs BPSK and QPSK modulation techniques for uplink and downlink data transmission, respectively [78]. Also, BPSK and QPSK modulation techniques are employed by licensed wireless microphones with low transmission power, as described in IEEE 802.22 standard [79]. In CRNs, SUs must detect the presence of PUs when they become active within a specified interval time, call it monitoring cycle, where its duration is dependent on the type of PUs, their applications nature, and QoS.

Definition 5.1.1 *Monitoring Cycle: is the time between the end of a sensing period and the end of the next sensing period for an SU, while the SU is transmitting its packet(s).*

During the sensing period (which is part of monitoring) an SU conducts in-band sensing, to find out whether the PU of the channel that is being accessed by the SU became active or not. If a PU presence is miss-detected during the sensing period, as a result, all the SU transmitted bits during the following monitoring cycle collide with the PU's transmission. Even though, the SU receiver can recover these collided bits while receiving them one by one, by employing our proposed technique in this chapter.

5.2 Motivation

When a PU becomes active it does not sense its licensed channel to detect whether it is being used by an SU or not. Therefore, the PU just starts transmission over its assigned channel. As a result, if an SU has been using this channel at that time, a collision occurs between the head of the first packet transmitted by the PU and the tail of the last transmitted SU packet. To the best of our knowledge there is no proposed work in literature to recover these collided packets for the SU. Therefore, this problem motivated us to propose a new scheme, which we
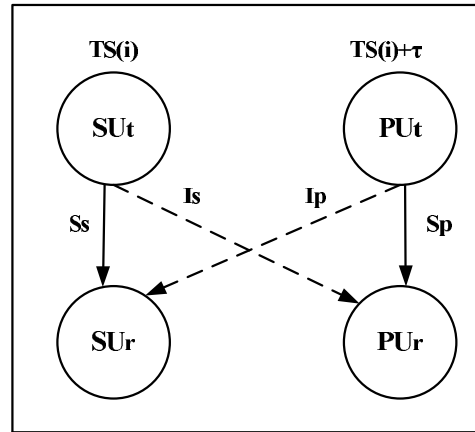
Figure 5.1: System Model.

call graceful hand-off, and employ the additive nature of the electromagnetic (EM) waves as a coding operation for the simultaneously transmitted signals, in order to allow the SU receivers to recover their collided sub-packets. Our proposed scheme results in energy saving, because the recovered collided packets will not be retransmitted, and therefore, the transmission energy is saved for the SU transmitters. Our work in this chapter is published in [74].

5.3 System Model

Figure 5.1 shows a sketch for our proposed model, a PU transmitter (PU_t) and its corresponding PU receiver (PU_r), and an SU transmitter (SU_t) and its corresponding SU receiver (SU_r). We assume the MAC protocol is time slotted. Therefore, at the beginning of each Time Slot (TS), say TS i (TS(i)), the SU_t transmits only if it senses the channel is idle (which means the PU is idle). However, if the PU transmitter becomes active, PU_t, after time τ, a collision occurs between the head of the first packet transmitted by the PU_t and the tail of the last packet transmitted by the SU_t, such that, $0 \leq \tau \leq T - \epsilon$, where T is the length of the time slot, and ϵ is a small time period. When the collision occurs the SU_r receives a superimposed signal of the SU_t's signal, call it S_s, and PU_t's signal, call it I_p. Therefore, SU_r considers I_p as an interference signal, and cancels its effect on its signal of interest, S_s. Our proposed scheme will be explained in details, when we present our proposed graceful hand-off mechanisms 1 and 2 for packets recovery, in Sections 5.5 and 5.6, respectively.

Our scheme is different from Physical layer Network Coding (PNC) [67] and Analog Network Coding (ANC) techniques [27], because we recover the packets at the receiver nodes without using a relay node as shown in Figure 5.1, while PNC and ANC techniques requires a relay node. Similar to PNC, our proposed scheme requires synchronization between SUs and PUs, similar to other CRN MAC protocols [80]. This synchronization can be implemented with the help of the Common Control Channel (CCC). The SU_t and SU_r communicate with each others iteratively to synchronize themselves to the PU. Also, the PU oscillator stays on when it goes to sleep, if the PU sleep time interval is small.

In our proposed packets recovery mechanisms, SUs modulation technique selection is based on the modulation technique employed by PUs. Let M_1 be a BPSK modulation scheme that is represented by A_1 and A_0 symbols with phase shifts 0 and π, respectively. Also, let M_2 be a BPSK modulation scheme that is represented by B_1 and B_0 symbols with phase shifts $\frac{\pi}{2}$ and $\frac{-\pi}{2}$, respectively, as shown in Figure 5.2. The QPSK, when employed, is represented by 4 symbols, such that each symbol codes two transmitted bits. As shown in Figure 5.3 symbols A_{11}, A_{01}, A_{00}, and A_{10} correspond to $'11'$, $'01'$, $'00'$, and $'10'$ bit combinations, respectively.

5.4 Model Assumptions

We introduce the following common assumptions:

- The Medium Access Control (MAC) protocol is time slotted.

- The modulation schemes for PUs and SUs are either both BPSK, or one is BPSK and the other is QPSK.

- Our proposed scheme mainly depends on phase shifts rather than received energy in order to recover the received signals.

- SUs and PUs are synchronized [80], as we explained in our system model, Section 5.3.

- The SUs can detect and recognize the modulation technique employed by PUs. Many methods have been proposed in literature, as in the survey in reference [81], to detect different modulation techniques.
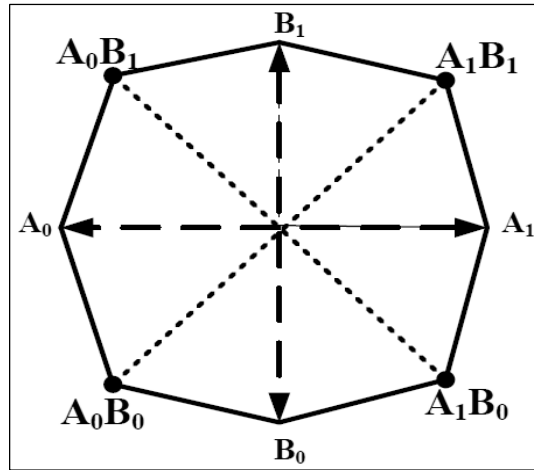
Figure 5.2: Mechanism 1 constellation diagram for two transmitters A and B.
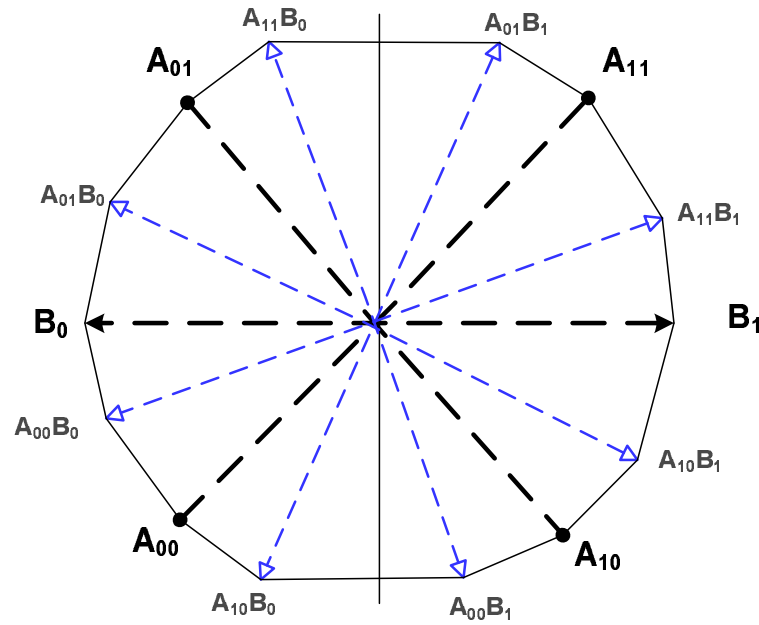
Figure 5.3: Mechanism 2 constellation diagram for 2 transmitters A and B, where A and B employ QPSK and BPSK (M_1), respectively.

- Mechanism 1 is employed when PUs use $M_1(M_2)$ and SUs use $M_2(M_1)$, as shown in Figure 5.2.

- Mechanism 2 is used when one of the PUs and SUs uses QPSK, and the other uses BPSK, as shown in Figure 5.3.

5.5 Graceful Hand-off Mechanism 1

This Section presents SUs' packets recovery protocols for collided packets.

5.5.1 SUs' Packets Recovery Protocol:

This subsection explains our proposed protocol for packets recovery at the SU side, when a collision occurs with the PU's packet head. Define SU_t and SU_r to be the transmitting and the receiving SUs, respectively. The steps for SU's packet tail recovery are as follows:

1. For the sake of exposition, let us assume SUs determined that the PU of the channel uses the M_1 BPSK modulation technique (as explained in Section 5.3), and let us call these symbol values A_0 (phase=π) and A_1 (phase=0). Therefore, the SU uses the M_2 modulation technique (with symbol values B_0 (phase=$\frac{-\pi}{2}$) and B_1 (phase=$\frac{\pi}{2}$)), which is orthogonal to M_1.

2. When SU_r receives a corrupted packet, due to an overlap between the tail of the received SU packet and the head of the PU packet, the corruption will be in the phase shifts of the received packet's tail bits, because their signals do not match SUs demodulation technique (neither $\frac{\pi}{2}$ nor $\frac{-\pi}{2}$).

3. To recover the corrupted symbols, SU_r checks if the tail bits match any of the phase shifts corresponding to two transmitters, as shown in Figure 5.2 and Table 5.1, to recover the corrupted signal. For example, if the phase shift for a received bit signal is $\frac{\pi}{4}$ or $\frac{3\pi}{4}$, then SU_r concludes that SU_t transmitted the B_1 bit symbol.

4. SU_r repeats the process in step 3 for all collided bit signals within the received packet's tail.

Table 5.1: Signals coding and decoding for two transmitter nodes and one receiver node in PNC scheme.

A	B	PNC Signal	Decoded Signals
0	0	signal with the phase difference $e^{j(-\frac{3\pi}{4})}$	A_0,B_0
0	1	signal with the phase difference $e^{j(\frac{3\pi}{4})}$	A_0,B_1
1	0	signal with the phase difference $e^{j(-\frac{\pi}{4})}$	A_1,B_0
1	1	signal with the phase difference $e^{j(\frac{\pi}{4})}$	A_1,B_1

Table 5.2: Signals coding and decoding for two transmitter nodes in PNC scheme, where transmitter A uses QPSK, and transmitter B uses BPSK.

A	B	PNC Signal	Decoded Signals
11	1	signal with the phase difference $e^{j(\frac{\pi}{8})}$	A_{11},B_1
01	0	signal with the phase difference $e^{j(\frac{7\pi}{8})}$	A_{01},B_0
00	0	signal with the phase difference $e^{j(-\frac{7\pi}{8})}$	A_{00},B_0
10	1	signal with the phase difference $e^{j(-\frac{\pi}{8})}$	A_{10},B_1
11	0	signal with the phase difference $e^{j(\frac{5\pi}{8})}$	A_{11},B_0
01	1	signal with the phase difference $e^{j(\frac{3\pi}{8})}$	A_{01},B_1
00	1	signal with the phase difference $e^{j(-\frac{3\pi}{8})}$	A_{00},B_1
10	0	signal with the phase difference $e^{j(-\frac{5\pi}{8})}$	A_{10},B_0

It is worth mentioning that the bit error rate (BER) for this mechanism, as shown in Figure 5.2, is similar to that of QPSK.

5.6   Graceful Hand-off Mechanism 2

In this section, we extend our work in the previous Section where PUs and SUs employ QPSK and BPSK, respectively, or vice versa. In Figure 5.3, assume that the PU uses QPSK modulation which is represented by symbols A_{11}, A_{01}, A_{00}, and A_{10}. Also, assume that the SU uses BPSK modulation technique which is represented by B_1 and B_0 symbols (M_1). Therefore, the possible received phase shifts when the PU and the SU transmit their signals simultaneously are represented by the four dash-dotted lines in Figure 5.3 and explained in Table 5.2. For example, when the received phase shift is $\frac{\pi}{8}$, this means that a collision has occurred such that a PU transmitted symbol A_{11} and an SU transmitted the B_1 symbol.

The packets recovery steps by the SU receiver node, when collisions occur between a PU and an SU packets, are similar to the steps presented in the previous section, except that the SU receiver node needs to use Table 5.2 to recover the collided packets. In Figure 5.3, the minimum received phase shift difference at the receiver is $\frac{\pi}{8}$ which is similar to the $16-$PSK modulation scheme. Therefore, 16-PSK BER can serve as an upper bound for the BER under

this mechanism.

5.7 Performance Analysis

In this section, we introduce two performance metrics to evaluate the efficiency of our proposed protocols for mechanisms 1 and 2 which are employed by SUs' receivers. First metric, the probability of successfully recovering the collided packets between the SU and the PU transmitters. Second metric, energy saving due to recovering the collided packets by their receivers, instead of retransmitting them again. Let us introduce the following notations:

- N: is the number of transmitted bits by an SU.

- K: duration (in bits) of monitoring cycle.

- $p_t(i, K)$: the probability for a PU to start its transmission at bit i of the K bits during the monitoring cycle, given that the PU became active.

- p_e: the probability that at least one bit cannot be recovered in the SU packet, which is also the probability that the SU packet will be corrupted due to collision.

- p_s: the probability of successful recovery of the SU's packets due to the collision with the PU's packet, and it is equal to $1 - p_e$.

- p_a: the probability for a PU to become active during a monitoring cycle, and corresponds to a geometric distribution.

- BER: represents the Bit Error Rate for the modulation schemes which are employed by PUs and SUs.

- e: is consumed energy to transmit one bit (Joules).

- E_{ws}: consumed energy for bits transmitted by an SU using one of our proposed mechanisms.

- E_{ns}: consumed energy for bits transmitted by an SU without using either of our proposed mechanisms.
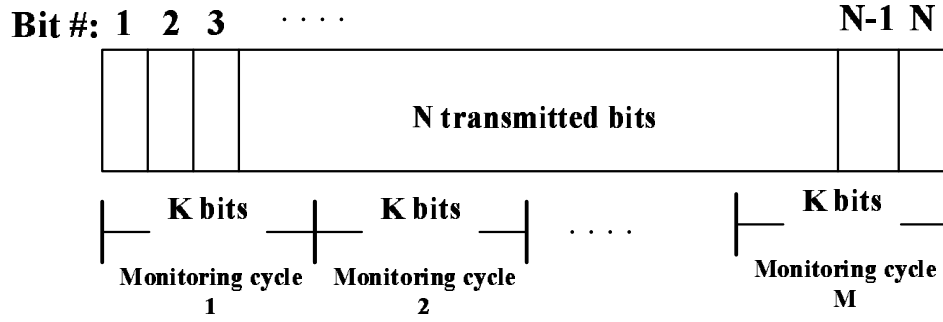
Figure 5.4: SU monitoring cycles representation over SU's transmitted packets' bits.

- ρ: energy saving percentage due to using our proposed mechanisms.

Figure 5.4 show an illustration for monitoring cycles, where SU transmits N bits totally, and the monitoring cycle length is equal to K bits. Therefore, the total number of monitoring cycles is equal to $\frac{N}{K}$.

5.7.1 Probability of Successful Collided Packets Recovery:

The probability of successful recovery of collided packets, p_s, is shown in equation (5.1). This corresponds to the probability of success in packet recovery. The $(1-BER)^{K-i+1}$ term in equation (5.1) represents the probability of recovering the $(K-i+1)$ collided bits of SU, such that the PU has started its transmission at the ith bit of SU packet which is being transmitted, as shown Figure 5.5. We assume that $p_t(i,K) = \frac{1}{K}$, $\forall i$, which corresponds to a discrete uniform distribution.

$$p_s = \sum_{i=1}^{K}(1 - BER)^{K-i+1}p_t(i,K). \tag{5.1}$$

5.7.2 Energy Saving:

In traditional wireless networks more than two users' packets may collide at the same time, e.g., slotted Aloha MAC protocols. However, in CRNs when packets collision occurs, it happens between an SU which is currently transmitting and one PU at most that becomes active[1]. Our proposed mechanisms 1 and 2 are customized for this collision scenario.

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[1]In this chapter, we assume there is only one PU assigned to each licensed channel.
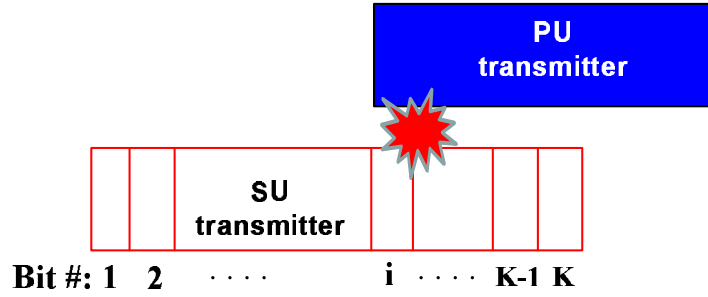
Figure 5.5: SU and PU packets collision, when the PU becomes active.

Let us focus on the saved energy by SU in this subsection. The total number of monitoring cycles is equal to $\frac{N}{K}$. Every some monitoring cycles a PU becomes active, and the average number of these cycles is equal to $\frac{1}{p_a}$, since the probability for the PU to become active, p_a, follows a geometric distribution. Therefore, the number of times the PU becomes active equals $\frac{\frac{N}{K}}{\frac{1}{p_a}}$. In equation (5.2), in the RHS, $K\frac{1}{p_a}$ in the first term represents the number of transmitted bits by the SU when it is able to successfully recover the collided bits with a probability equals to p_s at the last monitoring cycle in every $\frac{1}{p_a}$ monitoring cycles, at which the PU becomes active and collides with SU packet bits. However, the SU receiver may not be able to recover these collided bits in the last monitoring cycle successfully with a probability equals to $(1-p_s)$, and therefore, retransmits these bits. As a result, the total transmitted bits are $K\left(\frac{1}{p_a}+1\right)$ as shown in the second term in the RHS of equation (5.2). However in equation (5.3), since the collided packets are not recovered (our proposed recovery mechanisms are not employed by SUs), the SU transmitter retransmits the collided bits. Therefore, the total number of transmitted bits equals to $K\left(\frac{1}{p_a}+1\right)$. Equation (5.4) represents the saved energy percentage due to employing one of our proposed mechanisms for packet recovery.

$$E_{ws} = \frac{\frac{N}{K}}{\frac{1}{p_a}}[p_s K \frac{1}{p_a}e + (1-p_s)K(\frac{1}{p_a}+1)e]. \tag{5.2}$$

$$E_{ns} = \frac{\frac{N}{K}}{\frac{1}{p_a}}[K(\frac{1}{p_a}+1)e]. \tag{5.3}$$

$$\rho = \frac{E_{ns}-E_{ws}}{E_{ns}}*100\% = \frac{p_s}{\frac{1}{p_a}+1}*100\%. \tag{5.4}$$

5.8   Numerical Results and Discussion

In this section, we evaluate the performance of our two proposed mechanisms, using the performance metric introduced in the previous section, which is the probability of successful recovery for collided sub-packets, p_s. In our numerical results, we considered two data rates 1 Mbps and 6 Mbps with different monitoring cycle lengths. To find K for a Monitoring Cycle Time (MCT), $K =$ data rate $*$ MCT, e.g., if the data rate is 1 Mbps and the MCT= 20 ms, then $K = 20 * 10^3$ bits. It is worth mentioning that in IEEE 802.22 WRAN cell [82], the base station superframe size = 160 ms, and the Maximum Detection Time (MDT) frame to detect the PU when it becomes active should not exceed 2 sec. However, in public safety and cellular networks spectrum, MDT frame must be much less than 2 sec, due to the nature of the applications, in which the PU's sensitivity to interference by SUs is higher than that in TV spectrum. Therefore, the monitoring cycle length is dependent on the type of PUs and the applications. In our numerical analysis, we varied the monitoring cycle length from 4 ms to 2 seconds in order to study its effect on packet recovery efficiency, under different application requirements. The maximum tolerable BER is dependent on the applications nature, and their QoS requirements. Therefore, in our numerical analysis, we evaluated the performance of our proposed packets recovery mechanisms 1 and 2 with different values of BER. In general, increasing Signal-to-Noise Ratio (SNR) decreases BER. We obtained the QPSK and $16-$PSK theoretical BER values from the BER analysis tool in Matlab communication toolbox, where the channel type is AWGN.

5.8.1   Probability of Successful Collided Packets Recovery Results:

As stated earlier in mechanism 1, the BER rate is similar to that of QPSK modulation. Figures 5.6 and 5.7 show p_s with respect to the BER for QPSK (and its corresponding SNR (dB)) for data rates 1 Mbps and 6 Mbps, respectively, with different monitoring cycle times. The probability of successful recovery for the SU's packet when it collides with the PU's packet, p_s, increases by increasing SNR. Results show that with a small increase in SNR, p_s increases significantly. For example, when the monitoring cycle time is 20 ms and data rate is 1 Mbps,

p_s is 0.73 and 0.97 when SNR equals to 9 and 10, respectively, and therefore, p_s is increased by 32% when SNR is increased by just 1 unit.

In mechanism 2 the BER rate is upper bounded by the BER of $16-$PSK modulation. Figures 5.8 and 5.9 show p_s with respect to the BER of $16-$PSK (and its corresponding SNR) for data rates 1 Mbps and 6 Mbps, respectively, with different monitoring cycle times. The probability of successful recovery for the SU's packet when it collides with the PU's packet, p_s, increases by increasing SNR. Similar to mechanism 1, results show that with a small increase of SNR, p_s increases significantly. For example, when the monitoring cycle time is 50 ms and data rate is 6 Mbps, p_s is 0.03 and 0.67 when SNR equals to 16 and 18, respectively, therefore, p_s is increased by about 21 times when SNR is increased by just 2 units.

5.8.2 Energy Saving Results:

Figure 5.10 shows the saved energy percentage, ρ, for different p_s and their corresponding SNR (dB) (which are obtained from Figure 5.6 results in the previous Subsection) when our proposed mechanisms 1 is employed by SUs, data rate $=$ 1 Mbps, and the monitoring cycle time is 50 ms. The results show that the energy saving percentage, ρ, increases when the probability of the PU to become active during the monitoring cycle, p_a, increases, for six different scenarios where the p_s (and it corresponding SNR) are different. For example, when $p_a = 0.5$ and $p_s = 0.9$ (where SNR$= 10$ dB), the obtained energy saving is equal to 30.3%.

Figure 5.11 shows the energy saving percentage, with respect to monitoring cycle time (ms), when mechanism 2 is employed by SUs, data rate$= 6$ Mbps, and p_a is fixed and set to 0.4. Results show that increasing the monitoring cycle time decrease the saved energy due to recovering the collided packets, for five different scenarios which have different SNRs, e.g., increasing the monitoring cycle time from 4 ms to 100 ms, when SNR is 18 dB, causes a degradation in the saved energy percentage from 27.59% to 13.47%. Therefore it is a trade-off between the monitoring cycle length and saved energy. Figure 5.11 also shows that when SNR value is high, e.g., 22 dB, increasing the monitoring cycle time from 4 ms to 2 sec does not degrade the saved energy percentage which is about 28.54%.
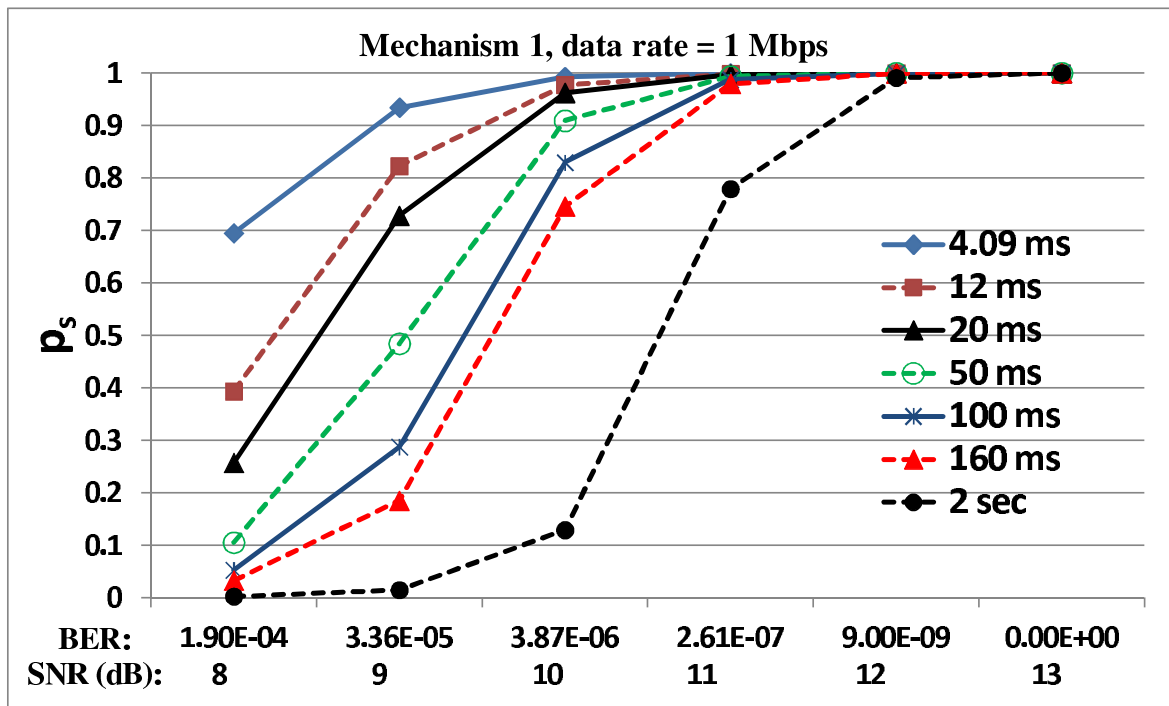
Figure 5.6: p_s for mechanism 1, data rate = 1 Mbps.
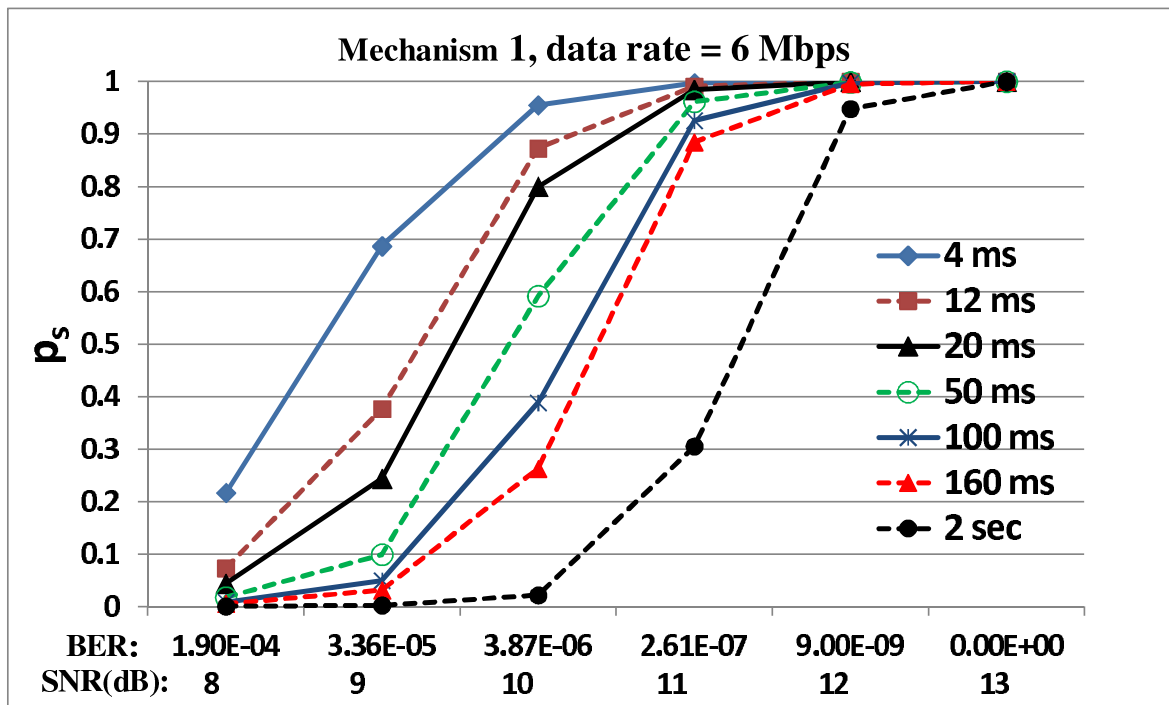
Figure 5.7: p_s for mechanism 1, data rate = 6 Mbps.
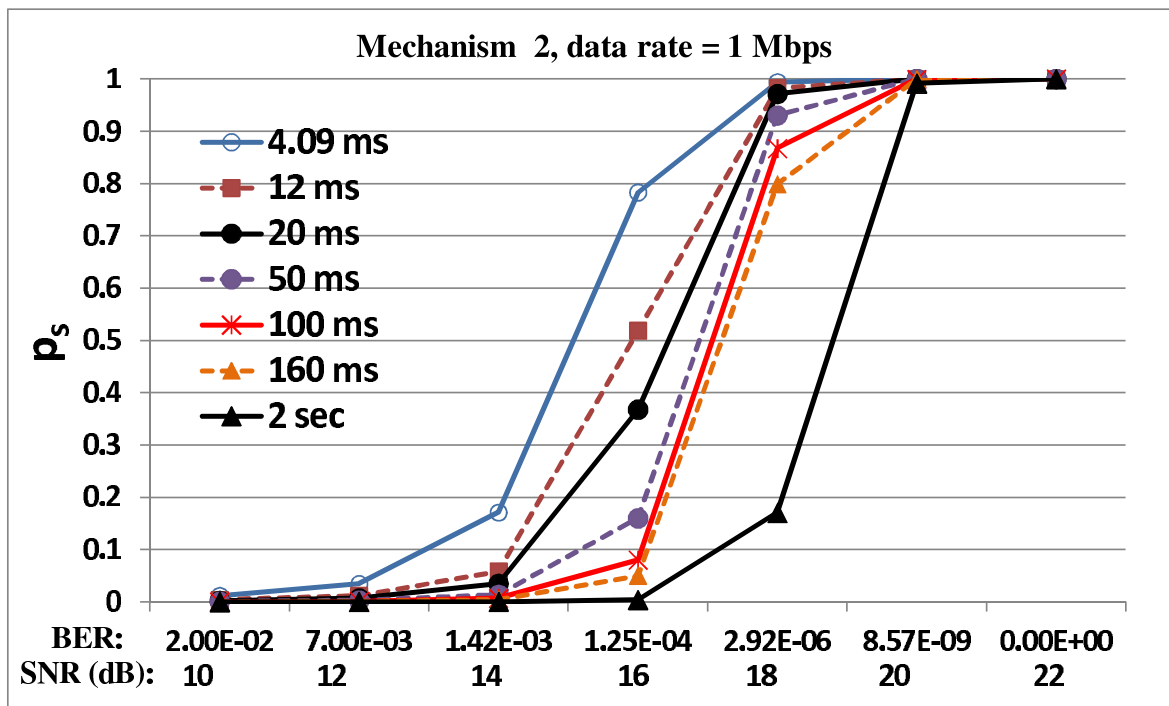
Figure 5.8: p_s for mechanism 2, data rate = 1 Mbps.
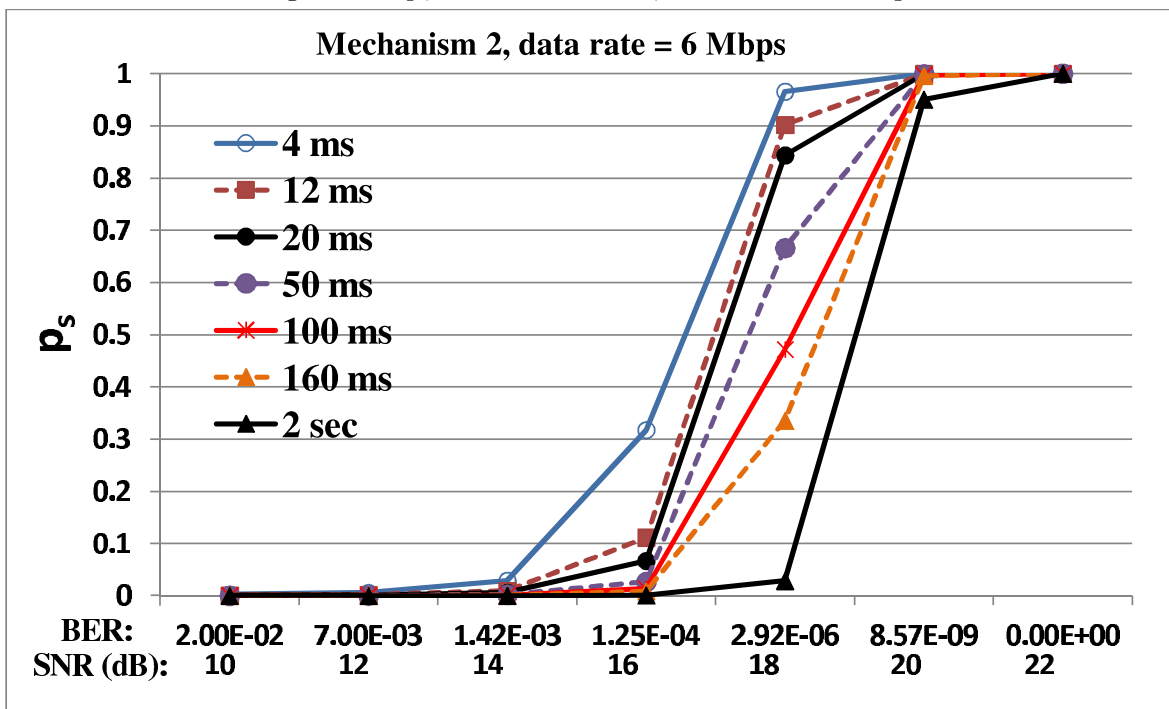
Figure 5.9: p_s for mechanism 2, data rate = 6 Mbps.
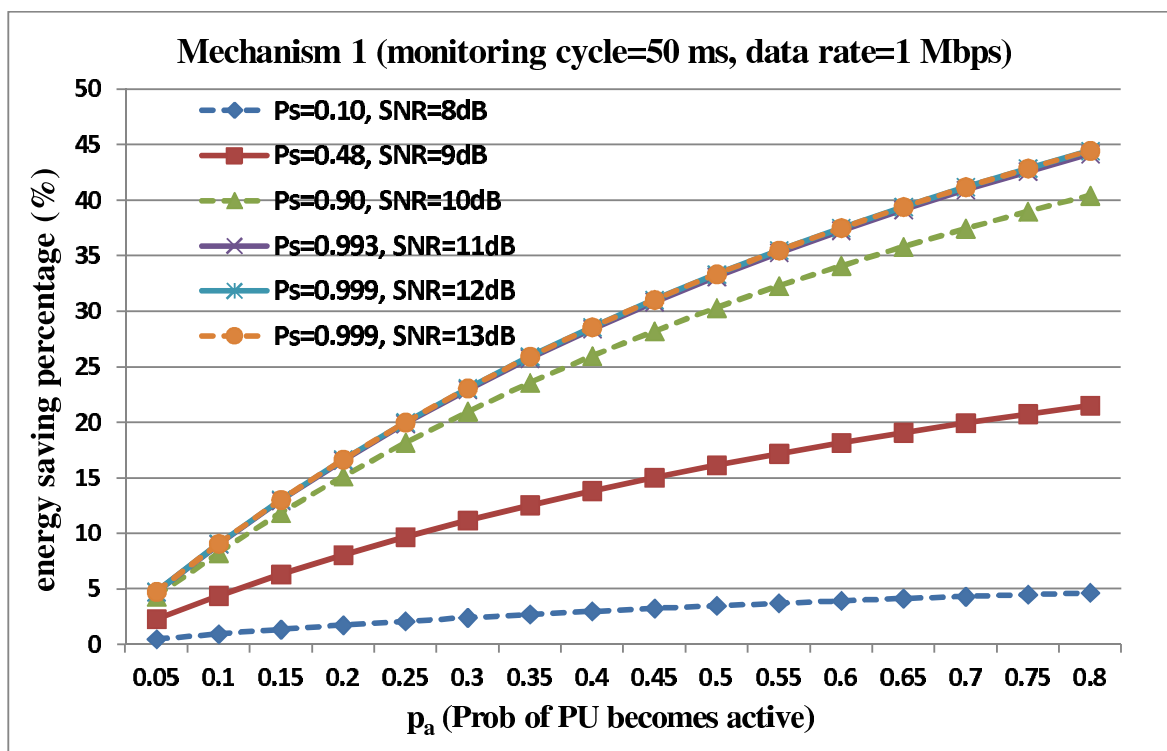
Figure 5.10: Energy saving percentage, with respect to p_a for mechanism 1.
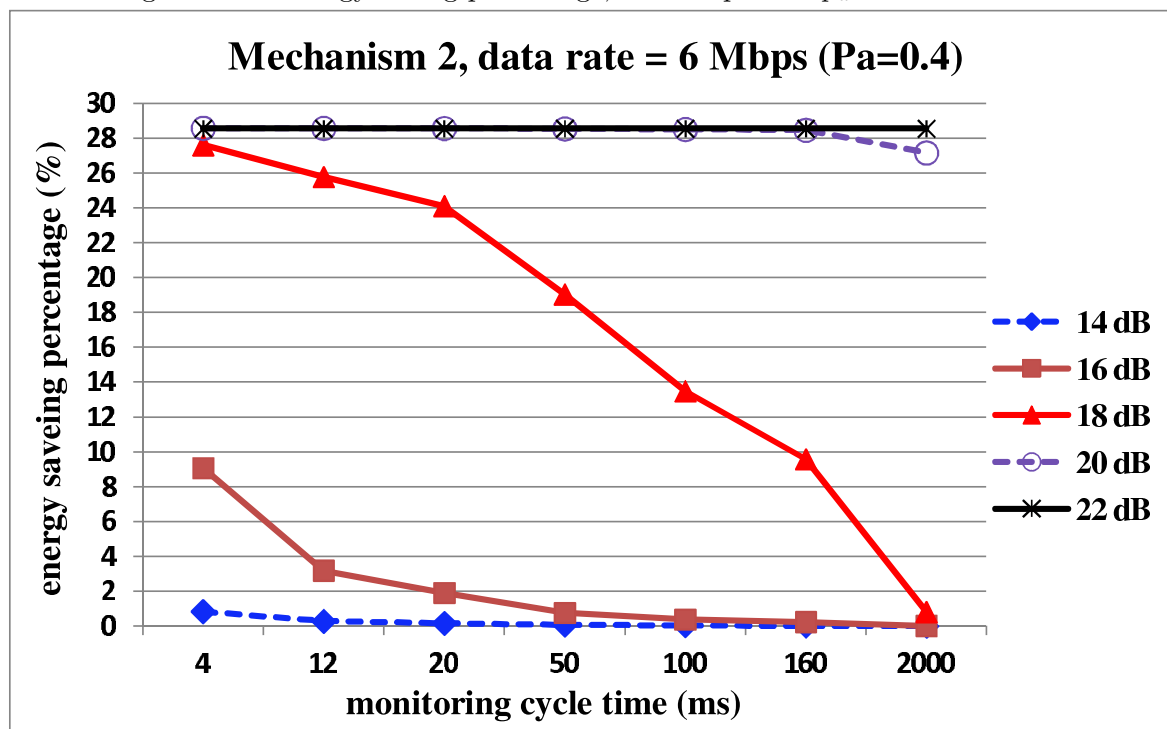
Figure 5.11: Energy saving percentage, with respect to monitoring cycle time, for mechanism 2 where data rate= 6 Mbps, and p_a is set to 0.4.

5.9   Chapter Summary

We propose two mechanisms, together with protocols, to be used to recover the sub-packets for an SU when they collide with a PU's packets in Cognitive Radio Networks (CRNs), when the PU becomes active while the SU is transmitting over the PU's channel. To recover these collided sub-packets, we propose that the SU's receiver employ the additive nature of the electromagnetic (EM) waves as a coding operation for the simultaneously transmitted signals by the PU and the SU transmitters, in order to allow the SU's receiver to recover their collided sub-packets. The SU's receiver considers the PU's transmitted packet's signals as an interference, and hence, cancels its effect in order to recover its corresponding received packet's signals. In mechanism 1, we assume PUs and SUs employ the standard Binary Phase-Shift keying (BPSK) and a 90 degree phase shifted version, i.e., orthogonal to BPSK, respectively, as their modulation techniques. In mechanism 2, we assume PUs and SUs employ BPSK and QPSK as their modulation techniques, respectively, or vice versa. Our numerical results show the efficiency of our proposed protocols for both mechanisms, since a high fraction of the collided packets can be recovered. The results also show that p_s increases by decreasing the BER (increasing SNR) or decreasing the monitoring cycle time for different data rates. Also, results show a high percentage of energy is saved when either one of our proposed mechanisms is employed by SUs, and it depends on the probability for a PU to become active, and the monitoring cycle time of SUs.

CHAPTER 6   Resilient Multicast Routing in CRNs using Multilayer Hyper-graph Approach

6.1   Introduction

In this chapter, we introduce the multicast problem for SUs group, Definition 6.1.1, in the network, such that the selected multicast routing tree contains that maximum feasible number of routing paths, Definition 6.1.2, to SU destinations. Finding a Multicast Routing Tree (MRT), Definition 6.1.3, in CRNs is more difficult than in traditional wireless networks, since more than one channel may used over the routing path, also channels switching time delay must be minimized, in order to reduce the MRT delay. The MRT delay is equal to the routing path which has the maximum routing latency.

Definition 6.1.1 *SUs Group: is a set of SUs that are within the same geographical locality of each others and has at least one channel common between them, and each SU can communicate with all SUs in its group with one transmission-hop.*

Definition 6.1.2 *Routing path: is a route from a SU source node to a SU destination node, which contains one/more transmission hops along SU groups, such that when two different groups communicate, an SU which has a common channel between them transmit data, while the communication between SUs within the same group occurs over a group common channel.*

Definition 6.1.3 *Multicast routing tree problem: finding a routing path, if feasible, from the source node to each SU destination, where the destination nodes are a subset of SU nodes in the network.*

Routing in CRNs is different from traditional wireless networks, due to many reasons such as follows:

- Multi-hop routing requires spectrum availability awareness (good sensing techniques).

- Packets Routing service is intermit, not continuous, given that the PUs activity is moderate or low, e.g., satellite or analog TV channels.

- Route maintenance mechanisms is required, due to PUs activity. Rerouting can be done by only switching to new available channels over the same link(s), or by selecting new SUs nodes.

- Selecting a channels for links over a route is a challenge, since channels with lower channel holding time by its licensed user must be selected, in order to improve routes stability.

- If PUs are very active and access their assigned channels more frequently, e.g., cellular channels, than other channel types, e.g., TV channels, finding an (End-2-End) E2E path is not practical, because route maintenance overhead is very high. Therefore, packet opportunistic forwarding is proposed as an alternative for the E2E route [35].

Providing a resilient multicast routing in CRNs is crucial, especially due to the opportunistic spectrum access nature of unlicensed users, SUs. Dynamic nature of channels availability may cause an SU lose one/more of its communication link with its neighboring SUs. Therefore, we are motivated in this work to propose a model to protect multicasting communication in CRNs. There are two approaches for providing survivability, protection and restoration. Usually, protection is preferred to restoration due to its speed of recovery.

Restoration strategy is reestablishing a routing path to the destination node from the source, when link failure occurs, if feasible. However, in protection strategy the rerouting paths are preplanned before a failure occurs. Among protection strategies, there are reactive strategies, which wait until the failure takes place, and then reroute the information over the preplanned backup path (backup resources may be shared between sessions). There is also the proactive class of strategies in which backup copies are transmitted on the protection path(s)

at the same time data is transmitted on the primary paths. The latter class is faster, but more expensive because backup paths cannot be shared between different sessions, which makes this scheme expensive, especially in wireless networks where transmission resources are scarce and limited. **In this chapter, we adopt the reactive strategy for protection. Notice that in CRNs, we protect against channel link(s) failure for one or more SUs nodes, such that these failures occur at the same time over the channel that is common between SUs, and this occurs when the PU of this channel becomes active again**.

In CRNs, failure occurs when a channel that is being used by an SU becomes unavailable due to a PU activity, and therefore the SU must stop accessing this channel, call it channel link failure. Our proposed protection strategy will be explained in details later in this Chapter. To build a Multicast Primary Routing (MPR) and protect it against single/multiple failures, a set of traditional QoS requirements are considered to select the primary and the backup paths such as the E2E transmission delay, and minimum channels capacity threshold. However, there are some QoS requirements which are related to CRNs operating nature that need to be considered as well besides the traditional QoS requirements, e.g., E2E channels switching delay, number of used channels (or resources) over the primary paths and backup paths in the MRT.

Some licensed channels, such as VHF and UHF band for TV channels (54 MHz-862 MHz), are not busy all the time, can be be utilized by SUs when they are idle as proposed in IEEE 802.22 standard [82]. New America Foundation study in [85] shows that the percentage of TV bands spectrum availability after each DTV transmission vary from 30% to 74% for urban and rural cites. In this chapter, we assume when the routing path, primary or backup, is established, it will be sustained for a while.

There is some recent work in literature for CRNs routing protection against PUs appearance which causes one or more channel links to fail. In [36], a protection method is proposed, in order to protect the primary path to the destination against a PU activity, and a backup path is selected based on Bayesian decision.

A multicast routing protocol in CR ad-hoc networks is proposed in [37], in order to find multicast routes using Minimal spanning tree-based routing algorithm, such that channels time is slotted and transmission are scheduled. In [38], a multi-session multicast trees construction method is proposed for multi-hop CRNs, in order to minimize the used network resources. Authors in [39], considers channels switching delay besides transmission time for a multicast routing in CR mesh networks. Their solution approach is based on a dynamic programming method. Authors in [40], developed a layered graph model for constructing an efficient routing and channels allocation algorithms to reduce adjacent channels interference, however, channels switching latency is not considered.

In conclusion, in all of the above studies, 1-to-M protection for multicast routing and SUs groups communication together with channel switching delay are not considered. Therefore, we are motivated in this Chapter to consider these factors.

6.2   Motivation

In this chapter, we are motivated to develop a model using multilayer hyper-graph [83], in order to model the fact that CRNs have multiple available channels. Our motivations are:

1. Constructing multicast primary routes, if feasible, for a source and a set of selected destination SU nodes, such that channels switching time delay is considered beside the transmission time delay.

2. Protecting the multicast routes, if feasible, such that the primary and backup paths are disjoint. Our disjointness notion will be clear in Section 6.5.

3. Minimizing the maximum path delay for the primary and backup paths, in order to reduce the multicast session delay.

4. Minimizing the number of used channel links that are used in the multicast routing tree, and in the backup paths.

6.3   System Model

Assume we are given a set of SU nodes, their available channels, the adjacency relations between SUs, which means that two SUs are adjacent on a certain channel, if the channel is available at both SUs and they are within communication range from each other. In order to form a group of SUs, a set of criteria can be considered such as the common channel between SUs with the same locality, the cumulative interference from neighboring nodes, path loss, and BER. Forming SUs' groups algorithm is part of our future work. In this chapter, we assume that the SUs groups are given, while forming their groups mainly is based on the common channel between SUs with the same geographical locality. We model each group of SUs nodes as a hyper-edge in a hyper-graph, definition 6.3.1. In order to model more than one licensed channel availability in CRNs, we use a multilayer hyper-graph such that each channel is represented by one layer.

Definition 6.3.1 *Hyper-graph: It is a graph in which a hyper-edge may connect multiple vertices, in CRNs, the hyper-edge contains SU nodes that have a common channel.*

We use a multilayer hyper-graph ($MLHG$), in order to model our network model, as follows:

- A Layer: it represents a frequency band (channel).

- Hyper-Edge[1] (HE): represents one or more SUs nodes which have a common channel between them, and within the transmission range of each others, one-hop links, over this channel, e.g., in Figure 6.1, HE_1 in layer 1 represents the communication links availability between SUs a, b, c, and d, over channel 1.

- An SU is represented by a node in each layer in the MLHG, such that a node in a layer belongs to a hyper-edge only if the layer corresponding channel is available. Also, a node in a layer may belong to more than one hyper-edge, when the corresponding SU node belongs to more than one SUs' groups in the same layer.

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[1]We use super-node, hyper-edge, and group terms interchangeably.

- Hyper-Edge cost: represents the transmission time delay[2] for SUs group that correspond to the hyper-edge.

- An SU can form a HE in a layer by itself, e.g., the corresponding channel layer is available for this SU only, since other SUs transmission within its locality cause an interference to PUs over this channel, when the PU becomes active. Or, there are no other SUs within its transmission range.

- Some SUs nodes do not form a HE in a layer, e.g., in Figure 6.1, SU j in layer 1 does not belong to any HE in its layer, because channel 1 is not available for this SU.

- Inter-layer edge: this is an edge between the same node in two different layers, and corresponds to switching between the two channels corresponding to the two layers.

- Inter-layer edge cost: represents the SU transceivers channels switching time delay between two channels, e.g., in Figure 6.1, SU b switching time delay from channel 1 to channel 2 where SU b nodes are in HE_1 and HE_4, respectively, is represented by the cost of the inter-layer edge that connects SU b nodes in HE_1 and HE_4.

  In Figure 6.1, assume the source node is SU b, and it has channels 1 and 2 available. We introduce a dummy node notation, called b_t, in order to represent the source node. Using the dummy node guarantees that the source node is tuned to the channel which results in minimum path's cost to destination(s). For example, assume one destination node, SU e, therefore, the source node, SU b should be tuned to channel 2, and not channel 1. Also for the same reason, we use the dummy node notion for all destination nodes, e.g., SU h, that has more than one channel available.

In Figure 6.1, channel 1 is not available for SUs i and j, channel 2 is not available for SUs a, f, and g. SUs a, b, c, and d have channel 1 available and they are within the same transmission range of each others, therefore, these SUs are grouped together and are represented by a hyper-edge. SU e in the first layer cannot communicate with SU h with one-hop although

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[2]For simplicity, we assume the transmission time delay for an SU node to other SUs nodes within any hyper-edge is the same for all SUs.
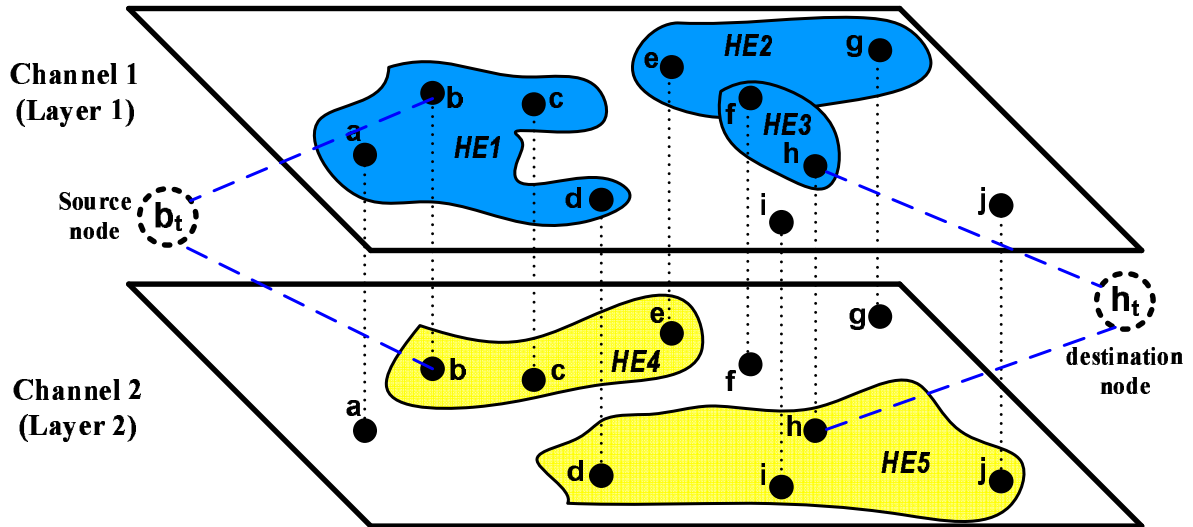
Figure 6.1: A multilayer hyper-graph representation.
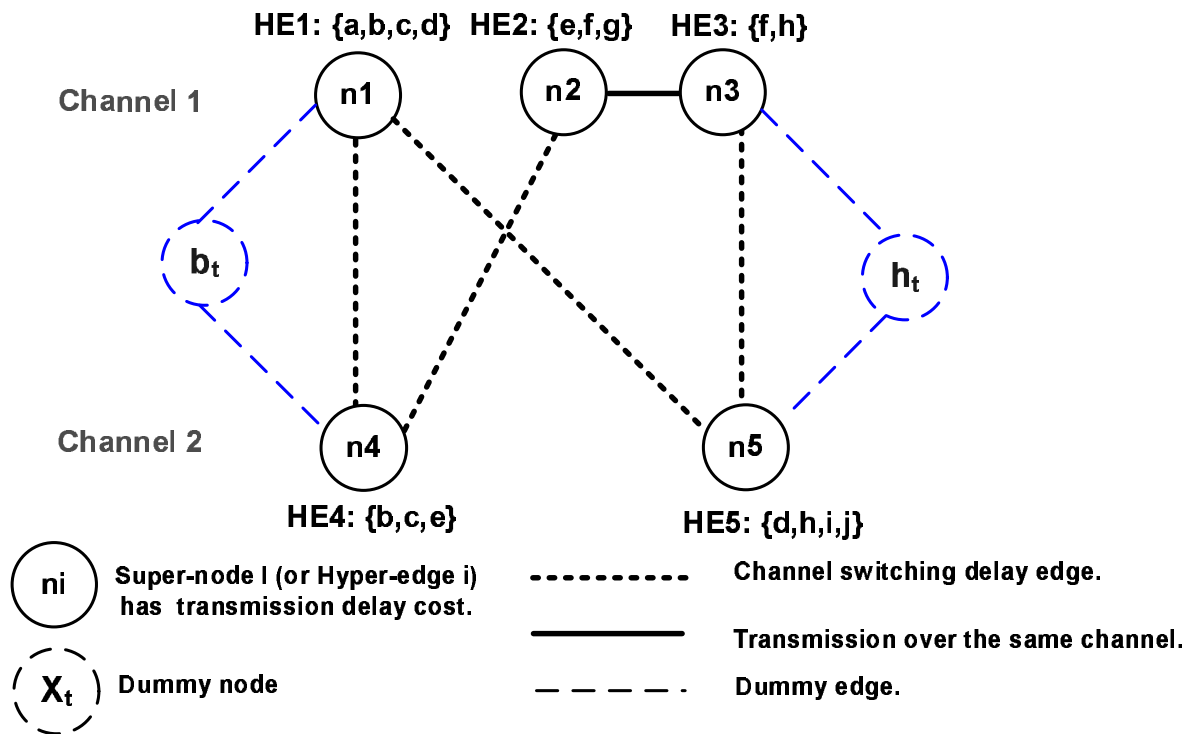
Figure 6.2: The mapped graph for the multilayer hyper-graph shown in Figure 6.1, by using the super-node notation.

both SUs have channel 1 common, because they are not within the transmission range of each others. Therefore, SU e transmits its data to SU f, and then SU f relays it to SU h (2-hop communication without channels switching time delay for SUs e, f, and h).

In order to construct the Multicast Primary Routes from a source to a set of destination SUs nodes in the multilayer hyper-graph that is shown in Figure 6.1, first we convert or map it to a simple graph as shown in Figure 6.2. The conversion process is based on the following concepts:

- Each hyper-edge is converted to one node, call it super-node, e.g., in Figure 6.2, super-node n_1 corresponds to SUs a, b, c, and d nodes that belong to HE_1 in layer 1 shown in Figure 6.1.

- When two HEs in the same layer have some common SUs nodes, the two HEs are connected by a link such that its cost is zero. For example, in Figure 6.1, HE_2 and HE_3 are represented by super-nodes n_2 and n_3, respectively, and are connected by a zero cost link. When SU f relays data between these two HEs, it does so without switching channels. Therefore, this link cost is equal to 0.

- Each super-node has cost equal to transmission time delay[3].

- If two hyper-edges belong to different layers and are connected by at least one inter-layer edge (vertical dashed edge in the MLHG), convert it to one simple link only, in order to connect the pair of super-nodes in the simple graph which correspond to these two hyper-edges in the $MLHG$.

Our goal is to find a resilient multicast routing with minimum E2E delay in terms of channels switching times and transmission times. As an illustration example, the primary and backup paths from the source node, SU b, to destination node, SU h, are shown in Figure 6.3. The primary path is represented by the solid lines path, b_t-$n1$-$n5$-h_t. The backup path is represented by the dashed lines path, b_t-$n4$-$n2$-$n3$-h_t. The primary and backup paths are

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[3]We assume all hyper-edges have the same transmission time delay, for simplicity.

$SRHEGs$ disjoint. After the primary and backup paths are selected in the simple graph, Figure 6.3, this graph can be mapped back to its original multilayer hyper-graph as illustrated in Figure 6.4.

For example, in Figure 6.3, if SU a needs to transmit a packet to SU h, these consecutive steps are required:

1. SU a (belongs super-node n_1) broadcasts the packet to SUs within its group nodes (or hyper-edge), SUs b, c, and d, over channel 1.

2. When SU d (belongs to super-node n_1) receives the packet over channel 1, switches to channel 2 (therefore becomes a node in super-node n_5).

3. SU d transmits the received packet to SUs within its group nodes over channel 2, in order to be received by SU h.

The channel switching time is the required time for an SU's transceiver to switch between two channels (1 ms per 10 MHz [84]). The transmission time refers to the required time for an SU in a group to broadcast a packet to other SUs within its group. Also, let us assume that channel rate is $10Mbps$, and packet size is 1500 bytes, therefore, packet transmission time is 1.2 ms. For the illustrated above example, we find the E2E delays for the primary and backup path that we discussed earlier for the source and destination nodes, SUs b and h , respectively. Based on our proposed algorithm, the primary path is b_t, HE_1, HE_5, and h_t, while the backup path is b_t, HE_4, HE_2, HE_3, and h_t, as shown in Figure 6.4. The primary path E2E delay is equal to ($1.2 + 1 + 1.2 = 3.4$ ms), while the backup path E2E delay is equal to ($1.2 + 1 + 1.2 + 1.2 = 4.6$ ms). Notice that edges that are connected to dummy nodes, e.g., b_t, have zero cost.

In our proposed model, we assume a super-node becomes unavailable (or fails) when a PU(s) of this channel becomes active. Since the transmission power of SU nodes which belongs to this super-node causes an interference to the PU(s) receivers protection area, therefore, SUs stop using this channel, call it SU channel link failure, Definition 6.3.2. Therefore, when a PU becomes active, at least one super-node failure occurs. Let's call the set of HEs that
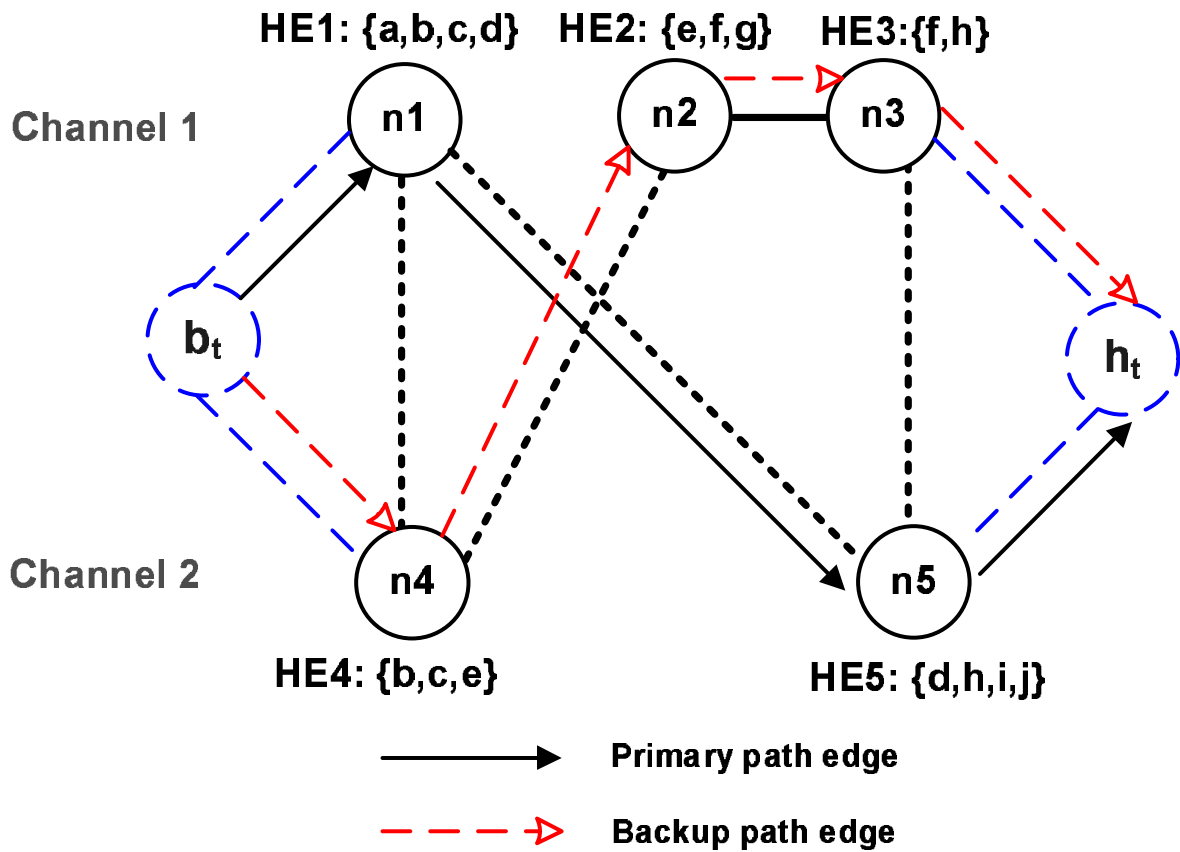
Figure 6.3: An instance of selected primary and backup paths from source node, SU b, to destination node, SU h, for the graph shown Figure 6.2.
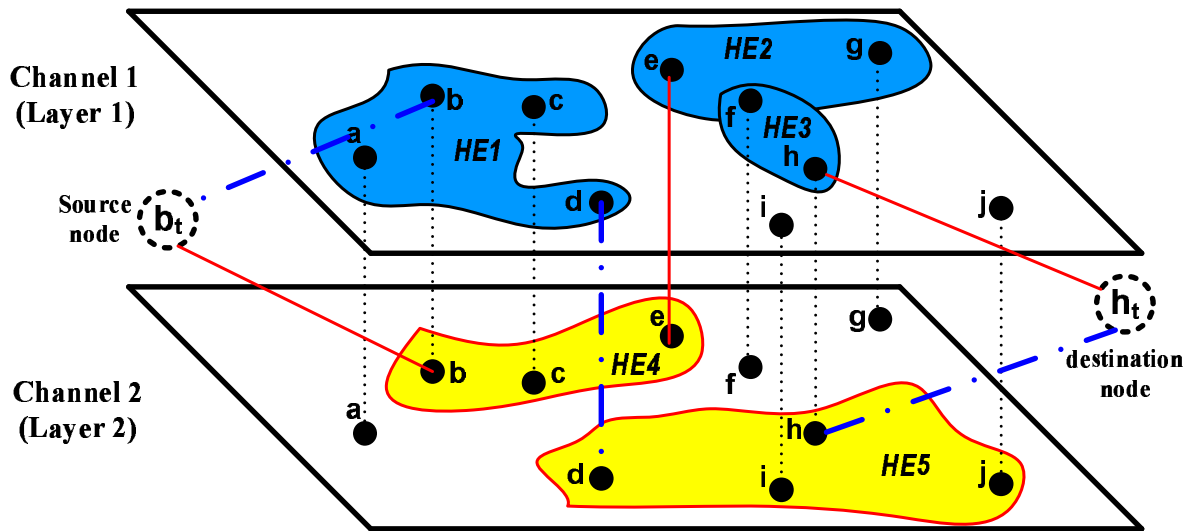
Figure 6.4: The selected primary and backup paths instance in Figure 6.3 represented by the multilayer hyper-graph.

fail together in the network a Shared Risk Hyper-Edge Group ($SRHEG$), Definition 6.3.3. For example, in Figure 6.1, assume HE_4 and HE_5 transmission areas are contained within a PU receiver protection area such that its corresponding PU transmitter transmits data over channel 2. If the PU becomes active these two HEs fail at the same time. Hence, HE_4 and HE_5 form a $SRHEG$.

Definition 6.3.2 *Channel-link (or Hyper-edge) failure*: *means that all SU nodes in the hyper-edge can no longer transmit data over their common channel, when this channel's PU becomes active.*

Definition 6.3.3 *Shared Risk Hyper-edge Group ($SRHEG$)*: *a group of one or more hyper-edges in one layer in the MLHG that use the same PU channel. The transmission ranges for SUs in these hyper-edges overlap with the protection range of the PU(s) corresponding receiver(s). When this PU becomes active, these SUs can no longer can access their corresponding channel.*

6.4 Multicast Primary Routes

We assume the Multicast Primary Routes (MPRs) have one source node and multiple destination SU nodes. The source and the destination nodes are a set of SUs where each destination may belong to one (or more) hyper-edges in different layers, e.g., SU b belongs to two hyper-edges in layers 1 and 2 as shown in Figure 6.1.

Our objectives for constructing an MPR in CRNs are as follows:

- Maximizing the number selected primary paths that are feasible.

- Minimizing the E2E delay including transmission times and switching times delays, by minimizing the maximum path E2E delay for the primary paths.

The MPR solution consists of:

1. A set of primary paths between the source SU node and the destination SU nodes, such that each destination SU node is associated with only one primary path, if feasible, these paths form a tree graph structure, call it Multicast Routing Tree (MRT), Definition 6.4.1.

2. The MRT solution determines the channel over which any pair of SUs along the primary routing paths must transmit and receive their data, in order to minimize the E2E delay including the transmission and switching delays.

Definition 6.4.1 *Multicast Routing Tree (MRT): is a number of routing paths from a source to a set of selected destination nodes in the network, such that the selected paths do not from a cycle.*

6.5   Protection Model

We consider a single failure model which occurs when PU, affecting a number of hyper-edges forming an SRHEG, becomes active. Therefore, none of the SUs that correspond to the SRHEG can transmit data using the PU's channel. In order to increase the network resiliency in CRNs, our protection assumptions are as follows:

- For each destination SU's node, there is a primary path and a backup path.

- The backup paths between the source SU node and the destination SU nodes, guarantee that each destination SU node is protected by only one backup path, if feasible, where the primary and the backup paths for a SU destination are SRHEGs disjoint.

Our model protects against one SRHEG failure for each destination, such that if the primary path fails the traffic is rerouted over the backup path, if it exists. When the backup path is used to carry data, the source node protects this backup path by finding a new backup path to the destination, if feasible, using our proposed algorithm in this chapter, which is SRHEG disjoint from the currently used backup path.

Our objectives for constructing the backup paths are similar to MPRs, these objectives are as follows:

- Maximizing the number selected backup paths that are feasible.

- Minimizing the E2E delay including transmission times and switching times delays, by minimizing the maximum path E2E delay for the backup paths.

6.6   Optimal Solution

In this Section, we present the Integer Linear Program (ILP) Formulation solution for the MPR and its protection model. The solution contains a primary and backup path for each SU destination, if feasible, such that this pair of paths is SRHEG disjoint. The objective of the ILP is to maximize the number of selected primary paths as the first priority, maximize the number of selected backup paths as the second priority, and the third priority is to minimize the maximum path delay for the primary and the backup paths.

6.6.1   Notations:

Let us define the following notations:

- PT: is the number of selected primary paths from the source node to different destinations.

- BT: is the number of selected backup paths from the source node to different destinations.

- T: is the maximum path delay between the primary and backup paths.

- N: is number of vertices (hyper-edges or super-node) in the simple undirected graph.

- α, β, and γ are the weighting factors for the objectives PT, BT, and T, respectively.

- s: is the source node index.

- d: is a variable for the index of a destination super-node.

- D: the set of destination super-nodes indices that contain destination SU nodes.

- g: is a variable for the index of a SRHEG.

- X_m^d: a boolean variable equals to 1, if the primary path from source super-node to destination super-node d passes through super-node m.

- Y_m^d: a boolean variable equals to 1, if the backup path from source super-node to destination super-node d passes through super-node m.

- P_{mn}^d: a boolean variable equals to 1, if the primary path from source super-node to destination super-node d uses link (m, n).

- B_{mn}^d: a boolean variable equals to 1, if the backup path from source super-node to destination super-node d uses link (m, n).

- T_d^p: is the primary path delay from the source node to destination d.

- T_d^B: is the backup path delay from the source node to destination d.

- L_{ij}: a binary variable that equals to 1, if link (i, j) is selected. Otherwise, 0.

- d_{ij}: it is the time for channels switching delay over link (i, j), and the transmission delay within the set of SUs in super-node j in the simple graph (transformed from the hyper-graph). We assume the transmission time in all super-nodes have the same transmission delay, for the sake of simplicity, but it can be easily extended to asymmetric transmission times.

- M_i^g: is an input binary parameter that equals 1, if super-node i belongs to SRHEG g, assuming we are given the set of super-nodes for each SRHEG.

- R_d^g: a binary variable which equals 1, if the primary path for destination super-node d passes through SRHEG g. Otherwise, 0.

- U_d^g: a binary variable which equals 1, if the backup path for destination super-node d passes through SRHEG g. Otherwise, 0.

6.6.2   ILP formulation:

$Maximize\ \alpha\ PT + \beta\ BT - \gamma\ T$

Subject to:

$$T_d^p = \sum d_{ij} P_{ij}^d,\ \forall i, j \in \{1, ..., N\}, \forall d. \tag{6.1}$$

$$T_d^B = \sum d_{ij} B_{ij}^d,\ \forall i, j \in \{1, ..., N\}, \forall d. \tag{6.2}$$

$$T \geq T_d^P, \forall d. \tag{6.3}$$

$$T \geq T_d^B, \forall d. \tag{6.4}$$

$$\sum_{i=1, i \neq s}^{N} P_{si}^d = X_s^d, \ \forall d. \tag{6.5}$$

$$\sum_{i=1, i \neq s}^{N} P_{is}^d = 0, \ \forall d. \tag{6.6}$$

$$\sum_{i=1, i \neq d}^{N} P_{di}^d = 0, \ \forall d. \tag{6.7}$$

$$\sum_{i=1, i \neq d}^{N} P_{id}^d = X_d^d, \ \forall d. \tag{6.8}$$

$$\sum_{i=1}^{N} P_{mi}^d = X_m^d, \ \forall d, \forall m \notin s, d. \tag{6.9}$$

$$\sum_{i=1}^{N} P_{im}^d = X_m^d, \ \forall d, \ \forall m \neq s, d. \tag{6.10}$$

$$P_{ij}^d + P_{ji}^d \leq 1, \ \forall i, j \in \{1, ..., N\}, \ \forall d. \tag{6.11}$$

$$\sum_{i=1, i \neq s}^{N} B_{si}^d = Y_s^d, \ \forall d. \tag{6.12}$$

$$\sum_{i=1,i\neq s}^{N} B_{is}^d = 0, \ \forall d. \tag{6.13}$$

$$\sum_{i=1}^{N} B_{di}^d = 0, \ \forall d. \tag{6.14}$$

$$\sum_{i=1}^{N} B_{id}^d = Y_d^d, \ \forall d. \tag{6.15}$$

$$\sum_{i=1}^{N} B_{mi}^d = Y_m^d, \ \forall d, \ \forall m \neq s, d. \tag{6.16}$$

$$\sum_{i=1}^{N} B_{im}^d = Y_m^d, \ \forall d, \ \forall m \notin s, d. \tag{6.17}$$

$$B_{ij}^d + B_{ji}^d \leq 1, \ \forall i, j \in \{1, ..., N\}, \ \forall d. \tag{6.18}$$

$$X_s^d = X_d^d, \ \forall d. \tag{6.19}$$

$$Y_s^d = Y_d^d, \ \forall d. \tag{6.20}$$

$$PT = \sum X_s^d, \forall d. \tag{6.21}$$

$$BT = \sum Y_s^d, \forall d. \tag{6.22}$$

$$\sum_{i=1}^{N} M_i^g X_i^d \le c.R_d^g, \ \forall g, \ \forall d, \ i \notin s \cup \mathcal{D}. \tag{6.23}$$

$$R_d^g \le \sum_{i=1}^{N} M_i^g X_i^d, \ \forall g, \ \forall d, \ i \notin s \cup \mathcal{D}. \tag{6.24}$$

$$\sum_{i=1}^{N} M_i^g Y_i^d \le c.U_d^g, \ \forall g, \ \forall d, \ i \notin s \cup \mathcal{D}. \tag{6.25}$$

$$U_d^g \le \sum_{i=1}^{N} M_i^g Y_i^d, \ \forall g, \ \forall d, \ i \notin s \cup \mathcal{D}. \tag{6.26}$$

$$R_d^g + U_d^g \le 1, \ \forall g, \ \forall d. \tag{6.27}$$

Equations (6.1) and (6.2) find the primary paths and backup paths E2E delays, respectively. Constraints (6.3) and (6.4) find the maximum path delay between the primary and backup paths. Constraints (6.5) and (6.6) guarantee that the super-node in which the SU source node has one unit of flow demand, if selected, and zero unit for the outgoing and incoming flows, respectively, that corresponds to the primary path to each destination. Constraints (6.7) and (6.8) guarantee that the destination super-nodes (which contains the destination SU nodes) have one unit of flow demand, if selected, and zero unit for the incoming and outgoing flows, respectively, that corresponds to the primary path. Constraints (6.9) and (6.10) guarantee flow conservation for the intermediate super-node except the source and the destination super-nodes have exactly one unit of incoming flow and one unit of outgoing flow. Constraint (6.11) guarantees that an undirected edge is selected at most once. Constraints $(6.12) - (6.18)$ are similar to the aforementioned constraints, except that they correspond to the backup paths.

Constraints (6.19) and (6.20) ensure the flow conservation such that if the super-node that contains the SU source node is selected in the ILP solution, therefore, its corresponding

destination super-node that contains the SU destination node must be selected which are associated with the primary paths and backup paths, respectively. Equations (6.21) and (6.22) find the number of selected primary and backup paths.

Constraints (6.23) set the binary variable, R_d^g, that corresponds to the $SRHEG$ to 1, if one or more of its corresponding super-nodes belong to the primary (where c is a large constant value, e.g., N). Constraint (6.24) sets R_d^g to zero. Constraints (6.25) and (6.26) are similar to constraints (6.23) and (6.24), however, they correspond to the backup paths. Constraint (6.27) ensures that the SRHEGs disjointness condition for the selected pair of the primary and backup paths for each destination.

6.7   Heuristic Algorithm

In this section, we introduce a heuristic solution, because the optimal solution found by the ILP that we propose in Section 6.6, its time complexity is not polynomial, it is NP-Complete. Therefore, we are motivated to propose a heuristic solution such that its complexity is time polynomial.

The heuristic solution finds the primary and backup paths for the multicast routes, such that each primary and backup paths pair that correspond to a destination are $SRHEG$ disjoint. Let us define the following notations:

- d_{max} the maximum path delay, which could be a primary or backup path.

- d_i: the super-node i which contains the SU destination node.

- C_p and C_b: are the number of primary and backup paths which are feasible in the network graph.

- P_i and B_i: the primary and backup paths, respectively, from source node to destination i.

- T_i^p: the E2E delay for the primary path from source node to destination i.

- T_i^B: the E2E delay for the backup path from source node to destination i.

The Heuristic Algorithm:

Inputs: a simple graph $G(V, E)$ which is the transformation of the multilayer hyper-graph, super-nodes IDs that correspond to the source SU node, and super-nodes IDs that correspond to each destination SUs node $(d_1, ..., d_{|D|})$.

Outputs: P_c and B_c which are the number of primary and backup paths, respectively, that are feasible for the set of D SU destination nodes, and the maximum path delay.

The heuristic algorithm steps:

1. Initialization, set $i = 1$, $d_{max} = -1$, $C_p = 0$, $C_b = 0$.

2. Find the shortest path, call it P_i, if feasible, and its corresponding E2E delay, T_i^p, from the super-node which contains the source SU node to d_i, using Dijkstra's algorithm, in the input graph, $G(V, E)$,

3. If P_i is feasible, then $C_p + +$.

4. If $(T_i^p > d_{max})$, then $d_{max} = T_i^p$.

5. Remove all super-nodes and their incident edges that belong to the $SRHEGs$ located over the primary path, P_i, e.g., if path P_i passes through super-node j which belongs to $SRHEG_k$, then all super-nodes that belong to $SRHEG_k$ and their incident edges are removed from graph $G(V, E)$. Call the modified graph $\overline{G}(V, E)$.

6. Find the shortest path, call it B_i, if feasible, and its corresponding E2E delay, T_i^B, from the super-node which contains the source SU node to d_i, using Dijkstra's algorithm, in $\overline{G}(V, E)$.

7. If B_i is feasible, then $C_b + +$.

8. If $(T_i^B > d_{max})$, then $d_{max} = T_i^B$.

9. Repeat steps 2 to 8 for all destinations, $i = 2, ..., |D|$.

10. Output d_{max}, C_p, and C_b.

The time complexity for Dijkstra's algorithm is $O(|E|logN)$, where $|E|$ and N are the number of edges and vertices in the graph. In our proposed heuristic algorithm, for each destination Dijkstra's algorithm runs 2 times, and the number of destination is $|D|$. Therefore, the total time complexity is $O(|D||E|logN)$.

6.8   Optimizing the number of used channels

In this section, we introduce a fourth objective, in which the number of used channels links in the network that is required to deliver data packets from the source node to all destination nodes is minimized. Let us introduce new notations as follows:

- LT: is the number of selected channel links.

- μ: weighting factor for the fourth objective.

- $\mathcal{A}$: the set of links between super-nodes.

In order to achieve this goal, the objective function is modified as follows:

$Maximize\ \alpha\ PT + \beta\ BT - \gamma\ T - \mu\ LT$

Also, new constraints are added to the constraints in Section 6.6, as follows:

$$LT = \sum_{(i,j)\in\mathcal{A}} L_{ij}. \tag{6.28}$$

$$L_{mn} \geq P_{mn}^d, \forall m,n,d. \tag{6.29}$$

$$L_{mn} \geq B_{mn}^d, \forall m,n,d. \tag{6.30}$$

Constraint (6.28) is used to find the total number of selected channel links for the multicast tree. Constraints (6.29) and (6.30) are used to set the corresponding binary variable for a link to 1, if it is selected either in the primary or/and the backup paths.

6.9 Simulation Results

In this section, we evaluate our proposed protection model for CRNs using the optimal and the heuristic solutions that we proposed in this chapter. We study three performance metrics: **First**, the number of primary paths (first priority). **Second**, the number of backup paths (second priority), **Third**, the maximum primary and backup paths delay (third priority). The highest priority is assigned for maximizing the number of primary paths, because our focus is to increase the network connectivity[4].

In our evaluation, the network parameters are as follows; the total number of SUs in the network is 25, and the number of hyper-edges (super-nodes) in each layer = 10, there is one source node and 8 destination SU nodes. The $SRHEGs$ size is set to one, such that each hyper-edge represents a $SRHEG$. In our simulation scenario, we assume the SUs groups that are located within transmission range of each others, called super-nodes, are randomly distributed. The ILP weighting factors α, β, and γ are set to 1000, 100, and 10, respectively. We chose these values after we ran some simulation experiments and studied the results, we found out these values meet our performance metrics priority rank.

In our simulation results in this section, each point is the average of 100 randomly generated network topologies. In each run the source node and the destination nodes are randomly and uniformly selected. Also, the number of available channels, and their IDs for each SU node are randomly and uniformly selected from the available channels. In all figures, the error bars represent the 95% confidence intervals.

6.9.1 Number of available channels effect:

In order to study the effect of the number of available channels, n, on the network performance, under the simulation scenario parameters that are described above, also the probability for PU being active is set to 0.3. Figure 6.5 shows that increasing n increases both the number of primary and backup paths for the optimal and the heuristic solutions. The heuristic

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[4]In this Chapter, we mean by network connectivity is the number of destination nodes that has at least one established path from the source node

solution for the number of primary paths is very close to the optimal solution such that the maximum percentage difference between the optimal and the heuristic solutions is up to 5.2%. One interesting observation is that this percentage decreases, accuracy increases, by increasing n, when $n = 2$, 4, 6, and 7, the difference percentages are 5.2%, 4.5%, 3.5%, and 2.9%, respectively. However, for the number of backup paths the difference between the optimal and the heuristic increases by increasing the number of channels. However, the accuracy increases by increasing the number of channels, e.g., when $n = 4$ and 7, the differences are 34.4% and 21.4%, respectively.

Figure 6.6 shows that the maximum path delay decreases, for primary and backup paths to the SU destination nodes, by increasing the number of available channels in the network. One interesting observation in Figure 6.6, the confidence intervals (CIs) for the optimal and heuristic solution overlap when $n = 2$, 4, and 6. This indicates that in some cases the heuristic solution is very close to the optimal solution for this scenario with these system parameters.

6.9.2 Probability of PU activity effect:

In order to study the effect of PU activities on the network performance, we use the above described scenario case study such that the number of available channels is fixed and set to 4. Figure 6.7 shows that increasing the probability of PU being active, call it p_a, decreases both the number of primary and backup paths for the optimal and the heuristic solutions. The difference percentage between the optimal and the heuristic solutions increases, accuracy decreases, by increasing p_a, e.g., when $p_a = 0.2$, 0.4, 0.6, and 0.7, the difference percentages are 2.1%, 9.4%, 18.3%, and 26%, respectively. Also, for the number of backup paths the heuristic solution accuracy decreases by increasing p_a compared to the optimal solution.

Figure 6.8 shows that the maximum path delay increases, for primary and backup paths to SU destination nodes, by increasing the probability of PU being active.

6.9.3 Minimizing the number of used channels links:

In this subsection, we show that the used channels resources can be optimized by adding a new objective, as explained in Section 6.8 which minimizes the number of used channel links in the constructed multicast routing tree (multicast Steiner tree). This objective has the **fourth** priority. Therefore, in this case study, we set the ILP weighting factors α, β, γ, and μ to 1000, 100, 10, and 1, respectively. Figure 6.9 shows that adding the fourth objective minimizes the number of used channel links up to about 30% compared to the optimal solution in section 6.6. Also in this case study, it is worth mentioning that when the fourth objective is applied the number of primary and backup paths, and the maximum path delay do not change. Only the number of used channel links is reduced.

6.10 Chapter Summary

In this chapter, we proposed a novel modeling approach for CRNs using a multi-layer hypergraph. We developed an Integer Linear programming (ILP) model and proposed a heuristic algorithm, in order to find the multicast primary paths and their backup paths, and to also minimize the maximum path delay for primary and backup paths.

Our simulation results shows the that when the number of available channels increases, the number of primary and backup paths increases and the maximum path delay decreases almost linearly. Also, the results show that when the probability of PU being active increases the primary paths in multicast session and their backup paths decreases, also the maximum path delay increases almost linearly.
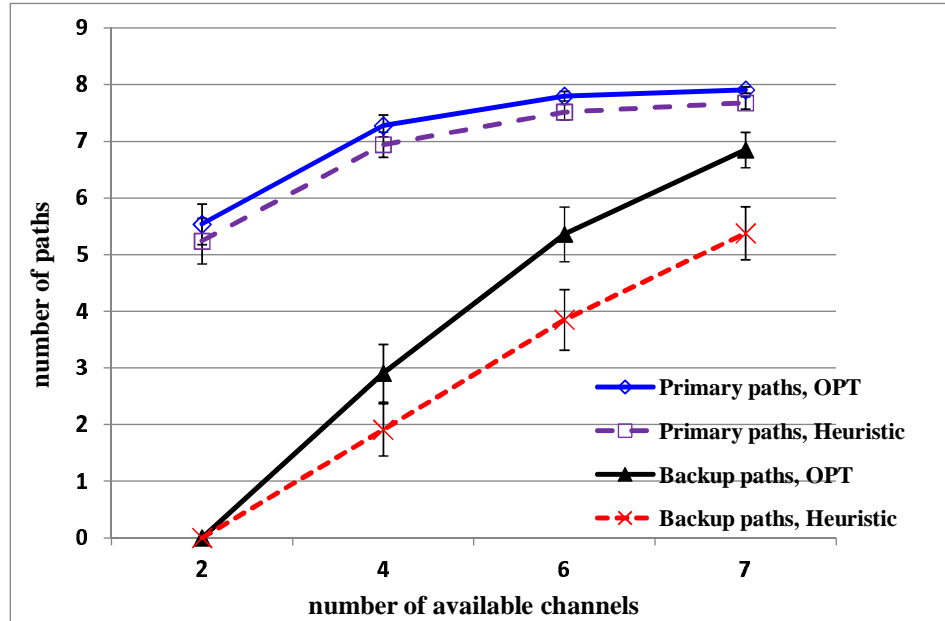
Figure 6.5: The average number of primary and backup paths for the optimal and Heuristic solutions with respect to the number of available channels.
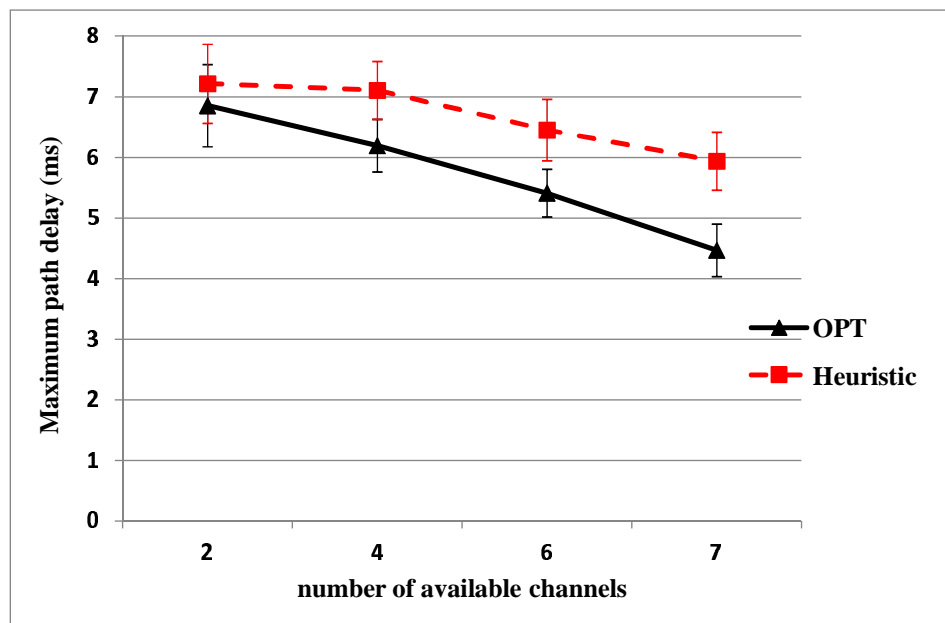
Figure 6.6: Maximum path delay to the destinations for the primary and backup paths.
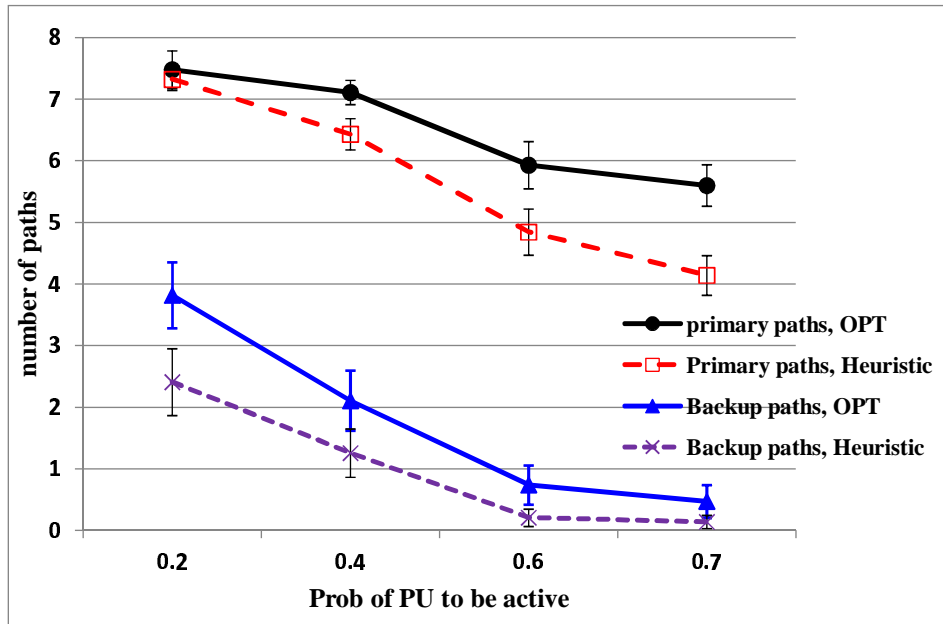
Figure 6.7: The average number of primary and backup paths for the optimal and Heuristic solutions with respect to the Prob of PU to be active, when N is set and fixed to 4.
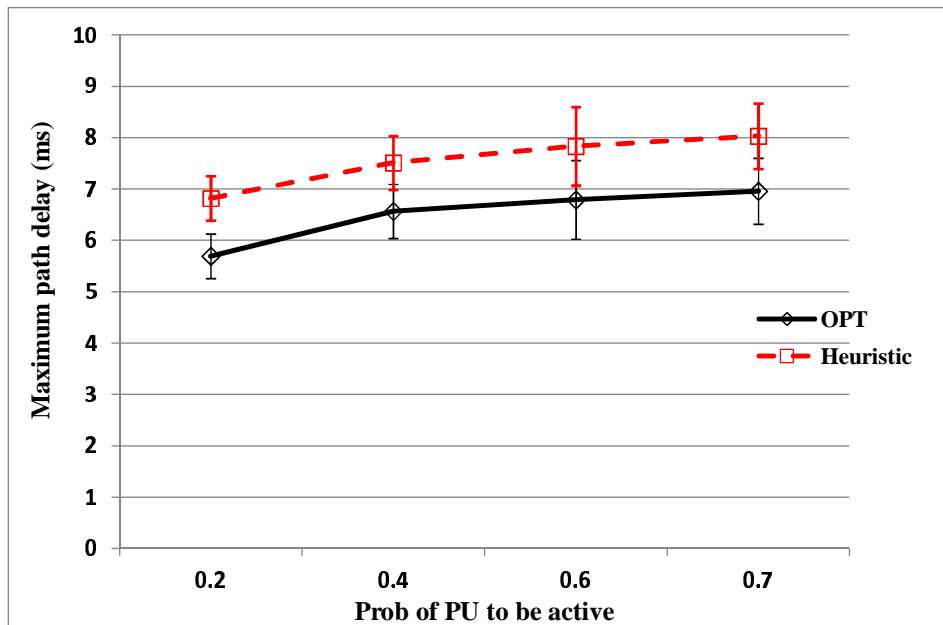

Figure 6.8: Maximum path delay to the destinations for the primary and backup paths, with respect to the Prob of PU to be active, when N is set and fixed to 4.
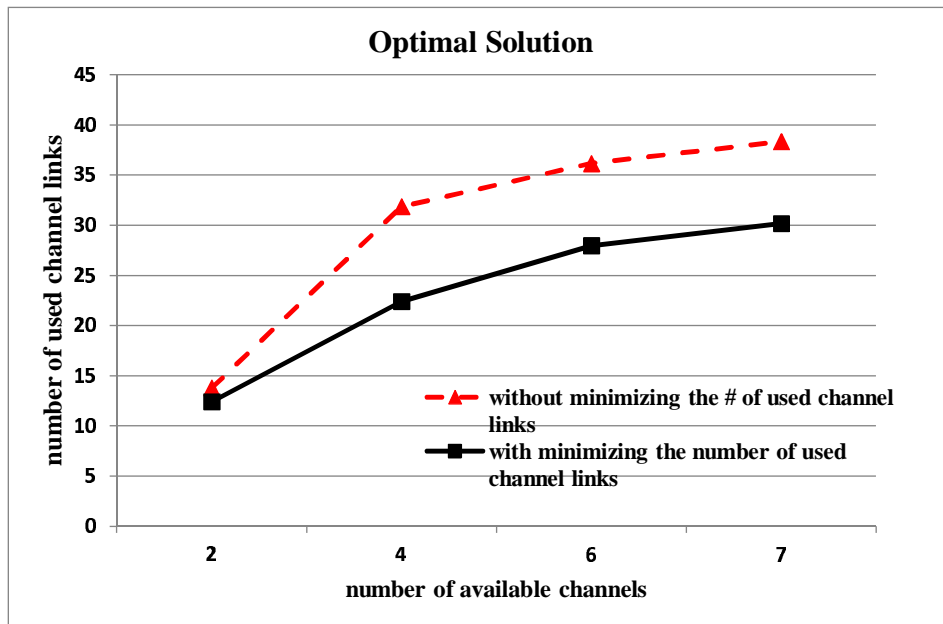
Figure 6.9: Optimizing the number of used channel links in the selected multicast Steiner tree.

CHAPTER 7 Conclusions and Future Work

7.1 Conclusions

In this dissertation, we have studied four important problems in Cognitive Radio Networks (CRNs). First, we introduced a model to evaluate SUs performance under heterogeneous channel access in CRNs. We used a Continuous Time Markov Chain (CTMC) modeling approach, and derived SUs' performance metrics, such as SUs admission and blocking probabilities, and their average waiting time in the system. In this model, SUs prioritize channels access based on their service rates, and switch or choose a channel type with higher service rate first, if available. We also consider SUs sensing rate and study its effect on SUs performance. Results showed that prioritizing channel access reduces the average waiting time for SUs in the system, also show that if sensing time is very small can have negligible effect on performance.

Second, we introduced a protocol to solve the problem of using a Common Control Channel (CCC) in CR-WMNs, in order to assign channels to SUs. Three novel and robust schemes are proposed, which employ the physical layer network coding (PNC) technique. Simulation results show that these three schemes reduce the network setup time overhead significantly, compared to CCC-based schemes or slotted time protocols where PNC is not employed.

Third, we proposed to enable SUs to recover their packets which collide with PUs' transmissions when a PU becomes active for two different scenarios in terms of the employed modulation scheme by SUs and PUs. Packets recovery is based on the received phase shifts for the combined received signals for the PU and SU such that they are synchronized. In our scheme when a collision occurs between an SU and a PU transmitted signals, the SU's receiver considers the PU's transmission as interference, and therefore, cancels its effect in order to recover its cor-

responding received packet's signals. Numerical results show that a high percentage of energy can be saved over the traditional scheme, in which our packets recovery mechanisms are not employed.

Finally, we proposed a novel multicast resilient routing approach to select primary and backup paths from an SU source to SUs destinations such that the end-to-end delay is minimized, which takes into consideration the latency due to channels switching times and transmission times. Our approach is based on a multilayer hyper-graph model. The primary and backup path to a destination are shared risk hyper-edge disjoint, in order to prevent a concurrent failure of these two paths, when the corresponding PU for these hyper-edges becomes active. We formulated an ILP model and developed a heuristic solution, in order to assess the accuracy of our heuristic solution. Results show that increasing the number of available channels in the network increases the number of feasible primary and backup paths, and that the maximum path delay decreases almost linearly.

7.2   Future Work

Our future work includes the following extensions:

- We plan to extend the work of chapter 4, in which we introduced uplink channel request and allocation schemes, by evaluating the BER for our three proposed schemes, PNC_{w1m}, PNC_{w2m}, and PNC_{w3m}.

- We also plan to extend the packet recovery mechanisms that introduced in Chapter 5 by considering modulation schemes other than $BPSK$ and $QPSK$.

- We also plan to extend the resilient multicast channel allocation and routing scheme introduced in Chapter 6 by considering the case of multiple multicast sessions.

APPENDIX A Baseline model

A.1 Baseline Model Global Balance Equations Formulation

Let's recall some baseline model variables definitions:

- v is the total number of SUs in the system.

- h is the total number of SUs being served in type 1 channels, $0 \leq h \leq (C_1 - p_1)$.

- The valid state space, call it ζ_2, for baseline model, as follows, (v, h, p_1, p_2, s), where: $0 \leq v \leq \beta$, $0 \leq h \leq (C_1 - p_1)$, $0 \leq p_1 \leq C_1$, $0 \leq p_2 \leq C_2$, and s is a binary variable, $s = \{0, 1\}$, given that for any state in the space $h \leq v$.

- let $\pi_{\hat{v}, \hat{h}, \hat{p_1}, \hat{p_2}, s}$ be the stationary vector where $v = \hat{v}$, $h = \hat{h}$, $p_1 = \hat{p_1}$, $p_2 = \hat{p_2}$, and s is a binary variable such that if $s = 1$, sensing is conducted by SU(s). Otherwise; no sensing.

The global balance equation depends on the number of SUs which is currently in the system, v. The Optimistic Bound (OB) is considered in the global balance equations formulation in this Appendix. However, the Pessimistic Bound (PB) can be obtained by a minor modification for the global balance equations. Recall in OB, if sensing is conducted, then we assume it is on a channel in type 2 (lower SUs service rate), i.e., all available channels in type 1 are being used.

Case 1: If $v < (C_1 - p_1) + (C_2 - p_2)$, $h \leq (C_1 - p_1)$, and $h \leq v$. Therefore, the global balance equations are (A.1) and (A.2).

$$\pi_{v,h,p_1,p_2,1}[\lambda_s + h\mu_{s_1} + (v - h - 1)\mu_{s_2}\mathbb{1}_{v-h\geq 1} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} +$$

$$(C_2 - p_2)\lambda_{p_2} + \Psi]$$

$$= \pi_{v-1,h-1,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{v\geq 1} + \pi_{v-1,h-1,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{v\geq 2} + \pi_{v-1,h,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{v\geq 1,h=C_1-p_1}$$

$$+ \pi_{v-1,h,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{v\geq 2,h=C_1-p_1} + \pi_{v+1,h+1,p_1,p_2,1}\left[(h + 1)\mu_{s_1}\right]\mathbb{1}_{h+1\leq C_1-p_1}$$

$$+ \pi_{v+1,h,p_1,p_2,1}\left[(v + 1 - h - 1)\mu_{s_2}\right] + \pi_{v,h,p_1+1,p_2,1}\left[(p_1 + 1)\mu_{p_1}\right]\mathbb{1}_{v\geq 1}$$

$$+ \pi_{v,h,p_1,p_2+1,1}\left[(p_2 + 1)\mu_{p_2}\right]\mathbb{1}_{v\geq 1} + \pi_{v,h,p_1-1,p_2,1}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{h<C_1-p_1+1,v\geq 1}$$

$$+ \pi_{v,h+1,p_1-1,p_2,1}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{h+1=C_1-p_1+1,v\geq 1} \qquad\qquad (A.1)$$

$$+ \frac{h}{C_1 - p_1 + 1}\pi_{v,h,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{h<C_1-p_1+1}$$

$$+ \pi_{v,h+1,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{h+1=C_1-p_1+1}$$

$$+ \frac{v - h}{C_2 - p_2 + 1}\pi_{v,h,p_1,p_2-1,0}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{v-h<C_2-p_2+1}$$

$$+ \pi_{v,h-1,p_1,p_2-1,0}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{v-h+1=C_2-p_2+1}$$

$$+ \pi_{v,h,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{v-h<C_2-p_2+1,v\geq 1}$$

$$+ \pi_{v,h-1,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{v-h+1=C_2-p_2+1,v\geq 1}.$$

In equation (A.1), in the RHS the first and second terms show an SU which newly arrives gives a higher priority to a channel in type 1 over a channel in type 2, if available. However, if there is no channel available in type 1, an SU selects a channel in type 2, if available, as shown in the third and fourth terms in the RHS. The eighth term to the last in the RHS, shows if a PU arrives to its channel while it is being used by a customer, the PU cause the SU to move to another channel within the same channels type, type 1, given that $h < C_1 - p_1 + 1$. However, if the number of SUs in type 1 equals to all available channels, $C_1 - p_1 + 1$, then the seventh term to the last in the RHS represents this case, where the interrupted SU in type 1 moves to a channel in type 2 ($h + 1$ becomes h on the LHS). The last term in RHS, shows when a PU arrives to its channel in type 2, given all available channels are occupied by SUs, the PU

interrupts an SU in its channel, and therefore the SU moves to a channel in type 1 ($h - 1$ becomes h on the LHS).

$$\pi_{v,h,p_1,p_2,0}[\lambda_s + h\mu_{s_1} + (v - h)\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2}]$$

$$= \pi_{v,h,p_1,p_2,1}\left[\Psi\right]\mathbb{1}_{v \geq 1} + \pi_{v+1,h+1,p_1,p_2,0}\left[(h + 1)\mu_{s_1}\right]\mathbb{1}_{h+1 \leq C_1 - p_1} + \pi_{v+1,h,p_1,p_2,0}\left[(v + 1 - h)\mu_{s_2}\right]$$

$$+ \pi_{v,h,p_1+1,p_2,0}\left[(p_1 + 1)\mu_{p_1}\right] + \pi_{v,h,p_1,p_2+1,0}\left[(p_2 + 1)\mu_{p_2}\right]$$

$$+ \frac{C_1 - p_1 + 1 - h}{C_1 - p_1 + 1}\pi_{v,h,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{h < C_1 - p_1 + 1}$$

$$+ \frac{C_2 - p_2 + 1 - (v - h)}{C_2 - p_2 + 1}\pi_{v,h,p_1,p_2-1,0}[(C_2 - p_2 + 1)\lambda_{p_2}]\mathbb{1}_{v-h < C_2 - p_2 + 1}.$$

$$(A.2)$$

Case 2: If $v = (C_1 - p_1) + (C_2 - p_2)$, $h \leq (C_1 - p_1)$, and $h \leq v$. Therefore, the global balance equations are equations (A.3) and (A.4).

$$\pi_{v,h,p_1,p_2,1}[\lambda_s + (C_1 - p_1)\mu_{s_1} + (C_2 - p_2 - 1)\mu_{s_2}\mathbb{1}_{C_2-p_2\geq 1} + p_1\mu_{p_1} + p_2\mu_{p_2} +$$

$$(C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2} + \Psi]$$

$$= \pi_{v-1,h-1,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{v\geq 1,h\geq 1} + \pi_{v-1,h,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{v\geq 1,h=C_1-P_1} + \pi_{v-1,h-1,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{v\geq 2,h\geq 1}$$

$$+ \pi_{v-1,h,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{v\geq 2,h=C_1-P_1} + \pi_{v+1,h,p_1,p_2,0}\left[(C_1-p_1)\mu_{s_1}\right] + \pi_{v+1,h,p_1,p_2,0}\left[(C_2-p_2)\mu_{s_2}\right]$$

$$+ \pi_{v+1,h,p_1,p_2,1}\left[(C_1-p_1)\mu_{s_1}\right] + \pi_{v+1,h,p_1,p_2,1}\left[(C_2-p_2-1)\mu_{s_2}\right]\mathbb{1}_{C_2-p_2\geq 1}$$

$$+ \pi_{v,h-1,p_1+1,p_2,0}\left[(p_1+1)\mu_{p_1}\right] + \pi_{v,h,p_1,p_2+1,0}\left[(p_2+1)\mu_{p_2}\right]$$

$$+ \pi_{v,h-1,p_1+1,p_2,1}\left[(p_1+1)\mu_{p_1}\right]\mathbb{1}_{v\geq 1}$$

$$+ \pi_{v,h,p_1,p_2+1,1}\left[(p_2+1)\mu_{p_2}\right]\mathbb{1}_{v\geq 1}$$

$$+ \pi_{v,h,p_1-1,p_2,1}\left[(C_1-p_1+1)\lambda_{p_1}\right]\mathbb{1}_{v\geq 1,h<C_1-p_1+1}$$

$$+ \pi_{v,h+1,p_1-1,p_2,1}\left[(C_1-p_1+1)\lambda_{p_1}\right]\mathbb{1}_{v\geq 1,h+1=C_1-p_1+1}$$

$$+ \pi_{v,h,p_1,p_2-1,1}\left[(C_2-p_2+1)\lambda_{p_2}\right]\mathbb{1}_{v\geq 1,v-h<C_2-p_2+1}$$

$$+ \pi_{v,h-1,p_1,p_2-1,1}\left[(C_2-p_2+1)\lambda_{p_2}\right]\mathbb{1}_{v\geq 1,v-h+1=C_2-p_2+1}$$

$$+ \frac{C_1-p_1}{C_1-p_1+1}\pi_{v,h,p_1-1,p_2,0}\left[(C_1-p_1+1)\lambda_{p_1}\right]\mathbb{1}_{h<C_1-p_1+1}$$

$$+ \pi_{v,h+1,p_1-1,p_2,0}\left[(C_1-p_1+1)\lambda_{p_1}\right]\mathbb{1}_{h+1=C_1-p_1+1}$$

$$+ \frac{C_2-p_2}{C_2-p_2+1}\pi_{v,h,p_1,p_2-1,0}\left[(C_2-p_2+1)\lambda_{p_2}\right]\mathbb{1}_{v-h<C_2-p_2+1}$$

$$+ \pi_{v,h-1,p_1,p_2-1,0}\left[(C_2-p_2+1)\lambda_{p_2}\right]\mathbb{1}_{v-h+1=C_2-p_2+1}.$$

$$\text{(A.3)}$$

In equation (A.3), the ninth term in the RHS, shows an SU is waiting in the VQ, and when a PU in a channel in type 1 finishes its transmission, the SU which is waiting moves to this channel, and therefore the system moves from state $\pi_{v,h-1,p_1+1,p_2,0}$ to state $\pi_{v,h,p_1,p_2,1}$, notice

that $h - 1$ becomes h. Recall, h is the number of SUs in type 1 channels.

$$\pi_{v,h,p_1,p_2,0}[\lambda_s + (C_1 - p_1)\mu_{s_1} + (C_2 - p_2)\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2}]$$
$$= \pi_{v,h,p_1,p_2,1}[\Psi]\,\mathbb{1}_{v\geq 1} + \frac{1}{C_1 - p_1 + 1}\pi_{v,h,p_1-1,p_2,0}[(C_1 - p_1 + 1)\lambda_{p_1}]\,\mathbb{1}_{h < C_1 - p_1 + 1}$$
$$+ \frac{1}{C_2 - p_2 + 1}\pi_{v,h,p_1,p_2-1,0}[(C_2 - p_2 + 1)\lambda_{p_2}]\,\mathbb{1}_{v-h < C_2 - p_2 + 1}.$$
$$(A.4)$$

Case 3: If $(C_1 - p_1) + (C_2 - p_2) < v < \beta$, $h \leq (C_1 - p_1)$, and $h \leq v$. So, equations (A.5) and (A.6) are the global balance equations.

$$\pi_{v,h,p_1,p_2,1}[\lambda_s + (C_1 - p_1)\mu_{s_1} + (C_2 - p_2 - 1)\mu_{s_2}\mathbb{1}_{C_2-p_2\geq 1} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1}$$
$$+ (C_2 - p_2)\lambda_{p_2} + \Psi]$$
$$= \pi_{v-1,h,p_1,p_2,1}[\lambda_s]\,\mathbb{1}_{v\geq 2} + \pi_{v+1,h,p_1,p_2,1}[(C_1 - p_1)\mu_{s_1}]$$
$$+ \pi_{v+1,h,p_1,p_2,1}[(C_2 - p_2 - 1)\mu_{s_2}]\,\mathbb{1}_{C_2-p_2\geq 1} + \pi_{v+1,h,p_1,p_2,0}[(C_1 - p_1)\mu_{s_1}]$$
$$+ \pi_{v+1,h,p_1,p_2,0}[(C_2 - p_2)\mu_{s_2}] + \pi_{v,h-1,p_1+1,p_2,1}[(p_1 + 1)\mu_{p_1}]\,\mathbb{1}_{v\geq 1}$$
$$+ \pi_{v,h,p_1,p_2+1,1}[(p_2 + 1)\mu_{p_2}]\,\mathbb{1}_{v\geq 1} + \pi_{v,h-1,p_1+1,p_2,0}[(p_1 + 1)\mu_{p_1}]$$
$$+ \pi_{v,h,p_1,p_2+1,0}[(p_2 + 1)\mu_{p_2}] + \pi_{v,h+1,p_1-1,p_2,1}[(C_1 - p_1 + 1)\lambda_{p_1}]\,\mathbb{1}_{v\geq 1}$$
$$+ \frac{C_2 - p_2}{C_2 - p_2 + 1}\pi_{v,h,p_1,p_2-1,1}[(C_2 - p_2 + 1)\lambda_{p_2}]\,\mathbb{1}_{v\geq 1}.$$
$$(A.5)$$

$$\pi_{v,h,p_1,p_2,0}[\lambda_s + (C_1 - p_1)\mu_{s_1} + (C_2 - p_2)\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2}]$$
$$= \pi_{v-1,h,p_1,p_2,0}[\lambda_s] + \pi_{v,h,p_1,p_2,1}[\Psi]\,\mathbb{1}_{v\geq 1} + \pi_{v,h+1,p_1-1,p_2,0}[(C_1 - p_1 + 1)\lambda_{p_1}]$$
$$+ \pi_{v,h,p_1,p_2-1,0}[(C_2 - p_2 + 1)\lambda_{p_2}] + \frac{1}{C_2 - p_2 + 1}\pi_{v,h,p_1,p_2-1,1}[(C_2 - p_2 + 1)\lambda_{p_2}]\,\mathbb{1}_{v\geq 1}.$$
$$(A.6)$$

In equation (A.6), the last term in the RHS, a PU arrives to a channel and terminates sensing with probability $\frac{1}{C_2-p_2+1}$. We assume, if $s = 1$, then sensing is conducted on a channel in type 2, as the OB analysis is assumed. However, in equation (A.5), the last term in the

RHS, shows that sensing has not been terminated, since the PU arrives to a channel where SU(s) are already being served and sensing is not being conducted, with probability $\frac{C_2-p_2}{C_2-p_2+1}$. However, this causes an SU interruption. Therefore, the SU moves back to the head of the VQ, and waits on a channel to become available.

Case 4: In this case $v = \beta$, $h \le (C_1 - p_1)$, and $h \le v$. As a result, equations (A.7) and (A.8) are the global balance equations.

$$\pi_{\beta,h,p_1,p_2,1}[(C_1 - p_1)\mu_{s_1} + (C_2 - p_2 - 1)\mu_{s_2}\mathbb{1}_{C_2-p_2\ge1} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} +$$

$$(C_2 - p_2)\lambda_{p_2} + \Psi]$$

$$= \pi_{\beta-1,h,p_1,p_2,1}\left[\lambda_s\right]\mathbb{1}_{\beta\ge2} + \pi_{\beta,h-1,p_1+1,p_2,1}\left[(p_1 + 1)\mu_{p_1}\right]\mathbb{1}_{\beta\ge1}$$

$$+ \pi_{\beta,h,p_1,p_2+1,1}\left[(p_2 + 1)\mu_{p_2}\right]\mathbb{1}_{\beta\ge1} + \pi_{\beta,h-1,p_1+1,p_2,0}\left[(p_1 + 1)\mu_{p_1}\right] + \pi_{\beta,h,p_1,p_2+1,0}\left[(p_2 + 1)\mu_{p_2}\right]$$

$$+ \pi_{\beta,h+1,p_1-1,p_2,1}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\mathbb{1}_{\beta\ge1} + \frac{C_2 - p_2}{C_2 - p_2 + 1}\pi_{\beta,h,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{\beta\ge1}.$$

$$\text{(A.7)}$$

$$\pi_{\beta,h,p_1,p_2,0}[(C_1 - p_1)\mu_{s_1} + (C_2 - p_2)\mu_{s_2} + p_1\mu_{p_1} + p_2\mu_{p_2} + (C_1 - p_1)\lambda_{p_1} + (C_2 - p_2)\lambda_{p_2}]$$

$$= \pi_{\beta-1,h,p_1,p_2,0}\left[\lambda_s\right]\mathbb{1}_{\beta\ge1} + \pi_{\beta,p_1,h,p_2,1}\left[\Psi\right]\mathbb{1}_{\beta\ge1} + \pi_{\beta,h+1,p_1-1,p_2,0}\left[(C_1 - p_1 + 1)\lambda_{p_1}\right]\quad\text{(A.8)}$$

$$+ \pi_{\beta,h,p_1,p_2-1,0}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right] + \frac{1}{C_2 - p_2 + 1}\pi_{\beta,h,p_1,p_2-1,1}\left[(C_2 - p_2 + 1)\lambda_{p_2}\right]\mathbb{1}_{\beta\ge1}.$$

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