MAC Protocol Design for Parallel Link Rendezvous in Ad Hoc Cognitive Radio Networks

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The most significant challenge for next wireless generation is to work opportunistically on the spectrum without a fixed spectrum allocation. Cognitive Radio (CR) is the candidate technology to utilize spectrum white space, which requires the CR to change its operating channel as the white space moves. In a CR ad-hoc network, each node could tune to a different channel; as a result, it cannot communicate with other nodes. This different tuning is due to the difficulty of maintaining Common Control Channel (CCC) in opportunistic spectrum network, and keeping the nodes synchronized in ad-hoc network. The CR ad-hoc network requires a protocol to match tuning channels between ad-hoc nodes, namely, rendezvous channels.

In this thesis, two distributed Medium Access Control (MAC) protocols are designed that provide proper rendezvous channel without CCC or synchronization. The Balanced Incomplete Block Design (BIBD) is used in both protocols to provide our protocols a method of rendezvous between CR ad-hoc nodes. In fact, the BIBD guarantees there is at least one common element between any two blocks. If the channels are assigned to the BIBD elements and the searching sequence to the BIBD block, there is a guarantee of a rendezvous at least in one channel for each searching sequence. The first protocol uses a single-BIBD sequence and a multi-channel sensing. Alternatively, the second protocol uses a multi-BIBD sequence and a single-channel sensing.

The single-sequence protocol analysis is based on the discrete Markov Chain. At the same time, the sequence structure of the BIBD in a multi-sequence protocol is used to define the Maximum Time to Rendezvous (MTTR). The simulation results confirm that the protocols outperform other existing protocols with respect to Time to Rendezvous (TTR), channel utilization, and network throughput. In addition, both protocols fairly

distribute the network load on channels, and share the channels fairly among network nodes. This thesis provides straight forward and efficiently distributed MAC protocols for the CR ad-hoc networks.

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List of Abbreviations

CR   Cognitive Radio

SU   Secondary User

PU   Primary User

CCC   Common Control Channel

TTR   Time to Rendezvous

CT   Connection Time

MAC   Medium Access Control

BIBD   Balanced Incomplete Block Design

IEEE   Institute of Electrical and Electronics Engineers

DySPAN   Dynamic Spectrum Access Network

WINNER   Wireless World Initiative New Radio

SDR   Software-Defined Radio

AWGN   Additive White Gaussian Noise

SNR   Signal to Noise Ratio

LO   Local Oscillator

RTS   Request To Send

CTS   Clear To Send

MMAC	Multi-channel Medium Access Control
CR-MAC	Cognitive Radio Medium Access Control
OFDM	Orthogonal Frequency Division Multiplexing
SRAC	Single-Radio Adaptive Channel
QCH	Quorum-based Channel Hopping
A-QCH	Asynchronous Quorum-based Channel Hopping
BD	Block Design
IBD	Incomplete Block Design
BBD	Balanced Block Design
H	Hadamard Incidence Matrix
MTTR	Maximum Time to Rendezvous
CSMA/CA	Carrier Sense Multiple Access With Collision Avoidance

Chapter 1

Introduction

1.1 Research Motivation

Currently, the commercial wireless spectrum is in high demand to be used for personal wireless communication. The wireless spectrum is a type of natural resource that has a similar availability in each country and world-wide. However, available useful spectrum bands are limited with respect to current technology, and in fact, the present spectrum regulations assign a fixed spectrum portion for each kind of wireless technology. Thus, this high demand leads to a shortage of spectrum availability for new users and new wireless technologies. Therefore, the spectrum bands should be utilized efficiently. Researchers have proposed a new strategy that opens the spectrum for Secondary Users (SU). The candidate technology, called Cognitive Radio (CR), is proposed for better wireless spectrum utilization.

It is essentially intended to escape from the fixed spectrum assignment and utilize the idle spectrum. Hence, CR has no licensed band on the wireless spectrum, *i.e.,* the

CR has to set its spectrum dynamically because CR seeks an opportunity to use and access licensed wireless spectrum portions. These portions exist when the licensed network, known as Primary User (PU), does not use its spectrum portions. The idea of utilizing the wireless spectrum was invented when the American Federal Communication Commission (FCC) reported that the wireless spectrum is utilized from 15% to 85% of its capacity [3]. The wireless spectrum usage is concentrated in certain regions of the entire wireless spectrum; conversely, some spectrum regions are lightly concentrated. In addition, the report mentions the variety of wireless spectrum utilization depends on the desired geographical region and the population of that region.

1.2   Problem Description

The unused spectrum portion for the CR network is not static because the activity of the PU is dynamic in nature (Figure 1.1). In this case, the connection of two nodes (a and b) is interrupted by the PU activity. These nodes then seek another idle spectrum portions. Each node could mismatch with other node spectrum portions; and consequently the node takes long time to match with another node's spectrum.

This dynamic behaviour causes the available spectrum (*i.e.,* the idle spectrum portion) moving for the CR. In this case, the CR network has to reconfigure its operation spectrum from time-to-time, depending on the PU activity. As a result, the basic function required from the CR is to support spectrum mobility. Spectrum mobility is defined as the function that maintains a seamless communication requirement during the transition to another spectrum when the PU appears again.

The spectrum mobility function provides the next available spectrum portion to the
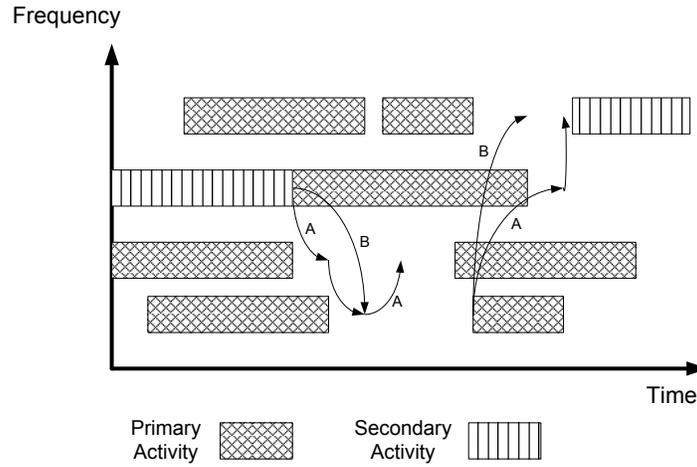
Figure 1.1: Spectrum Status.

CR network if the current used spectrum becomes unavailable. This function can be implemented easily if the spectrum availability is known. In reality, the spectrum availability has the same behaviour as the PU activity. Unfortunately, the PU activity is not known to the CR network, and thus, it is unyielding to model the spectrum availability. Consequently, defining the spectrum mobility function becomes more challenging.

The Common Control Channel (CCC) is proposed in CR literature [4, 5, 6, 7, 8, 9] to coordinate and exchange information about CR functions including the mobility function. The CCC is not feasible for CR networks for several reasons [10, 11, 12, 13].

- The channel band could be unavailable to the CR network for a long time;

- The channel could suffer jamming or high interference;

- The channel may cause a bottleneck problem in the network communication system;

- Channel degradation, regardless of the reasons, reduces the CR network QoS;

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- The channel has to be reserved when this reservation conflicts with the CR concept, such as underutilization spectrum.

For an infrastructureless network like ad-hoc networks, a new feature should be considered. In ad-hoc network, there is no master ad-hoc node that could coordinate the CCC channel. Furthermore, an ad-hoc network that works as a CR network has several special characteristics that should be taken into account during protocol design [9]. These characteristics are

- Ad-hoc topology is continuously changing, and works in a distributed manner

- CR ad-hoc network has to efficiently utilize the desired spectrum without external coordination

The distributed function is performed at each CR ad-hoc node individually, depending on node view and decision. As a result, the distributed function could lead to a mismatch between operation points of the CR ad-hoc nodes, such as frequency, bandwidth, and transmission power. These operation points are not pre-defined for the CR ad-hoc because these points are not static as required for the CR network. To overcome this problem, some operation points are assumed to be known. However, if there is no information exchange between the PU and the CR ad-hoc, the operation frequency cannot be known.

Let us focus on the operation frequency in a distributed network. When each ad-hoc node has a local view of the spectrum, each node has a different decision and operating frequency. An ad-hoc node independently observes its environment and decides to access the idle spectrum. The problem that arises in this context is how ad-hoc nodes match the operation frequency to successfully communicate with eachother and mitigate the spectrum
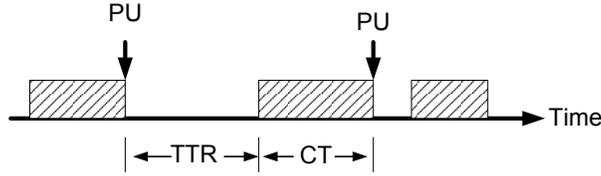
Figure 1.2: Cognitive Radio Activity.

mobility affect. In other word, how the CR ad-hoc nodes select the same frequency band to be sensed and accessed. Due to the variety of spectrum selection by the CR ad-hoc, the sender node and receiver node could face a frequency mismatch problem.

In this thesis, an algorithm that satisfies CR ad-hoc requirements is proposed. The proposed algorithm matches any pair of CR ad-hoc nodes with the same operating frequency. Once a pair is matched, it can establish a successful connection. This connection will continue until the PU appears on that frequency or the CR ad-hoc pair finishes its data exchange. When the PU appears, the CR ad-hoc nodes must switch to another idle frequency band. The proposed algorithm defines how the switching process performs subject to a minimum time required for pairs to be matched again. This time is called Time to Rendezvous (TTR), or time to connect [14].

Figure 1.2 depicts the CR ad-hoc node activity. When the PU appears at certain point in time, the CR ad-hoc pair stops its transmission and searches for another idle spectrum. After the pair finds an idle spectrum, it establishes a new connection. The time from the PU appearing to the time of the new connection starting is called the (TTR). Similarly, the time from new connection starting to the time of the PU appearing is called Connection Time (CT). It is clear that the CR ad-hoc network throughput increases as the TTR is reduced and the CT is increased.

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1.3 Research Objectives and Contribution

In this thesis, we focus on spectrum sharing and spectrum mobility functions. We want to minimize the time that any of CR ad-hoc nodes spend to meet each other at the same spectrum portion. Hereafter, we will call the meeting process "rendezvous". The next available spectrum portions is assumed to be unknown for the CR ad-hoc nodes. Also, there is no prediction process for next available spectrum. The CCC is eliminated from our assumptions because it is not reliable as discussed previously.

We design two Medium Access Control (MAC) protocols that satisfy the requirements for our system. The Balanced Incomplete Block Design (BIBD) is used to achieve our goal. The BIBD easily allows any CR ad-hoc pair to rendezvous in the same spectrum portion without any central controller. In other words, the proposed MAC protocols work in a distributed manner. The BIBD also provides the protocols with an asynchronous property as identified in protocols design.

It is expected that the proposed protocols outperform the existing protocols with respect to performance metrics, such as TTR, channel utilization, and network throughput. The simulation results confirm this improvement.

1.4 Thesis Structure

This thesis is organized as follows. Chapter 2 provides a general view of cognitive radio and its functions description. The MAC protocol classifications and its issues are provided in this chapter. The system model, related work, and design tools are presented in Chapter 3. Moreover, this chapter includes the proposed protocols, protocols analysis, and simulation

results. Conclusions and future work are presented in Chapter 4.

Chapter 2

Cognitive Radio and MAC Protocols Overview

This chapter discusses Cognitive Radio (CR) requirements that are important to design of CR related protocols. The designer has to know the space and limitation of the desired system before starting any design. This chapter presents details for the most important CR functions related to design. Additionally, we implement a description for CR MAC protocols and their classifications.

2.1 Cognitive Radio

With the invention of the CR, the CR is expected to utilize the spectrum in an opportunistic manner by dynamically accessing the spectrum. Instead of the current static spectrum assignment, the Institute of Electrical and Electronics Engineers (IEEE) establishes a Dynamic Spectrum Access Network (DySPAN). This symposium develops new technologies

dynamically accessing the wireless spectrum [2]. In Europe, a project called Wireless World Initiative New Radio (WINNER) develops a new concept in radio access [15].

2.1.1 Cognitive Radio Functions

The four main CR functions are spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing [16].

1. Spectrum Sensing: Detects unused Primary User (PU) spectrum to be shared without harmful interference with the PU.

2. Spectrum Management: Captures the best available spectrum band that has been sensed by the spectrum sensing function.

3. Spectrum Mobility: Maintains a seamless communication during a transition to another idle spectrum.

4. Spectrum Sharing: Provides a fair spectrum scheduling method among coexisting CR users.

These functions are produced periodically in a cyclic manner [17, 16, 18]. The CR node starts with spectrum sensing to allocate all unused spectrum (*i.e.,* spectrum holes). Once this function is completed, the CR node moves to the spectrum management function to select the best unused spectrum. Next, the spectrum sharing function is performed to properly access that spectrum. During the established connection between CR nodes, the CR nodes perform the first two functions frequently. When the results from the spectrum sensing and spectrum management functions change, the spectrum sharing and the spectrum mobility functions should change too; all functions start over.

2.1.2   Cognitive Radio Definition

One of the CR definitions defines the CR as a radio that can change its transmitter parameters, such as frequency, power and modulation scheme, based on interactions with the surrounding environment in which it operates. In [19], Motila includes the CR in the Software-Defined Radio (SDR). His case and Haykin's view [20] define the CR as an intelligent wireless communication system that is aware of its surrounding environment and adapts its internal state by making corresponding changes in certain operating parameters in real-time with high reliable communication and efficient utilization of the radio spectrum.

By consulting the CR research literature, it is clear that the first definition becomes more interest for the current CR research especially in the frequency parameter. Most of the current research focuses on the frequency of the CR to create a new technology that efficiently utilizes the spectrum. As a result, the CR definition based on current research is the radio that has no licensed spectrum, *i.e.,* Secondary User (SU), and seeks opportunistically to access the PU licensed spectrum without harmful interfering with the PU.

2.2   Cognitive Radio Functions Description

Discussion regarding CR details is critical because research in this area is in its preliminary stage and because of the optimistic view researchers routinely hold. In the following subsections, we provide details about each of CR functions that are needed for our design.

2.2.1 Spectrum Sensing

The CR is designed to utilize the wireless spectrum, and the CR have to be aware of the unused spectrum portion. This awareness completely depends on the sensing function as one of the CR fundamental functions. At the beginning of studying the CR technology, a suitable spectrum sensing should be carefully selected. To do so, we support all possible spectrum sensing that could be used for the CR.

The spectrum sensing techniques that are used in CR technology are investigated. The CR awareness is the responsibility of the spectrum sensing function. Furthermore, the main objective of the spectrum sensing in the CR is to provide a suitable spectrum portion to be used by the CR user. This spectrum portion is accessible by the CR network and should not cause any harmful interference with the PU. Alternatively, since the CR is designed to utilize the wireless spectrum, the CR has to have efficient spectrum sensing to avoid miss detection. The idle spectrum miss detection leads to the degradation of spectrum usage, and consequently the CR network throughput. Only the CR is responsible for utilizing the unused spectrum. Therefore, the CR should have the ability to sense and allocate the unused PU spectrum. There are different spectrum sensing techniques for the CR [21].

Primary User Transmitter Sensing

One approach to avoid interfering with the licensed network and detect idle spectrum is to sense the PU network transmitters' activities. This strategy is typically categorized by three schemes [22, 16]: match filter detector, energy detector, cyclostationary feature detector.

(a) **Match Filter Detector**

The match filter is the optimal transmitter detector in an Additive White Gaussian Noise (AWGN) environment [23], particularly if the characteristics of the transmitter signal are known. The match filter maximizes the signal-to-noise ratio (SNR). This maximization is required for a weak signal detection. As a result, the accuracy of the spectrum sensing is increased.

In addition, the match filter needs less computation time than other detectors. This reduces the sensing time when time is crucial to the CR. This time is bounded if the match filter required samples are known. The required samples are bounded by the reciprocal of SNR ($O(1/SNR)$) [24]. However, a match filter requires prior knowledge about the characteristic of the PU transmitter because the received signal will be demodulated. The match filter should also be coherent with the transmitter signal.

For the CR, the information about the PU network characteristics are unknown or not accurate. For this reason, the match filter is not a candidate to be the CR detector.

(b) **Energy Detector**

The energy is the optimal detector if the noise level is determined, and when there is insufficient information about the PU transmitter [24]. This scheme is similar to the radiometer or the spectrum analyzer. The cost of accuracy of the energy detector is the samples that are required, which are bounded by the reciprocal of square of SNR ($O(1/SNR^2)$).

In order to sense the PU existence [23], the output signal from the bandpass filter with bandwidth W is squared and integrated over the observation interval T. The
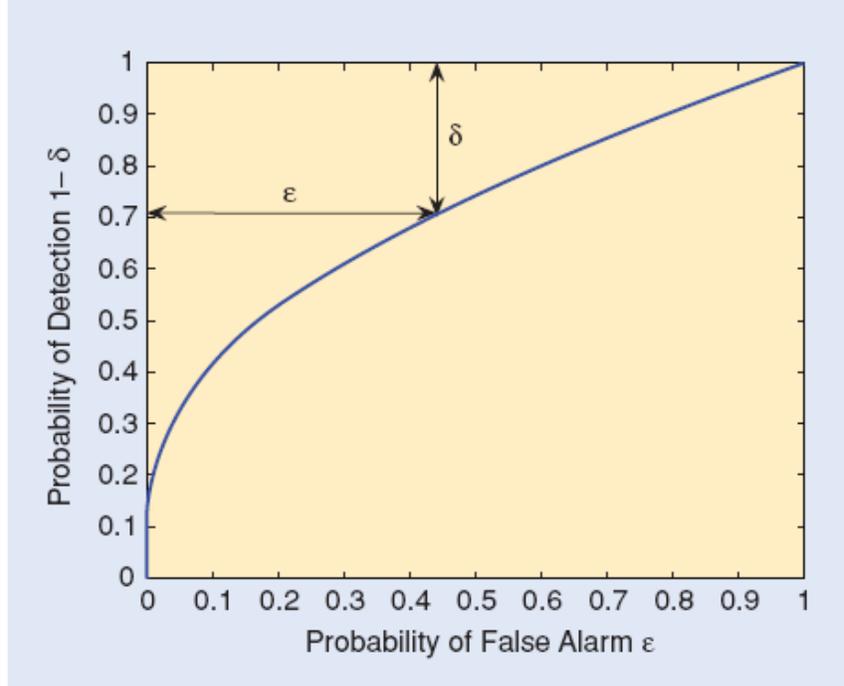
Figure 2.1: False Alarm versus Detection Probabilities [2]

result Y is compared with a threshold λ to decide whether a PU is present or not.

In a non-fading environment, the detection probability P_d and false alarm probability P_f are given as follows:

$$P_d = P\{Y > \lambda/H_1\} = Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) \tag{2.1}$$

$$P_f = P\{Y > \lambda/H_0\} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)} \tag{2.2}$$

where γ is SNR, m = TW, $\Gamma(.)$ and $\Gamma(.,.)$ are complete and incomplete gamma function, $Q_m(.)$ is generalized Marcum Q-function, and H_1 and H_0 is the PU present and absence hypothesis, respectively. As the simulation in [2], a small false alarm probability (ε) implies a large miss detection probability (σ) (Figure 2.1).

In the shadowing and the multi-path fading environment, the false alarm probability P_f is independent of Γ. This independence occurs when the amplitude gain of the channel varies due to the shadowing or the fading. The detection probability depends on instantaneous SNR as follows:

$$P_d = \int_x Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) f_x(x) dx \tag{2.3}$$

where $f_x(x)$ is the probability distribution function of SNR under fading.

The energy detector performance is susceptible to the uncertainty in the noise power. The threshold is variant from a PU to another because each PU has a different transmission power. The presence of any interference in the detection band confuses the energy detector. Furthermore, in the frequency selective fading, it is not clear how to set the threshold with respect to channel notches [25]. Moreover, the energy detector does not differentiate between modulated, noise, and interference signals. In addition, the energy detector does not work for the spread spectrum signal. Finally, the energy detector is excellent choice for fast, but not accurate, sensing.

(c) **Cyclostationary Feature Detector**

In general, the wireless systems modulate their transmitted signals on sine wave carriers. This wave embeds a periodic feature in the modulated signal. This feature is characterized as a cyclostationary feature. The periodic feature is detected by analyzing a spectral correlation function.

The main advantage of the spectral correlation function is that it differentiates the noise energy from the modulated signal energy. This advantage is a result of the fact that the noise is a wide-sense stationary signal with no correlation. Moreover, the

modulated signals are cyclostationary with a spectral correlation due to the embedded periodic of the sine wave.

In addition, the cyclostationary detector distinguishes the feature of the received signal, such as a modulation scheme [16]. The reference [23] provides further detail regarding the power spectral density and the power correlation function.

The spectral density function has a highly distinct spectral correlation functions for different modulation type (such as BPSK, QPSK) that have identical power[25]. The simulation in [26] provide that the exploitation of channel correlation at the Physical layer is more effective than the exploitation at the MAC layer to improve the CR throughput.

The cyclostationary detector is robust compared to the uncertainty of the noise power, and therefore, has better performance in fading environment than the energy detector. However, the cyclostationary feature detector is complex in computation and requires a significant long observation time. In fact, the cyclostationary detection time increases linearly with SNR reduction [27]. Final words, the features that result from cyclostationary detector are helpful for the CR.

Primary User Receiver Sensing

The CR must detect the presence of the PU to avoid interfering with it. However, the CR has assumed that many devices in the primary network, such as TV and cellular phones, are passive. In reality, all receivers emit power that leak from the Local Oscillator (LO) at the RF front-end.

The work in [28] exhibits that the CR sensor can detect the exact channel of the PU

receiver. The sensing is occurs in milliseconds with a high detection probability. As a result of this technique, the CR network could operate in a high dense urban environment without interfering with the PU receivers. In addition, this technique is robust against signal shadowing, and is suitable for the decentralized CR networks.

In reality, the PU receiver does not tune in the channel that carries data. In other words, if the CR uses this channel, no PU data are lost. The PU receiver signal cause more confusing to CR and increases the probability of miss detection.

Cooperative Spectrum Sensing

The transmitter detection model cannot prevent the hidden terminal problem (shadowing) or overcome the channel fading. Therefore, sensing information from other CR users is required for a more accurate detection. The cooperative detection scheme is the spectrum sensing method where the CR users exchange their sensing results. This cooperation prevents the shadowing problem. Moreover, the cooperative sensing degrades the effect of the multi-path fading. In addition, the cooperative sensing is used to avoid transmitting in an interference area as proposed in [29].

The cooperative spectrum sensing is performed as either centralized or distributed sensing. In centralized cooperative sensing, a center node collects all sensing results, and then executes the correct decision [30]. Conversely, in distributed cooperative sensing, all CR users exchange their sensing results.

An adaptive centralized cooperative spectrum sensing method is proposed in [31]. In this work, the sensing parameters are optimized and adapted to the number of cooperative users. The simulation of this work confirms this method can achieve maximum sensing

efficiency.

The shadowing and Rayleigh Fading are investigated in [32] using spectral correlation based on the cyclostationary theory, and obtains maximum sensing efficiency by cooperative sensing as well. In [32], the cooperative sensing based on energy detection is investigated using weighted combining. The results indicate the cooperative scheme increases the system performance.

One of the problems in cooperative sensing is how the results from various users are combined. The CR nodes may have different sensitivities and sensing time as discussed in [30]. While cooperative sensing is more accurate, it sacrifices certain resources, such as a spectrum band, which are valuable to the CR network. Moreover, in the most cases it requires a control channel to exchange the sensing data.

Different spectrum sensing techniques are used for the CR. Each technique has its advantages and disadvantages with compromises between accuracy and complexity for each one. Deciding which is better choice is difficult, and therefore, we select the most suitable one that satisfies our requirements or combines more than one sensing technique. For example, in the standard IEEE 802.22, two stages of sensing are used: fast and fine sensing [7]. The fast sensing is based on a energy sensing detector and fine sensing is based on a feature detector.

2.2.2   Spectrum Sharing

The greatest challenge in a CR network is the coexistence of the SUs with the PUs. This coexistence is called spectrum sharing. For example, after the SUs allocate spectrum portions for access, they decide which node transmits at a certain time to avoid many

nodes transmitting in an overlapping manner. The SU receiver should be informed to which spectrum portion it tunes into. Both of the SU transmitter and the SU receiver should negotiate to move from one spectrum portion to another with reliable communication.

The spectrum sharing function is classified into three main categories [16]

1. Architecture

   - Centralized

   - Distributed

2. Allocation behavior

   - Co-operative

   - Non-cooperative

3. Access technique

   - Overlay

   - Underlay

   - Underlay with interference avoidance

In the centralized architecture, sharing decisions are made at one node. In contrast, for distributed architecture, each SU node independently accesses the spectrum based on its observations and decisions. The major difference is the second architecture does not need an infrastructure as the first one does.

The spectrum sharing allocation behaviour works as co-operative or non-cooperative. The co-operative behaviour considers the impact on other SUs. The non-cooperative behaviour creates a competition among the SUs.

The spectrum sharing access techniques follow three schemes: overlay, underlay, and underlay with interference avoidance. The overlay scheme occurs when the SU transmits power similar as the PU does. If the SU transmits at the same time as the PU transmission, the SU signal overlays the PU signal. Similarly, the underlay scheme occurs when the SU spreads its power into the whole available bandwidth, as in CDMA or UWB. If the instantaneous transmission occurs, the SU signal underlays the PU signal. The underlay with interference avoidance scheme is similar to the underlay scheme, but it avoids the band where the PUs exist, as in the OFDM technique.

2.2.3   Spectrum Mobility

As required by the CR network to utilize the spectrum, the CR is temporarily occupied unused spectrum bands. The PU has priority to access its own spectrum bands whenever it wants to transmit. Hence, the CR vacates this band when the PU appears. As a result, the CR stops its transmission at this time. It is inefficient if the CR waits until the PU finishes its transmission on that band. An alternative strategy to overcome this issue requires the SU to switch to another idle band once the PU appears on a current ongoing band. This mechanism is named spectrum handoff; the situation of switching is known as the spectrum mobility. The CR must implement a spectrum mobility function to improve its QoS [16, 33].

There are two mechanisms to perform the spectrum handoff in the CR networks [34, 35]. In the first mechanism, the CR prepars a pool or a list of spectrum bands. When the spectrum handoff is required, the CR selects the best available band from the spectrum pool or list. In the second mechanism, the spectrum handoff is executed when it is required. For instance, when the PU appears, the CR searches for an idle spectrum. In both mechanisms,

the successful establish a useful connection and handoff latency are important performance metrics [36, 37].

2.3   Medium Access Control

In the following subsections, we present a general review of MAC classifications, and a narrowing from the general MAC protocol to our specific CR-MAC protocol.

2.3.1   General MAC Protocol

Medium Access Control (MAC) is the second layer of IEEE networking layers. This layer offers the best delivery of data over a physical medium from terminal to terminal. The delivery should lose as little transmitted data as possible. The best delivery results from a better designed algorithm providing access to a share physical medium.

The MAC protocol has two mechanisms that is either a reservation-based, or contention-based mechanism.

The reservation-based mechanism (also known as channel-based MAC) A specific portion from the channel is reserved for any network terminal that share the medium. In this mechanism, the channel is divided into the number equal to the number of the network terminals. The channel is divided in different dimensions, such as time, frequency, code, and space.

The contention-based (also known as packet-based MAC) Each terminal tries to win the whole channel at certain time. The contention leads to collisions between

the terminals. The MAC protocol must reduce the number of collisions as much as possible.

The reservation-based MAC needs an infrastructure or centralized entity, while the contention-based MAC does not. Consequently, based on MAC infrastructure required, a centralized MAC and a distributed MAC is another MAC classification [38].

2.3.2   Wireless MAC

Wireless network's terminals are connected over the spectrum that represents the physical medium for the wireless network. This medium is different than wired media, such as cable or optical fiber. The wireless medium suffers more signal attenuation and interference, plus fading and shadowing effects. As a result, a wireless network should have a special MAC protocol.

The most common problems in a distributed wireless network are the hidden as well as the exposed terminal problems. The hidden terminal problem is shown in Figure 2.2. Assuming we have three terminals (A, B, and C), each terminal has a transmission range that is shown as a circle around that terminal. The terminals A and C cannot receive each other's signals, while terminal B can receive signals from terminals A and C. If data is sent from terminal A to terminal B at the same time data is sent from terminal C to terminal B, the collision of data occurs as terminal B. This collision occurs because terminal A is hidden from terminal C, and vice versa.

The exposed terminal problem is shown in Figure 2.3. If we have four terminals (A, B, C, and D), terminal B is sending to terminal A and C has data to be send to D. The terminal C waits for free medium because the medium is sensed busy at terminal C due to
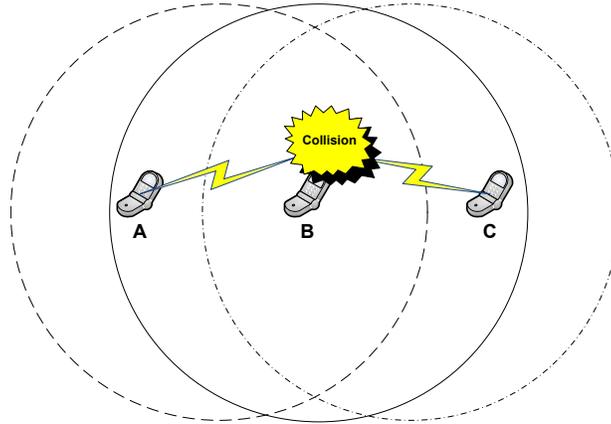
Figure 2.2: Hidden Terminal Problem
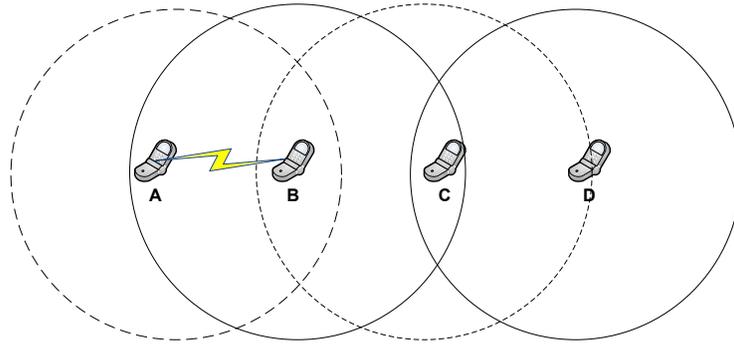
Figure 2.3: Exposed Terminal Problem

terminal B transmission. Terminal C waiting is not necessary because terminal A is out of terminal C's transmission range. This problem is called an exposed problem because terminal C is exposed to terminal B transmission, and vice versa.

The Request To Send (RTS) and Clear To Send (CTS) handshaking mechanisms have been proposed to solve these two problems. To solve a hidden terminal problem, terminal A begins to send an RTS packet to terminal B that terminal B can receive but terminal C cannot receive, *i.e.,* terminal C is out of range of terminal A. Then, terminal B replies by a CTS packet that both terminal A and terminal C can receive. At this point, terminal C detects that terminal B communicates with other. Consequently, terminal C does not

send data to terminal B, thus avoiding a collision at terminal B. The RTS packet is small which results in a significant collision reduction in the RTS transmission period.

To solve an exposed terminal problem, terminal B must send an RTS packet to terminal A. Terminal A replies to terminal B with a CTS packet. Terminal C only receives the RTS from terminal B but not a CTS from terminal A. At this time, terminal C detects that the desired destination of terminal B is out of its range. As a result, terminal C can start a new negotiation with terminal D.

2.3.3   Multi-Channel MAC Protocol

In a wireless environment, the spectrum band is wide enough to separate the band into multi-channels. The multi-channels capability is proposed to permit simultaneous transmissions over the network spectrum band; each transmission uses a different channel. Therefore, the network throughput is increased, and the contention and delay are decreased. With this kind of network, a different MAC protocol is required, also known as a multi-channel MAC (MMAC) protocol.

After the multi-channels proposal, the researchers propose multi-radios wireless devices. The multi-radios devices usually use one radio for data transmission while the second radio is used for a controlling information exchange. Based on the number of radios, the MMAC is classified into two categories:

- Control separation MMAC using two or more radios

- In-band control MMAC using single radio

The control is needed among network entities to ensure successful negotiation and

transmission. In a single radio MMAC, the data transmission is interrupted by control periods whenever needed. The multi-radios MMAC, or control separation protocol, always tunes one radio on a predefined common control channel. Thus, the other radio is used continually for data transmission.

The common control channel is categorized based on its operation principle. A comprehensive survey of these MMAC categories is published in [39, 40]. The common control channel is used for one of the operations: rendezvous, reservation, signalling, and hybrid.

Another MMAC classification is based on multi-channels rendezvous techniques [41]. The MMAC is either a single or multiple rendezvous protocol. The single rendezvous protocols force all terminals to exchange the control information over one channel. In multiple rendezvous protocols, any network pair can exchange the control information and data traffic simultaneously over any channel [42]. The research of [43, 44] provides a relevant survey and numerical comparison for this kind of MMAC classification.

Figure 2.4 summarizes the classifications of the MAC protocols. The shadowed block indicates to the class of our MAC protocols.

2.3.4 Cognitive Radio MAC Protocol

The CR seeks white spectrum space, and then establishes its connection over this white space. During a CR protocol design, the priority of the PU on the spectrum usage should take into account. The PU existing in the MAC protocol is a special issue for the CR. For example, the CR MAC should associate with the sensing scheduling and the sensing result. Therefore, the CR MAC is different than other MAC, and thus identified as the cognitive radio medium access control (CR-MAC) protocol.
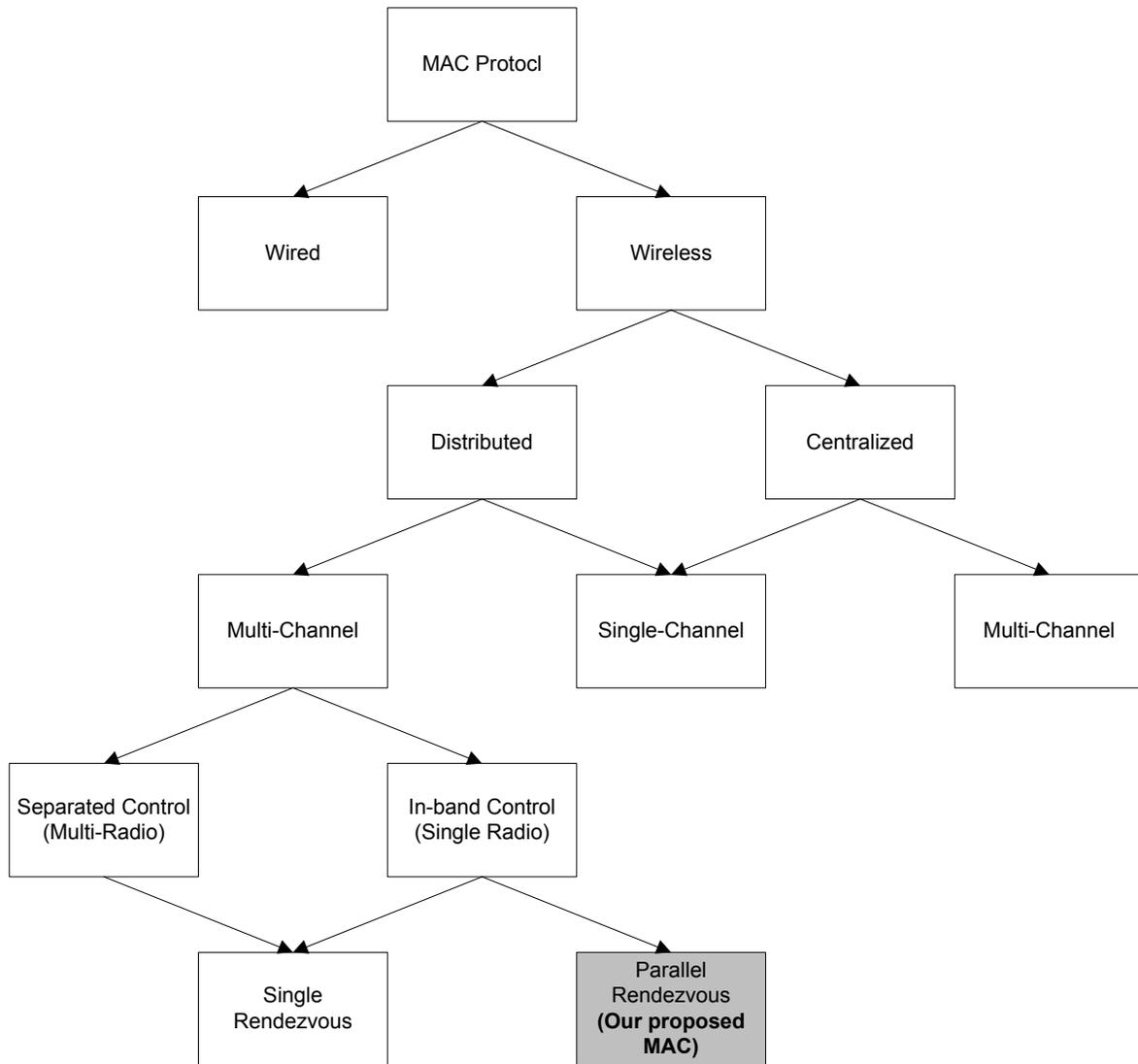
Figure 2.4: MAC Protocol Classification

The CR should adapt multi-channels protocol such as MMAC, because the white space appears in many spectrum portions. For simplicity, the minimum possible bandwidth of the white space is defined as a channel. If we know the PU channel division, we can divide the CR spectrum band into channels corresponding to the PU channels.

Similar to other wireless networks, the CR network could be supported with an infrastructure network or not be supported as ad-hoc network. Based on this supporting, the CR networks are classified into centralized and ad-hoc networks. A centralized CR network is formed when a special network entity works as a central network coordinator, *e.g.,* a base station [45, 46]. In an ad-hoc CR network, there is no single network entity or coordinator. The coordination process occurs in distributed manner where each terminal has its own action that is result from its observation and decision. The MAC protocol for an infrastructure and an infrastructure-less network are well surveyed in [1].

The CR-MAC protocol has different approaches depending on its operation principle.

Random Access CR-MAC. After sensing duration, each terminal randomly accesses allocated white space. The advantage of this protocol is that there is no needed for synchronization.

Time Slotted CR-MAC. The time slots schedule access to the white space similar to the TDMA. This protocol needs global synchronization to determine time slots barriers.

Hybrid CR-MAC. This protocol is a mix of the other protocols. It exists randomly for control signalling, but it is time slotted for data access.

We summarize in Table 2.1 the classifications of the CR-MAC [1]. The shadowed cell indeicates where our proposed protocols are located in these classifications. The protocols

Cognitive Radio MAC Protocols

		Random Access	Time Slotted	Hybrid
Centralized		CSMA MAC[48]	IEEE 802.22[45]	DSA Driven MAC[49]
Distributed	**Single Radio**	SRAC MAC[6] HC-MAC[7]		OS-MAC[50] POMDP[51] SCA-MAC[52]
	Multi-Radio	DOSS[8] DCA-MAC[55]	C-MAC[53]	SYN-MAC[54] Opportunistic MAC[56]

Table 2.1: Cognitive Radio MAC Protocols [1]

that are in the same class as our protocols are discussed in Section 3.2. Meaningful surveys in [1, 47] contribute to this classification topic.

Chapter 3

Ad Hoc Cognitive Radio MAC Protocols

In this chapter, the details of the system model and its problem are defined. The challenge in this thesis is the mismatch in channel selection that results from the CR spectrum mobility with lack of infrastructure in the ad-hoc network. We also provide related works in this chapter.

The main focus of this chapter is to design two MAC protocols that match the selected channel between ad-hoc pairs and minimize the Time to Rendezvous (TTR). These MAC protocols take advantage of the Balanced Incomplete Block Design (BIBD). The BIBD advantage is that there is at least one common element between any pair of blocks. The channels are mapped into block elements in our MAC protocol design, and the channels visiting sequence time is mapped into BIBD blocks. As a result, there is at least one common channel matched between any ad-hoc pair.
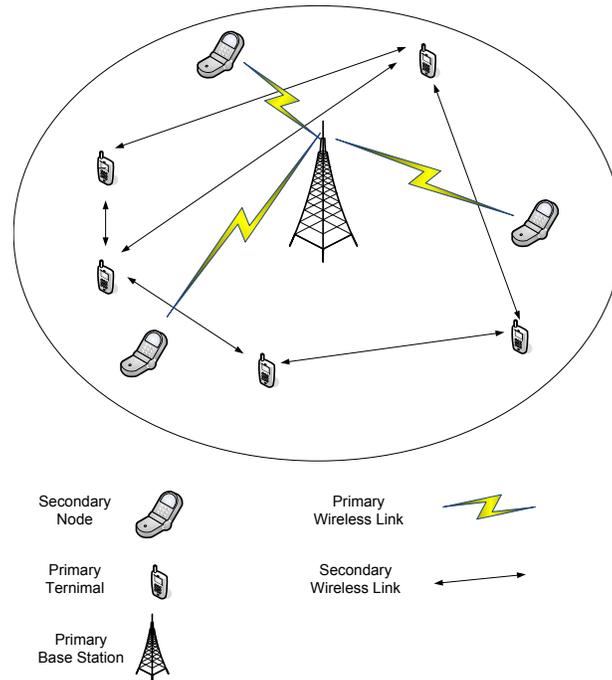
Figure 3.1: System Model

3.1   System Model

In this section, we discuss our system model (Figure 3.1). This system contains two types of networks: Primary network that is called the primary spectrum user (PU), and secondary network that is called the secondary spectrum user (SU). The PU is the licensed network where the SU is the unlicensed network. Figure 3.1 depicts the secondary nodes under the coverage area of the PU.

We consider the SU as an ad-hoc network, which works in a distributed manner. The following assumptions exist for this system model:

1. Each SU has only one transceiver;

2. No control channel is used;
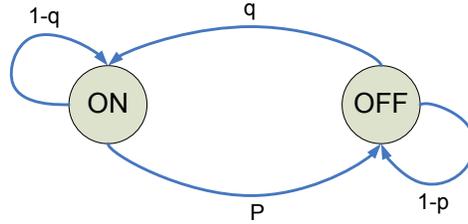
Figure 3.2: Primary User Activity Model
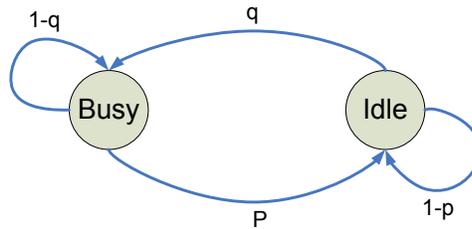
Figure 3.3: Channel Model

3. The PU activity is unknown;

4. The spectrum sharing uses an overlay spectrum access approach (Section 2.2.2).

The channels are assumed to be independently used by the PU. Each channel state is modeled to be either idle or busy from the point view of the SU. Actually, this model corresponds to the PU activity on the channels. The PU is either ON or OFF regardless of the PU traffic. Figure 3.2 and 3.3 present the PU activity model and the corresponding channel model. These figures represent the channel state model as the two state discrete Markov Chain with transition probability between the states. These probabilities are used for analysis and simulation of our proposed protocols.

In such system, the SU seeks the opportunity to access the PU spectrum subject to efficiently utilize this spectrum and avoid interfering with the PU. In addition, the SU has cognitive radio capability to utilize the spectrum. In this system model, the time delay

between two adjacent successful rendezvous is the main performance metric for our design. This time delay is called TTR. We also use the channel utilization and network throughput as a performance evaluation for our system.

3.2   Related Works

Link rendezvous refers to the ability of two or more radios to meet other radios and establish a successful link on one operation point, *i.e.,* one communication channel. There are two approaches toward link rendezvous [57, 10]. The first one works in an existing of the network infrastructure, or head node, that assigns channels to the rest nodes. The second approach works in a distribution manner without an infrastructure or head node. The Common Control Channel (CCC) can work in both approaches to simplify the link rendezvous protocol. In this thesis, we consider the system model as a distribution system that is working without the CCC. For a similar system, there are two major approaches for channel rendezvous:

1. Multi-Channel Visiting;

2. Single -Channel Visiting:

    (a) Random Based;

    (b) List Based;

    (c) Probabilistic Based;

    (d) Sequence Based.

3.2.1   Multi-Channel Visiting

The work in [58] is aided by the software-defined-radio (SDR) that is able to scan many channels at once. The CR band is divided into frequency bins, similar to the orthogonal frequency division multiplexing (OFDM), that is appropriate to its data channel bandwidth. The node senses the whole band and then drops unavailable bins that are used by the PU. An attention signal is sent to the rest of the bins. Once a node recognizes this signalling and communicates with the sender, it simply replays in only one bin to establish the link at this bin. This protocol needs global synchronization to receive the signalling.

The work in [6] proposes MAC module known as the Single-Radio Adaptive Channel (SRAC). This module uses the legacy MAC protocol to be a dynamic spectrum access supported by the MAC. The SRAC offers a feature that is called adaptive channelization. The adaptive channelization feature is provided by combining multiple fixed channels as required. The spectrum is divided into atomic channels; each atomic channel has a minimum possible bandwidth that could be used as a stand-alone connection. The radio has a filter for each atomic channel to support an ability of dropping unnecessary channels or used channels by the PU. The atomic channels can be combined to form a wider bandwidth single channel.

3.2.2   Single-Channel Visiting

This approach is based on one channel sensed at a time, that is, the SU node visits the channels one by one in different ways. The channel visiting is performed by one of the four visiting approaches: random-based, list-based, probabilistic-based, and sequence-based.

(a) **Random-Based.**

The work in [10] as well as in [59, 60] propose a random rendezvous protocol. The sender CR node selects the channels randomly and sends a beacon signal to idle channels. The sender then waits for a response on each visited channel. Another node can also choose the channel randomly and wait for a beacon on that channel. If no beacon is received, then the node will again choose the next channel randomly.

(b) **List-Based.**

The authors of [10] propose two channel rendezvous protocols. The first protocol is called the exhaustive protocol. With this protocol, the sender CR node performs a quick visit over the list of channels, and sends a beacon signal to the idle channels. Then, the sender node waits for a response from each channel. Another node performs a slow search, enough for the sender nodes to finish visiting all channels. The second protocol is called the sequential protocol. This protocol is similar to the exhaustive protocol but it is different in the manner it visits the channels. With an exhaustive protocol, the visiting process starts from the lower channel in the list and moves to the higher one. After all channels are visited, the visiting process starts again. In contrast, the sequential protocol performs the visiting process by moving forward, *i.e.,* from lower to higher, and also by moving backward, *i.e.,* from higher to lower.

In [6], the SRAC offers another set of features named the "as-needed" use of the spectrum, and cross-channel communication. The "as-needed"' use of the spectrum feature is proposed for efficiently using the spectrum. Each node has a preferable receiving channel as identified in [61]. This channel is known for the first hop neighbour nodes. When any neighbour node intends to establish a connection, it immediately tunes in a desired neighbour's receiving channel and starts negotiation for communication.

The cross-channel communication feature helps sub-networks to connect to each other if we split each sub-network based on the available spectrum. The sub-network starts with a common channel that all sub-networks use to connect with other network. This channel is the first idle channel when all channels are sorted in the list. If the PU appears on ongoing channel, the sub-network jumps automatically to next idle channel and so on. This work does not take into account the interference that could be caused on the PU receiver as explained in observation 1. Additionally, the cross-channel feature does not guarantee or defines the limit of the link rendezvous.

In [7], the limitation of the hardware is considered. The single radio is assumed to be able to sense a single channel at a time. To do so, the sensing function performs sequentially over a channel list. Sensing all channels is inefficient; however, transmitting over the first idle channel limits network capacity and throughput. Based on hardware constraint, this research proposes the tradeoff between a spectrum access opportunity and a sensing overhead. The scheme illustrates the rule that many channels are needed to sense the subject for best throughput using optimal stopping problem method. The same concept is proposed in [62] as the channel skipping rule. This research requires global synchronization, which is difficult to maintain in a distributed network without a central entity. Moreover, the CCC has several limitations (Section 1.2).

(c) **Probabilistic-Based.**

In [63], the probability prediction is used based on experimental results. These results found the PU traffic model follows a geometric distribution. This distribution is used to predict idle and busy channels. Based on the geometric distribution, the next idle channel is known at the current time by selecting the most preferred idle

34
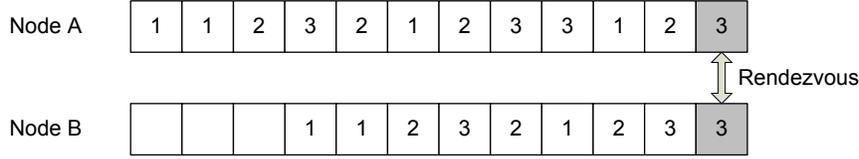
Figure 3.4: Rendezvous in Sequence Permutation

channel. This mechanism probabilistically provides a rendezvous rule for the CR nodes. Similar to this rendezvous rule, idle channels are allocated based on the statistical history of these channels [52]. The channel prediction could based on the channel occupation history as indicated in [64]. The prediction process needs a lenghtly learning time to initiate a network. The time to accomplish this learning is not applicable for a short-time CR network.

(d) **Sequence-Based.**

In [65], the authors use a decentralized rendezvous approach applying a sequence-based protocol. The idea originates from the mathematical property of certain repeated permutations. If the CR nodes have a pre-defined sequence, there is a guaranteed to rendezvous with others. The sequence results from the permutation of N channel and each node follows this sequence.

For example, if we have three channels $\{1, 2, 3\}$, the simple permutation is to leave the order as it is. This permutation is repeated N times; before any repetition, the same order permutation element is inserted. The result is a sequence of $\{\underline{1}, 1, 2, 3, \underline{2}, 1, 2, 3, \underline{3}, 1, 2, 3\}$. The rendezvous of this sequence is illustrated in Figure 3.4.

The authors also derive the upper bound to the TTR and its expected value. The advantage of this research is that the network works probably in asynchronous manner. However, there is no mention of how to design or select the most suitable sequence,

even though as the author said there are some sequences that cannot rendezvous forever.

The material in [13] proposes two protocols to establish control channel in a dynamic spectrum access network. These protocols are based on a quorum system. The quorum system guarantees that there is a common element between any two blocks. By assigning the channel index to this system, there is a guaranteed rendezvous over one channel between any network pairs.

The first protocol is a synchronized MAC protocol known as the Quorum-based Channel Hopping (QCH). This protocol assigns one channel to a minimal cyclic quorum system in each cycle. Similarly, the majority cyclic system is assigned to a random channel that is not the channel for the minimal system of that cycle. As a result, any node needs to perform a number of the channel cycles. The global synchronization is required among the network' nodes because the rendezvous is guaranteed within a cycle period. This protocol does not efficiently utilize the majority cyclic system, which has the same properties as the minimal system. Moreover, the maximum time to rendezvous linearly increases with the number of channels.

The asynchronous MAC protocol is known as the Asynchronous Quorum-based Channel Hopping (A-QCH). This protocol assigns channels to both majority and minimal cyclic systems, and it requires one cycle to guarantee the rendezvous. If there is a time shift due to an asynchronous node, then the rendezvous is guaranteed. The minimal and majority channel assignments limit the protocol's ability to two channels only.

Most of the previous studies do not consider the sensing overhead. The studies assume the sensing results are externally provided. The sensing function is the essential function for the CR and the dynamic spectrum networks. This function must be considered in any design, especially in the MAC protocol design. The coexistence of the SU with the PU cannot be managed without the spectrum sensing function. Including the spectrum sensing in the MAC design presents new challenges to this protocol. Consequently, the performance of the MAC protocol is completely changed by this function.

The sensing function is considered in our design. Moreover, we build a better sequence than the existing sequences using BIBD. The overhead of the sensing function is not always undesired to the MAC protocol; it has some advantages as we see in the design of our first protocol. The first protocol uses a single BIBD sequence and takes advantage of the feature sensing. The second protocol is designed by constructing a multi-BIBD sequence.

However, the benefit of the block design (BD) in tournament [66] supports our choice to design a MAC protocol using a BD. The BIBD was used in the design of wireless MAC protocol. For instance, the BIBD is used to design a collision-free MAC protocol [67, 68], a power-saving MAC protocol [69, 70, 71], and frequency and spatial reused MAC protocol with directional antennas [72].

3.3   Balanced Incomplete Block Designs

In this section, the definition and certain details of the Balanced Incomplete Block Design are discussed to help us understand and implement our protocols.

In the combinatorial theory, BD or the incidence system, is related to the method where distinct objects are arranged in different sets or blocks. If we have v distinct objects and

we arrange these objects into b blocks, each block contains k different objects, then all possible unordered combinations are provided by $b = \binom{v}{k} = \frac{v!}{k!(v-k)!}$ blocks.

If the BD has a block combination less than b, it is known as a Incomplete BD (IBD). Additionally, when any two objects combine in the same block, in a similar number of blocks, this design is called a Balanced BD (BBD).

For instance, if we have $v = 7$ distinct objects and we want to have blocks from each of these objects to contain $k = 3$ objects, then by the previous equation we have $b = 35$ blocks. When we take less than 35 blocks, the blocks combination in this case is incomplete because not all blocks are taken. However, when any pairs of the objects, *e.g.,* object 1 and 5, exist in the same number as any other pairs, e.g. objects 2 and 3, then this block design is balanced because all pairs are equally likely to appear. Therefore, the full definition of a BIBD is

A balanced incomplete block design (BIBD) is an arrangement of v distinct objects into b blocks; such that, each block contains exactly k distinct objects, each object occurs in exactly r different blocks, and every pair of distinct objects a_i, a_j occurs together in exactly λ blocks [73].

From the definition, the BIBD includes five parameters $\{v, b, r, k, \lambda\}$. The relations between these parameters should satisfy the BIBD conditions as follows.

$$bk = vr \tag{3.1}$$

$$r(k - 1) = \lambda(v - 1) \tag{3.2}$$

For example, $\{7, 7, 3, 3, 1\}$ means seven ($v = 7$) distinct objects could be arranged in

38

|	Objects (v)						
	1	2	3	4	5	6	7
1		■		■		■	
2	■			■	■		
3			■	■			■
4	■	■	■				
5		■			■		■
6	■					■	■
7			■		■	■	

Table 3.1: Example of BIBD

seven $(b = 7)$ blocks, each block containing three $(k = 3)$ different objects, each object occurring in three $(r = 3)$ different blocks, and each pair of these seven objects occurring only once $(\lambda = 1)$. Such BIBD is called symmetric when $v = b$, then $k = r$; this case uses three parameters $\{v, k, \lambda\}$ instead of five.

Table 3.1 depicts this example where the rows represent the possible blocks and the columns represent the distinct objects. The bolded squares correspond to the objects that belong to the blocks. When the table is converted into a matrix by making each bolded square equivalent to one and othe empty squares equivalent to zeros, then the resulting matrix is shown in equation (3.3). This matrix is called the incidence matrix J of this system.

$$
J = \begin{bmatrix}
0 & 1 & 0 & 1 & 0 & 1 & 0 \\
1 & 0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 1 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 & 1 \\
1 & 0 & 0 & 0 & 0 & 1 & 1 \\
0 & 0 & 1 & 0 & 1 & 1 & 0
\end{bmatrix}
\tag{3.3}
$$

Aspect to the symmetric BIBD mentioned is that there are λ common objects between any pair of blocks. In addition, the complement of the incidence matrix by replacing the ones with zeros, and vice versa, is also a BIBD with parameters $\{v, b, b - r, v - k, k - \lambda\}$.

The issue is how to build a BD that is BIBD. The BIBD can built using the well known method that is called Hadamard Incidence Matrix (H) [74]. The Hadamard Matrix is defined as the matrix that satisfies $HH^T = nI$, where n is the order of Hadamard Matrix and I is the identity matrix. The normalized Hadamard matrices are built starting from the first (3.4) and the second (3.5) order. The general form is given by Eq.(3.6), where $\otimes$ is the Kronecker matrix product.

$$
H_1 = \begin{bmatrix} 1 \end{bmatrix}
\tag{3.4}
$$

$$
H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}
\tag{3.5}
$$

$$H_{2^k} = H_2 \otimes H_{2^{k-1}} = \begin{bmatrix} H_{2^{k-1}} & H_{2^{k-1}} \\ H_{2^{k-1}} & -H_{2^{k-1}} \end{bmatrix} \tag{3.6}$$

The relation between the Hadamard Matrix and the symmetric BIBD (sometimes known as the Hadamard Design) is provided by the design $\{v, k, \lambda\} = \{4t - 1, 2t - 1, t - 1\}$, where $t \geq 2$ and $4t = n$ is the order of Hadamard Matrix. After removing the first row and the column from the $4t$ Hadamard matrix and replacing any -1 by zero, the result is exactly the incidence matrix design J as shown in equation (3.3).

Next, we illustrate how the BIBD with parameters $\{7, 3, 1\}$is built. We need to construct a Hadamard Matrix with order $4t = n = 8$ as follows. The result is presented in equation(3.3) and Table 3.1.

$$H_4 = H_2 \otimes H_2 = \begin{bmatrix} H_2 & H_2 \\ H_2 & -H_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \tag{3.7}$$

$$H_8 = H_4 \otimes H_4 = \begin{bmatrix} H_4 & H_4 \\ H_4 & -H_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix} \tag{3.8}$$

3.4 Ad Hoc CR-MAC Protocol

The main constraint for the SU is the impact on the PU due to the coexistence of the SU on the same spectrum with the PU. This constraint is taken into account during the MAC protocol design. The impact is described as interference to the PU signal. The SU reduces the impact as much as possible by frequently stopping its transmission and sensing the currently used band for the PU presence.

The frequent sensing is needed because the PU activities are unknown to the SU. As a result, the SU transmission should be slotted. The slotting starts with a sensing period, and then a transmission period. The slot duration is T which defines the maximum PU interference time caused by the SU and can be managed by the PU. Figure 3.5 depicts the structure of the MAC slots for the SU. Note that the transmission does not happen if the
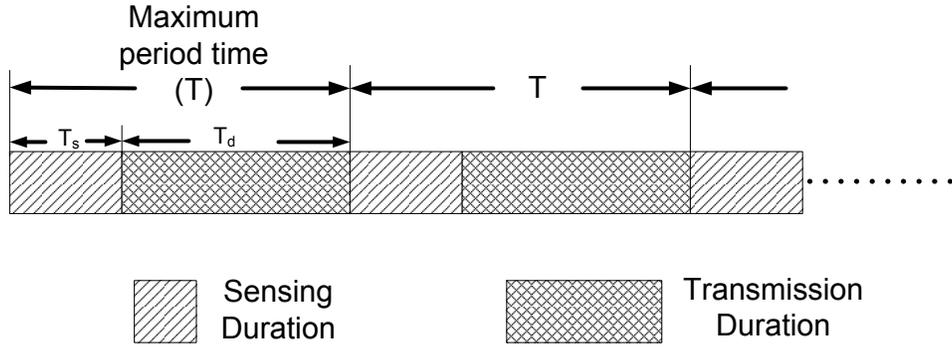
Figure 3.5: The SU MAC Slot Structure

result of the sensing indicates to the PU existence on the desired spectrum band. In the case of the PU existence, the SU performs another function, such as changing the desired spectrum band, which depends on the MAC design.

Based on this structure, the SU senses a desired spectrum band within the sensing duration. Then, the SU node tends to send or receive data with other nodes if the band is idle. Both nodes that need to exchange data with each other have to sense and access the same spectrum band to exchanging each other signalling. This meeting in the same spectrum is called rendezvous in the frequency domain. The rendezvous is unpredictable and unmanageable in the case of CR ad-hoc networks for two reasons. First, ad-hoc networks lack an infrastructure that can be used to manage the rendezvous. Second, the common control channel suffers many problems as previously discussed before.

The BIBD can be used to ensure that any two ad-hoc nodes can communicate with each other without the required infrastructure or control channel. The ad-hoc nodes can reach others by following a sequence generated by BIBD. Given there are two channels $C_1 \& C_2$, and that we need to use the BIBD feature to guarantee the rendezvous. If return to the BIBD example, we discover that the BIBD guarantees the overlapping between

	Time Slots						
	1	2	3	4	5	6	7
1	C_2	C_1	C_2	C_1	C_2	C_1	C_2
2	C_1	C_2	C_2	C_1	C_1	C_2	C_2
3	C_2	C_2	C_1	C_1	C_2	C_2	C_1
4	C_1	C_1	C_1	C_2	C_2	C_2	C_2
5	C_2	C_1	C_2	C_2	C_1	C_2	C_1
6	C_1	C_2	C_2	C_2	C_2	C_1	C_1
7	C_2	C_2	C_1	C_2	C_1	C_1	C_2

Sequence

Table 3.2: Protocol Schedule for Two Channels

any two blocks in an active state (*i.e.*, $BIBD = 1$). Moreover, the complement of BIBD ($i.e., BIBD = 0$) supports another BIBD that also guarantees the overlapping between any two blocks. We assign C_1 to an active BIBD, and C_2 to an inactive BIBD; we assign a channel visiting sequence to the BIBD blocks. The result is a channel sequence as shown in (Table 3.2). This sequence guarantees the rendezvous over any channel within time equals v slots.

The handshaking procedure between the sender and the receiver is important to confirm the pair complete rendezvous and establishes a useful connection. In fact, the beacon signal is not suitable for an ad-hoc network because of hidden or exposed terminal problems as reviewed in the MAC literature (Section 2.3.2). Hence, we used RTS/CTS handshake mechanism. While the CR nodes have the capability of sensing, two benefits are gained from this handshaking. First, the spectrum sensing function is used to perform the CSMA/CA access mechanism that increases the network throughput and channel utilization [75]. Second, the spectrum sensing period in reality is a hearing period, which is used for hearing a handshake signalling for a saturated MAC.

Another advantage that encourages us to use the BIBD is the resulting sequence that
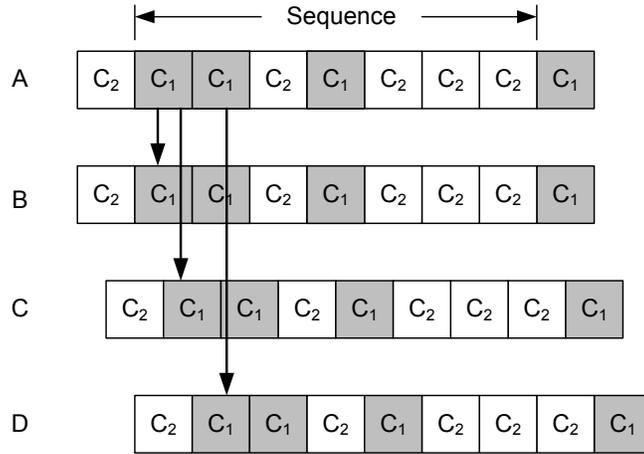
Figure 3.6: Asynchronous BIBD Example

does not need synchronization between the SU nodes. For instance, a sequence from a Paley type I Hadamard Matrix [74] is used as a simple explanation. This sequence is illustrated in Figure 3.6.

There are three possible cases in Figure 3.6. First, the source and destination nodes are synchronized as in case nodes A and B. In this case, the rendezvous over channel C_1 is trivial. Second, the source and destination nodes are slightly shifted in time as in case nodes A and C. They could rendezvous if the overlapping time is sufficient to exchange an RTS and CTS handshaking. Third, if the source and destination of a second case are shifted more than the RTS and CTS packets exchange time, they are considered as having shifted one slot, similar to the nodes A and D case. In this case, the pair has also complete rendezvous because of the BIBD sequence that guarantees the rendezvous for any possible time shift. Moreover, all cases are applicable to channel C_2 as well.

We observe from the previous discussion the BIBD is used for only two channels. In the

next subsections, we propose two protocols to manage the multi-channel. The first protocol has the advantage of the BIBD and the capability of the feature sensing detection. The BIBD guarantees the rendezvous if the channel list is divided into two groups; each group is assigned to a different BIBD state. The feature sensing has the ability to sense multi-channel in each group at once. We call this protocol the single-sequence protocol because only one BIBD sequence is used. The single-sequence protocol uses feature sensing to sense multi-channel.

The second protocol uses only the BIBD sequence. The channel list is divided into two groups; each group is assigned to a different BIBD state. Within each group, the channel list is also divided into two sub-groups; each sub-group protocol is assigned to the BIBD state. This procedure is repeated until each group contains only one channel. We call this protocol multi-sequence protocol because many BIBD sequence are used. The multi-sequence protocol uses energy sensing to sense only one channel.

Consequently, the MAC design of these protocols is different as we explained in the next subsections.

3.4.1   Single-Sequence MAC Protocol

Assuming the available spectrum to the CR ad-hoc network is divided into C equal bandwidth channels. These channels are separated into two groups of adjacent channels, group 1, $G1 = \{1, 2, \ldots, C/2\}$, and group 2, $G2 = \{C/2 + 1, C/2 + 2, \ldots, C\}$. Each node follows a pre-defined BIBD sequence of taking one value of the BIBD for each MAC frame or time slot. For instance, each node at the first MAC frame starts with the value of the first row and the first column of the BIBD. Then, the node follows the first row sequence. Next,

	Time Slots						
	1	2	3	4	5	6	7
1	G2	G1	G2	G1	G2	G1	G2
2	G1	G2	G2	G1	G1	G2	G2
3	G2	G2	G1	G1	G2	G2	G1
4	G1	G1	G1	G2	G2	G2	G2
5	G2	G1	G2	G2	G1	G2	G1
6	G1	G2	G2	G2	G2	G1	G1
7	G2	G2	G1	G2	G1	G1	G2

(Row label: **Sequence**)

Table 3.3: Single-Sequence MAC Protocol Schedule

it takes the value of first column and second row up to the end of second row. The same procedure is for the third BIBD row until the end of the BIBD. When the node reaches the end of the BIBD, the node starts again. When the value of the BIBD is active ($BIBD = 1$) at that time, the node selects G1 for sensing and access; otherwise the node selects G2. The MAC schedule corresponding to Table 3.1 is shown in Table 3.3.

Choosing a type of sensing depends on the proposed MAC requirements. The sensing at the beginning is used for hearing the handshake signalling. This MAC required a sensing type able to distinguish between the PU and the SU signalling in case of a demodulate the SU RTS packet. Additionally, this MAC requires a sensing type that is able to sense multiple channels at one time in parallel processing. As discussed in Section 2.2.1, the best choice is the cyclosationary feature sensing that satisfies these requirements. Indeed, the feature sensing is able to sense multiple channels at once [58, 14, 76, 15].

In reality, we do not need this complex sensing to perform the spectrum sensing periodically where the periodic sensing is needed to double check of the existing of the PU. Because of periodic sensing, the feature sensing takes place only at the beginning of each connection. Alternatively, the remaining periodic sensing performs using energy sensing

for a less required time and complex computation. Accordingly, the switching between the different sensing types during a connection is proposed in IEEE 802.22 draft standard [45]. Feature sensing is called fine sensing and energy sensing is called fast sensing in this standard.

The proposed MAC flow chart is presented in Figures 3.8 and 3.7. First, the node uses feature sensing to sense all channels in a selected group subject to the BIBD as evident in Table 3.3. When the node has data to send, it pick-ups the first available idle channel to send its RTS, then it waits for the CTS reply. If the CTS is received, both nodes start exchanging the data. If the CTS is not received, the source follows the BIBD sequence, and starts the same process again.

The process is the same for the receiver except during the sensing time. If the node receives RTS during sensing period and this RTS carries the node ID, then replay CTS to the source. After a successful establishment, this pair continues using this channel while they are periodically (*i.e.,* after time T) sensing the ongoing channel using energy sensing. Once a pair complete rendezvous on one channel, it stays on the same channel until the PU appears again or the pair finishes its connection. When the pair reports a PU presence in this channel, it restarts the rendezvous procedure by following the BIBD again to establish a new connection. The overall MAC flow chart is combined and presented in Figure 3.9.

Figure 3.10 exhibits the MAC frames for five nodes, where FS and ES refer to the feature sensing and energy sensing duration respectively. This figure depicts the rendezvous process between these five nodes and when there are two channels. Node 1 and node 2 rendezvous and establish their connections over channel C_1. Node 3 at this time skips this channel to utilize other unused channels by following the BIBD sequence. Node 3 attempts to rendezvous with node 4 but node 4 is already connected with node 5 and do not reply
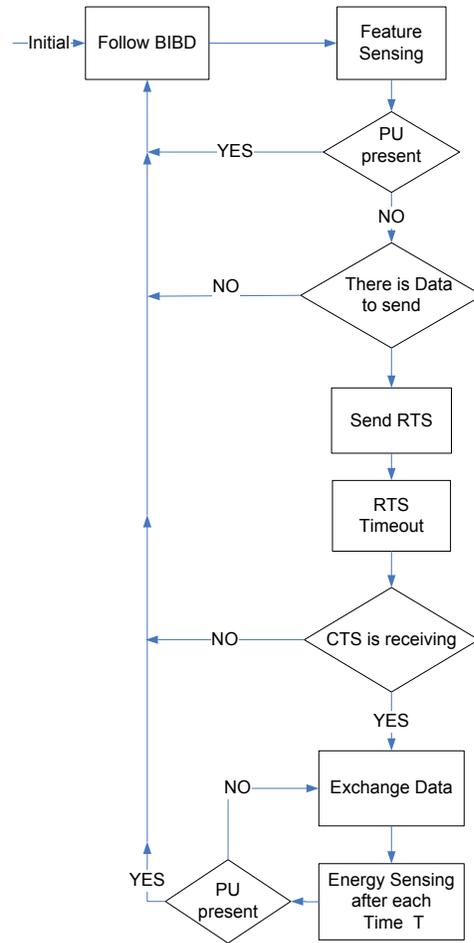
Figure 3.7: RTS Flow Chart
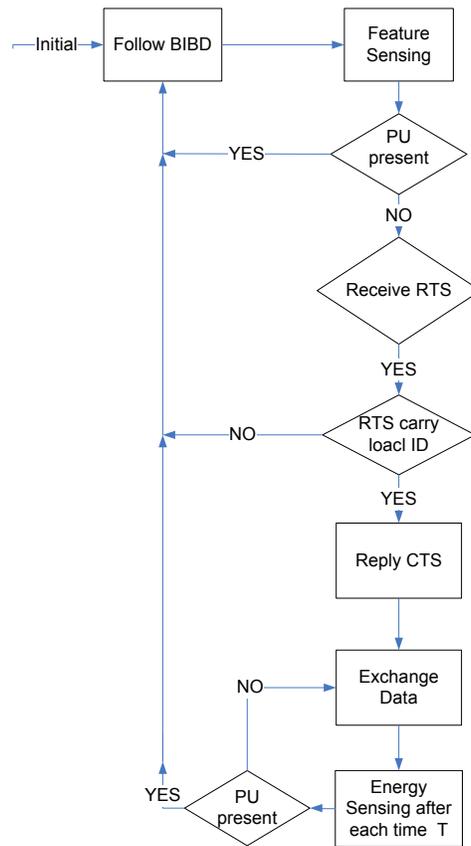
Figure 3.8: CTS Flow Chart
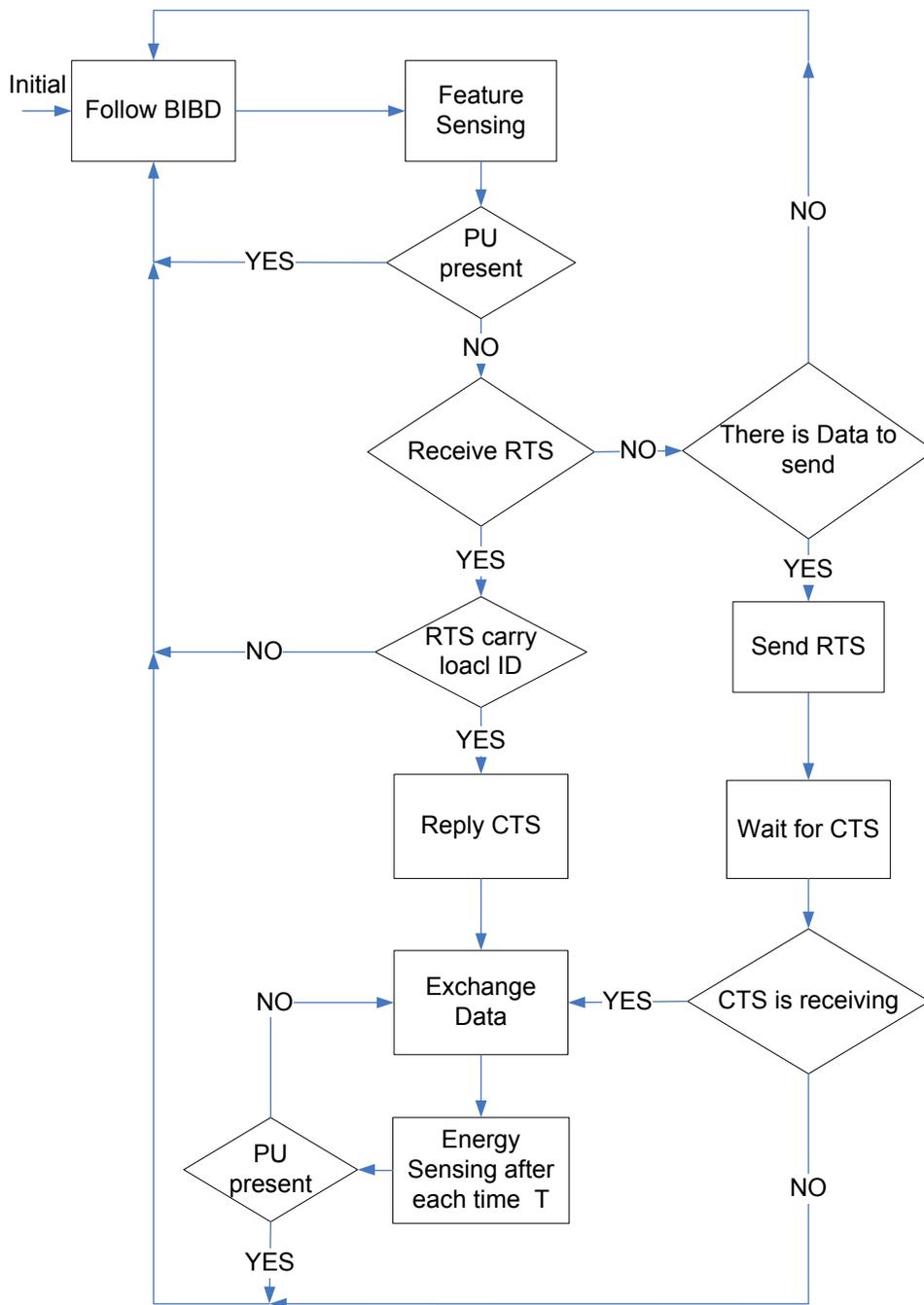
Figure 3.9: MAC Protocol Flow Chart
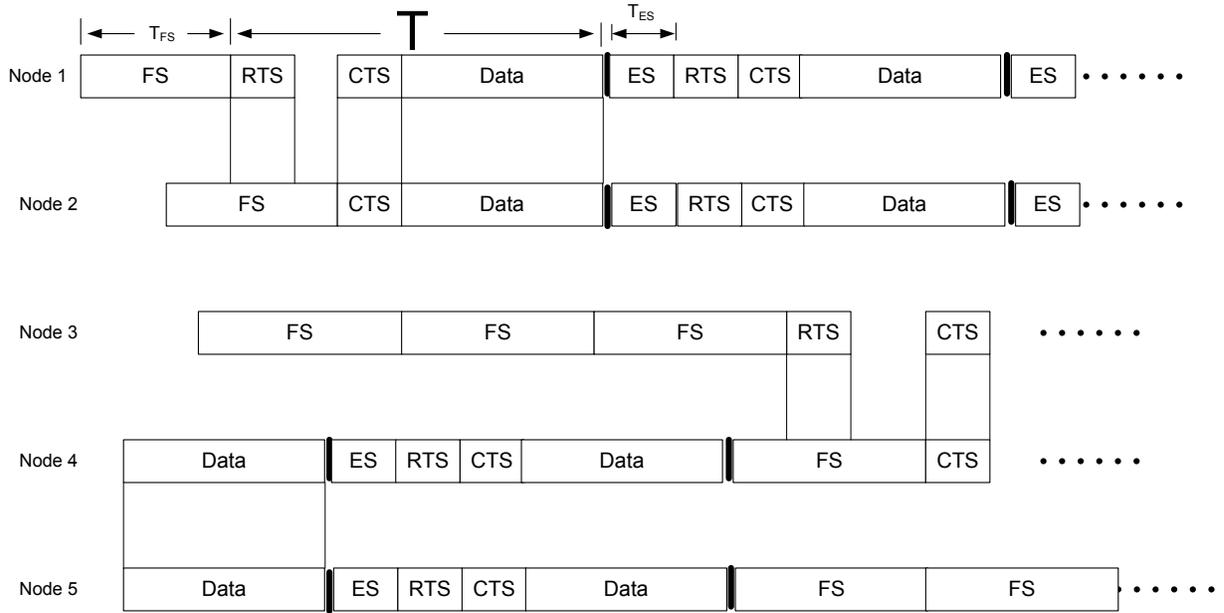
Figure 3.10: MAC Frame

to node 3. After node 4 and 5 finish their transmissions, node 3 can establish a connection with node 4 over channel C_2.

3.4.2 Multi-Sequence MAC Protocol

We discuses in previous sections how the BIBD is used in our design for two channels. How to assign the channels when there are more than two channels is challenging because the BIBD has a capacity of two states. We must use another BIBD sequence inside each BIBD state. The construction of a complete sequence is follows.

Assume we have C channels that are separated into two groups of adjacent channels, group 1, $G1 = \{1, 2, \ldots, C/2\}$, and group 2, $G2 = \{C/2 + 1, C/2 + 2, \ldots, C\}$. For the first iteration, each group is assigned to different BIBD state. For instance, if we have $BIBD = \{1, 1, 0, 1, 0, 0, 0\}$, the group sequence will be as $H = \{G1, G1, G2, G1, G2, G2G2\}$.
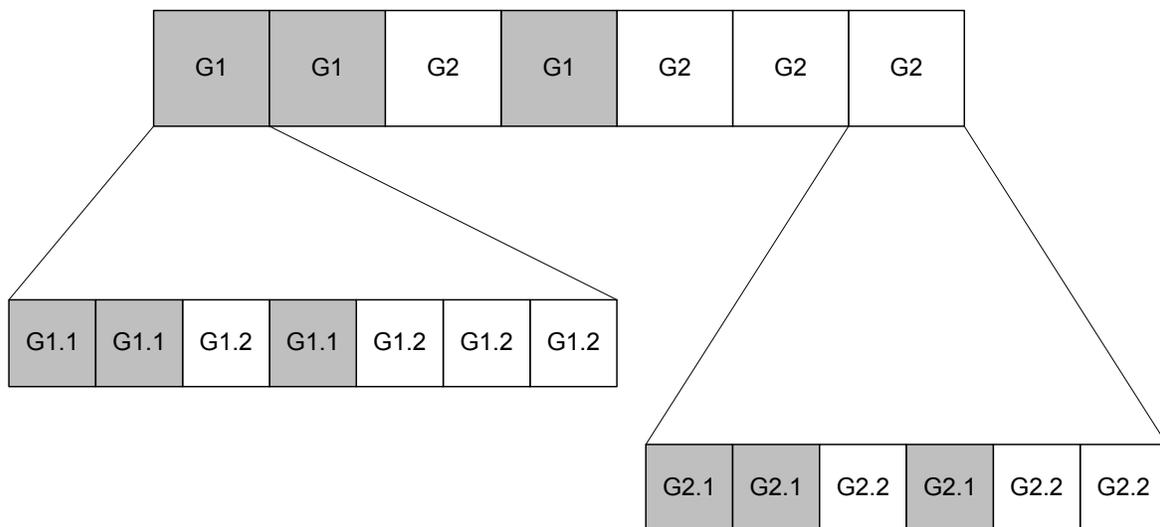
Figure 3.11: Multi-Sequence MAC Protocol Schedule

After the first iteration, each group is divided into two sub-groups, where $G1 = \{G1.1, G1.2\}$ and $G2 = \{G2.1, G2.2\}$. For the second iteration, each subgroup is assigned to one BIBD state. For instance, using the last BIBD sequence we have a sequence inside $G1$ and $G2$ as these sequences $\{G1.1, G1.1, G1.2, G1.1, G1.2, G1.2, G1.2\}$ and $\{G2.1, G2.1, G2.2, G2.1, G2.2, G2.2, G2.2\}$ respectively.

The second iteration is repeated until we reach the grouping of the two channels. We need i iterations equal to $\log_2 C$. Figure 3.11 discloses the first two iterations to build a sequence for the multi-channel. Given the length of each BIBD sequence is v, then the result sequence length is equal to v^i.

For example, if we have four channels ($C = 4$) and $BIBD = \{1, 1, 0, 1, 0, 0, 0\}$, the channels list is divided into two groups, $G1 = \{1, 2\}$, and $G2 = \{3, 4\}$. The first iteration
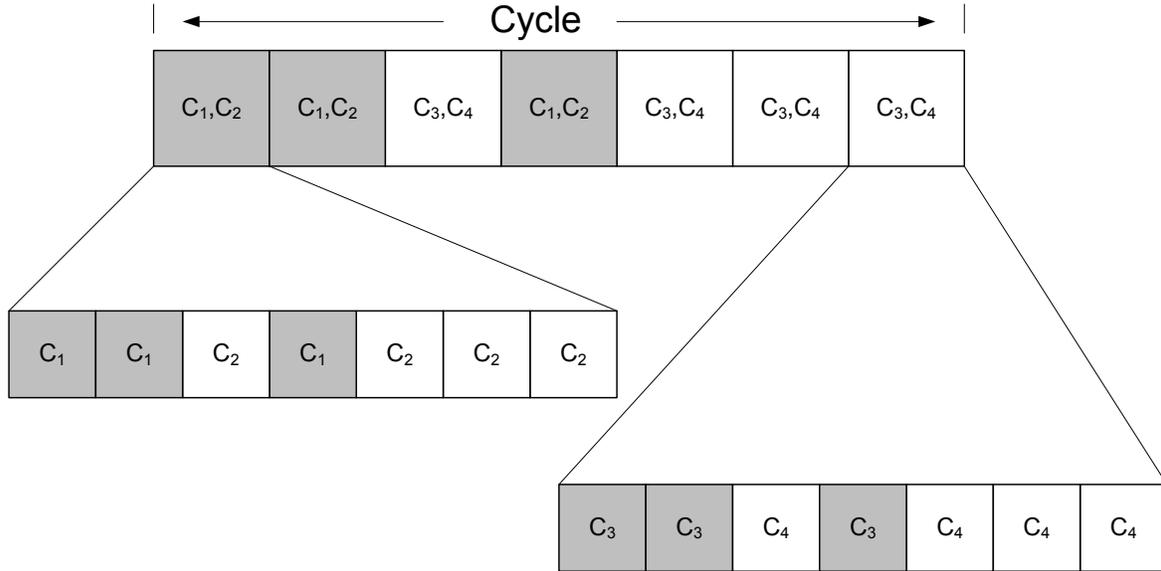
Figure 3.12: Multi-Sequence MAC Protocol Example

has the resulting sequence as $H = \{HG1, HG1, HG2, HG1, HG2, HG2, HG2\}$. Next, we divide each group into two further sub-groups, $G1.1 = \{1\}$, $G1.2 = \{2\}$, $G2.1 = \{3\}$, and $G2.2 = \{4\}$. After the second iteration, we have these two sequences for each group $HG1 = \{1, 1, 2, 1, 2, 2, 2\}$, and $HG2 = \{3, 3, 4, 3, 4, 4, 4\}$. We describe in Figure 3.12 the structure of this sequence. Due to space limitations we list the final sequence as $H = \{1, 1, 2, 1, 2, 2, 2, 1, 1, 2, 1, 2, 2, 2, 3, 3, 4, 3, 4, 4, 4, 1, 1, 2, 1, 2, 2, 2, 3, 3, 4, 3, 4, 4, 4, 3, 3, 4, 3, 4, 4, 4, 3, 3, 4, 3, 4, 4, 4\}$.

The result sequence is quite long if the BIBD sequence results from the Hadamard Matrix as in the single-sequence protocol. For simplicity, this protocol uses a special BIBD sequence that results in a cyclic Hadamard Matrix. One known cyclic Hadamard Matrix is Paley type I. The [74] has the explanation for a constructed Paley type I. The advantage of

Cycle

C_2	C_1	C_1	C_2	C_1	C_2	C_2	C_2	C_1
C_2	C_2	C_1	C_1	C_2	C_1	C_2	C_2	C_2
C_2	C_2	C_2	C_1	C_1	C_2	C_1	C_2	C_2
C_1	C_2	C_2	C_2	C_1	C_1	C_2	C_1	C_2
C_2	C_1	C_2	C_2	C_2	C_1	C_1	C_2	C_1
C_1	C_2	C_1	C_2	C_2	C_2	C_1	C_1	C_2
C_1	C_1	C_2	C_1	C_2	C_2	C_2	C_1	C_1

Figure 3.13: Asynchronous Cyclic BIBD Sequence

using a cyclic BIBD sequence is that only one sequence is needed. The rest of the sequences are driven actually from this known sequence by taking all possible sequence translations. The translation is given by

$$BIBD_h^t = BIBD_h \quad (mod \quad v) \tag{3.9}$$

where $BIBD_h$ is the hth element in BIBD sequence, and $BIBD_h^t$ is the hth element in the translated BIBD. The module operation generates the cyclic pattern for this sequence. This kind of cyclic BIBD often known as the cyclic difference-set in the number theory.

The cyclic BIBD guarantees the rendezvous between any SU pairs even with unsynchronized pairs as we describe in Fig. 3.13. This figure depicts the rendezvous occur over the subgroup $G1.1$. The same rendezvous also applies for other subgroups and groups.

The flow charts for this protocol are the same as with the single-sequence protocol except for the sensing type at the beginning of each link rendezvous. In this protocol, we use the energy sensing detection instead of the feature sensing detection.

3.5 Performance Evaluation

In this section, the analysis and simulation of our protocols are presented to confirm the validation of our protocols assumptions. In the first subsection, the analysis is explained for both proposed protocols and the performance metrics of these protocols. In the next subsection, the simulation details are provided with the results that confirm the contribution of our protocols.

3.5.1 Protocol Analysis

In this subsection, the analysis is explained for both proposed protocols. For the single-sequence MAC protocol, the Markov Chain MAC model is used. For the multi-sequence MAC protocol, the sequence structure is used to drive the Maximum Time to Rendezvous (MTTR).

Single-Sequence MAC Protocol Analysis

Assuming we have C channels and N nodes, as proposed in our protocol, the channel list is divided into two groups for channels (*i.e.,* G1 and G2). Each group contains m channels where $m = C/2$. The BIBD sequence guarantees that a rendezvous occurs for each group of channels because each group is assigned to a different BIBD state.

Assuming the S_i represent the state of the system at time t. The system state represents the number of channels that are used by the SU at time t. For analysis purposes, we consider channels access and release occur in discrete time. The time interval between any adjacent events is virtual slotted. Now, we can model our system using the discrete Markov Chain.

The state space for our system is given by

$$S = \{0, 1, \ldots, r\} \qquad (3.10)$$

where r is the minimum of n_p SU pairs or m channels, $i.e.,$ $r = \min(n_p, m)$, because the system state cannot exceed the number of the SU pairs if this number is less than the number of channels. The result steady-state vector of the Markov Chain is given as

$$\Pi = \{\pi_0, \pi_1, \ldots, \pi_r\} \qquad (3.11)$$

Our protocol does not need synchronization among the SU nodes. As a result, each node has a different starting time and a different time shift on the BIBD sequence. Therefore, at any time the number of nodes having the same hop in the BIBD sequence is equal. In other words, the nodes are equally likely to select the starting hop from the BIBD sequence. For instance, if the sequence size is $v = 4$ and there are $N = 12$ nodes in the system, then each hop out of v, there are $n/v = 3$ nodes that have this hop at any time. Following the same concept for our system, we can see there are n nodes tuned in at a given group as in equation (3.12)

$$n = \begin{cases} N\frac{k}{v} & on~G1 \\[2mm] N\frac{v-k}{v} & on~G2 \end{cases} \qquad (3.12)$$

The number of pairs n_p that can communicate over each group is $n_p = n/2$. These n_p nodes start sensing, and then, access the first idle channel. Consequently, only one pair uses the first channel at any virtual slot. We ignore the possibility of a collision because our protocol is asynchronous. The resulting Markov Chain for this system is shown in
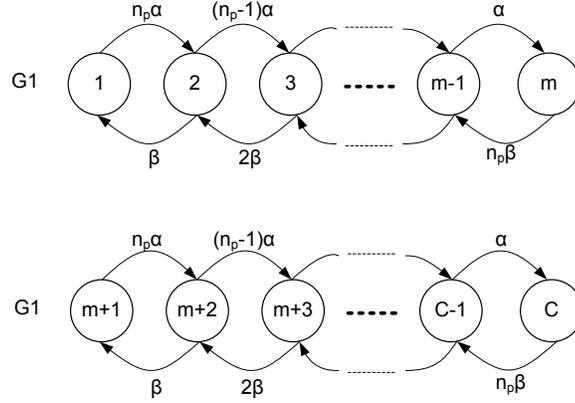
Figure 3.14: System Markov Chain

Figure 3.14. where β is the channel release rate, and α is the arrival rate to each group.

To calculate these two parameters, the protocol scenario need to describe more. At the beginning, the source node senses the group channels using the feature sensing with time given by T_{FS}. Then, if there are idle channels, the source node sends a RTS packet over the first idle channel or follows the BIBD and senses again. After successfully sending the RTS, the source node waits for the RTS timeout which is given by $RTS_{Timeout} = T_{FS}$. When the source receives the CTS packet, both the source and the destination nodes use the channel for one file time. The file size is uniformly distributed form a to b packets. The average file size in this case equals $c = \frac{a+b}{2}$. Each packet requires time T_{packet} to transmit. After each packet sending, both the source and destination perform energy sensing with time T_{ES}. Therefore, the pair spends time using the channel equals to

$$T_{use} = T_{FS} + c \times (T_{ES} + T_{packet}) \qquad (3.13)$$

Then, the channel is released with a rate equal to the inverse of this time; that is

$\beta = 1/T_{use}$. The arrival rate equals the number of nodes that tune to this group of channels. If we know the node spends a time equal to the feature sensing time and the RTS timeout before any switch to other group, then the arrival rate is as follows.

$$\alpha = \frac{n}{2T_{FS}} \tag{3.14}$$

As a result, the steady-state for the Markov Chain is given by

$$\pi_i = \binom{r}{i} \left(\frac{\alpha}{\alpha + \beta} \right)^{r-i} \left(\frac{\beta}{\alpha + \beta} \right)^{i} \tag{3.15}$$

The channels availability happens if the PU does not use them. Figure 3.3 depicts that any channel will be idle with the probability

$$P_{idle} = \frac{q}{q + p} \tag{3.16}$$

The probability of f channels to be idle is provided by the next equation.

$$P_{C_f} = \prod_i^f P_{idle} = \prod_i^f \left(\frac{q}{q + p} \right) \tag{3.17}$$

Because the PU uses each channel independently, this probability becomes.

$$P_{C_f} = \left(\frac{q}{q + p} \right)^{f} \tag{3.18}$$

The resulting steady-state after considering the channels availability is as follows:

$$\pi_i = \binom{r}{i} \left(\frac{\alpha}{\alpha+\beta}\right)^{r-i} \left(\frac{\beta}{\alpha+\beta}\right)^i \left(\frac{q}{q+p}\right)^i \tag{3.19}$$

Then, the average number of channels used by the SU is shown in Eq. (3.20)

$$L = \sum_i^r i\pi_i \tag{3.20}$$

Apply Little's Law, which is known as

$$L = \alpha W \tag{3.21}$$

$$W = \frac{L}{\alpha} \tag{3.22}$$

where W is the node average delay time to access a channel.

The probability that the receiver does not belong to any connection is simplified as

$$\frac{n - 2L - 1}{n - 1} \tag{3.23}$$

We assume that each node has a full queue and always attempts to send data. Therefore, the number of nodes that attempt to send the RTS equals to

$$n - 2L \tag{3.24}$$

After sending the RTS, the source waits for the RTS timeout to receive the CTS. On average, the receiver replies after half of this time. The time required for successfully

meeting destination of TTR is stated by this equation.

$$TTR = \left(\frac{n - 2L - 1}{n - 1}\right)(n - 2L)\,w + \frac{T_{FS}}{2}. \tag{3.25}$$

Multi-Sequence MAC Protocol Analysis

For this protocol, the sensing function is different than single-sequence protocol. In a single-sequence protocol, the sensing is made for a group of channels, but for the Multi-Sequence Protocol the sensing is made only for single channel. Therefore, the observation of this protocol is limited for single channel. As a result, the rendezvous only depends on the BIBD sequence. In this case, we provide the derivation of the MTTR.

Assuming we have C channels, this channel list in each construction iteration is divided into two groups. To do so, the number of iterations that are required to construct the desired sequence is i, which is given by

$$i = \log_2 C \tag{3.26}$$

We know that the BIBD sequence is v block long. As the BIBD property supplies, the rendezvous is guaranteed within v time slots. For instance, if we have two channels, the rendezvous over any of these channels is limited by v. In reality, this happens for any sub-groups that are driven from the sequence construction iterations. For one iteration before i (*i.e.*, $i - 1$), the rendezvous is guarantee within v^2 because the sub-groups result from i iteration are assigned to v block of BIBD. The same procedure is repeated until the

61

Parameter	Value
Feature Sensing Time (T_{FS})	24.2 ms
Energy Sensing Time (T_{ES})	1 ms
MAC Frame (T)	10 ms
RTS	20 Bytes
CTS and ACK	14 Bytes
Data Rate	1.5 Mb/s
Packet/File	uniform (1,10)
PU Residue Time	= 10 ms (=T)

Table 3.4: Simulation Parameters

first iteration. As a result, the MTTR is

$$MTTR = v^i \tag{3.27}$$

3.5.2   Protocol Simulation

In this section, we present the simulation results to validate our proposed protocol assumptions. Our simulation code is built and implemented under the MATLAB environment using discrete event simulation [77, 78, 79].

For this simulation, the physical layer and the sensing function are assumed to be perfect. The PU accesses each channel independently according to Figure 3.2. The MAC parameters are adopted form the CR IEEE 802.22 draft standard [45, 80, 81, 82]. Moreover, the mechanisms for the RTS/CTS [75, 83], and the CSMA/CA [84] are taken from the standard IEEE 802.11 [85, 86]. The simulation parameters are listed in Table 3.4.

The analysis from Subsection 3.5.1 reveals the guideline for the correct implementation of our simulation. For this purpose, we compare the simulation results with the analysis
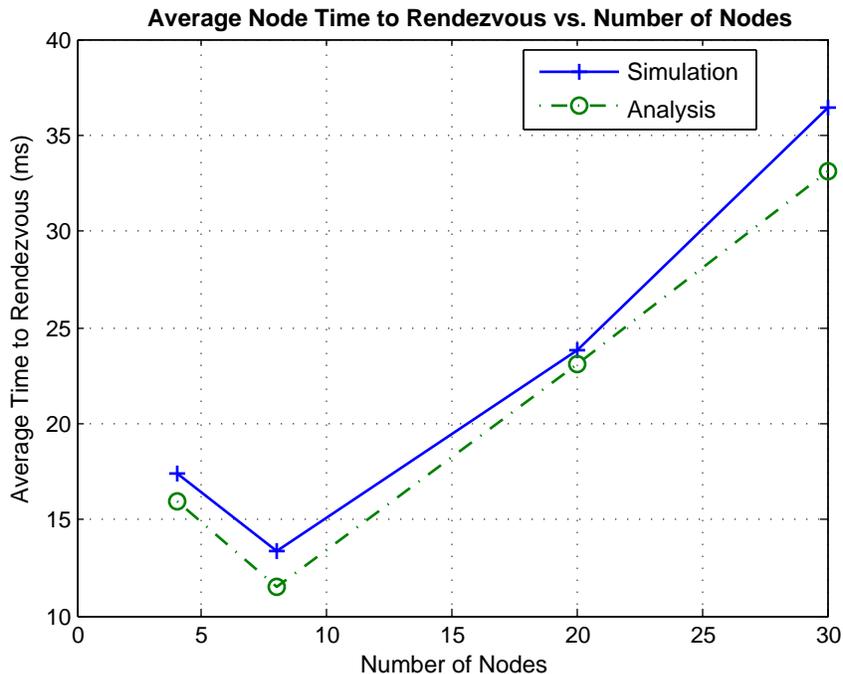
Figure 3.15: Average TTR for Simulation and Analysis versus Number of Nodes

equations of the single-sequence protocol (Figure 3.15). The TTR performance metric is plotted for a four-channel system ($C = 4$). The minimum point in the convex shape points to where the number of pairs equals the number of channels. At this point, there is only one channel for each pair. As a result, the TTR is minimum.

We compare our proposed protocols (*i.e.,* single-sequence and multi-sequence protocols) with other MAC protocols that have been done in this area, such as using a permutations sequence [65] and a blind random rendezvous [65, 10]. Figure 3.16 presents the TTR versus the number of channels for a 20-node network size. The multi-sequence protocol has a lower TTR than other protocols as we expect because the sequence is a function of ($\log_2 C$) that derives from sequence construction analysis. Moreover, the single-sequence protocol is not affected by the number of channels because it always divides the channel
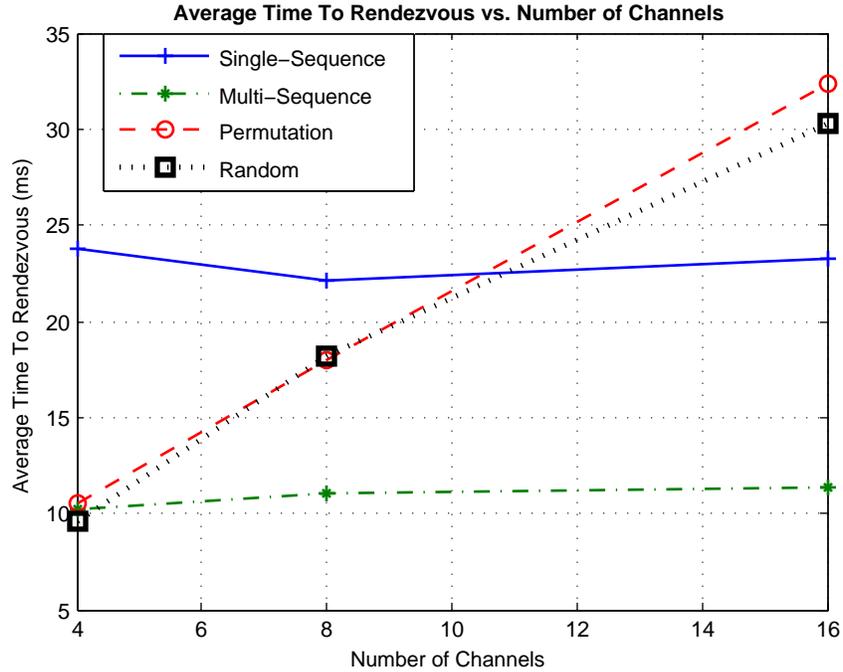
Figure 3.16: Average TTR Comparison versus Number of Channels

list into two groups.

The same comparison is made for a different number of nodes in Figure 3.17. For this comparison, the number of channels equals eight ($C = 8$). The single-sequence is influenced by the number of nodes in the network. This protocol can observe multiple channels during the sensing operation and allocate and access more channels. As a result, there are more channels being used, which lead to an increase in the TTR. The multi-sequence protocol outperforms all other protocols.

For the same number of nodes, Figures 3.18 and 3.19 implement the average channel utilization versus the number of channels and the number of nodes, respectively. The single-sequence protocol provides higher channel utilization than others, which is a result from the capability of this protocol to sense multiple channels.

64
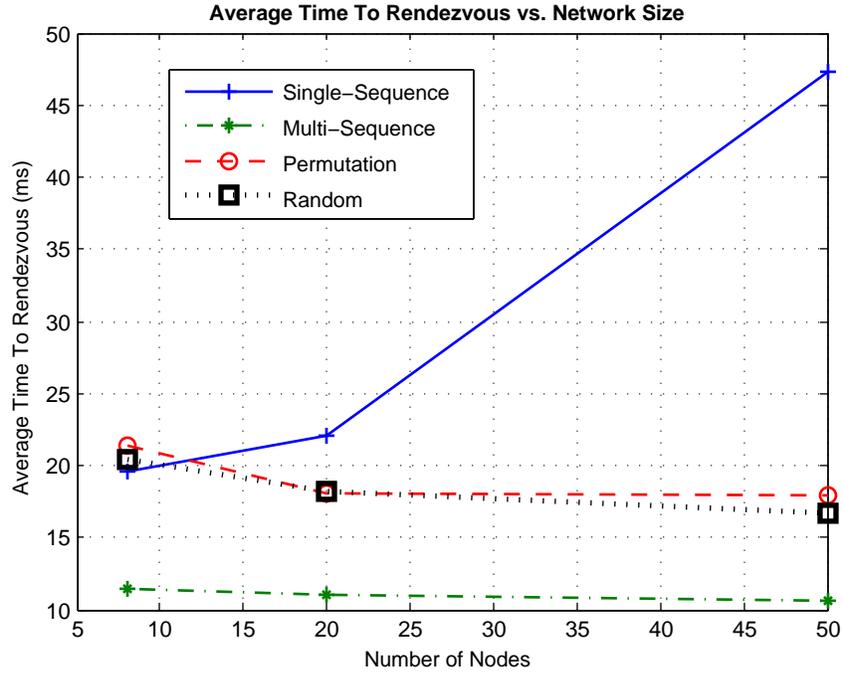
Figure 3.17: Average TTR versus Number of Nodes

The network throughput is plotted in Figures 3.20 and 3.21. The single-sequence protocol is dominant for the network throughput. Furthermore, the multi-sequence protocol is superior than existing protocols. This performance metric is related to channels utilization; in other words, the more channel utilization, the more network throughput is earned. Although, the number of flows in the network is known because the data rate is known for these protocols. The number of flows is calculated by dividing the network throughput by the data rate.

The impact on the PU can be tested. The existence of the PU on the channels is a function of the transition probability (Figure 3.2). The probability of leaving the channels

65
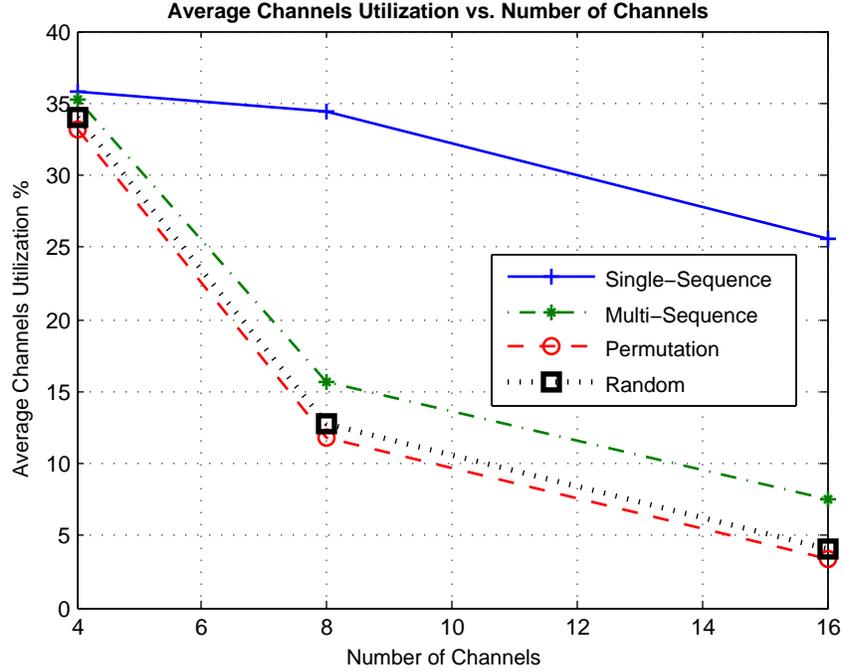
Figure 3.18: Average Channels Utilization Comparison versus Number of Channels

idle or busy are respectively presented by the following equations.

$$P_{idle} = \frac{q}{q + p} \tag{3.28}$$

$$P_{busy} = \frac{p}{q + p} \tag{3.29}$$

The value of transition probability (*i.e., p&q*) of the Markov Chain is set as a variable to test the impact on both the PU and the SU networks. Figure 3.22 depicts the average channels utilization versus the probability of the channel to be busy (q). The utilization decreases when the busy probability increases; because our protocols are conservative and skip the channel if it senses the PU present. Consequently, the network throughput decrease (Figure 3.23). Additionally, the multi-sequence protocol has a better utilization and
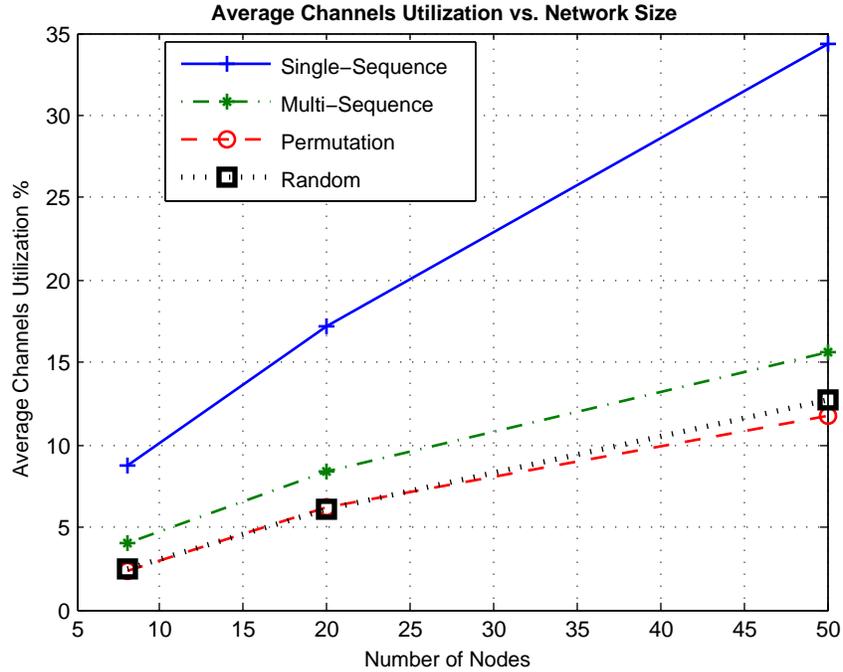
Figure 3.19: Average Channels Utilization Comparison versus Number of Nodes

throughput than multi-sequence protocol.

To examine how much the SU causes collisions with the PU, Figure 3.24 presents the effect of a busy channel probability on collisions with the PU. The collision is low when the channels are most likely to be used by the PU t as we expect. This low collision occurs because of the collisions happen only at the RTS packet. Furthermore, when the busy channel probability is low the collisions could happen during data transmission, which the longest MAC part.

The last test is the protocol fairness. The fairness is the determination of how the resources (channels) are allocated to the network users. We use the Jain fairness index [87] which is well known in the networking area. The Jain fairness index is stated by the
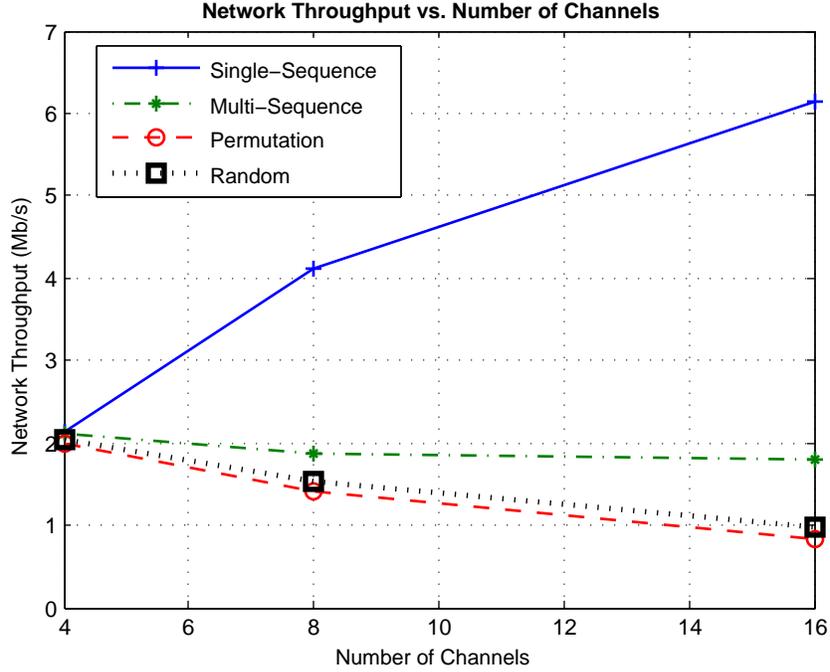
Figure 3.20: Protocols Throughput versus Number of Channels

equation

$$I = \frac{(\sum x_i)^2}{x \sum (x_i)^2} \tag{3.30}$$

x is the number of nodes and x_i is the throughput of node i. Figure 3.25 depicts the fairness of the single-sequence and the multi-sequence protocols for an eight-channel system($C = 8$). The single-sequence protocol is fair when the number of nodes is equal to the number of channels or greater. However, it has less fairness when a low number of nodes exists; if a node leads others in sending the RTS, it becomes the sender until an other node leads the RTS sending. This case happens only for a simulation run with one or two pairs. The multi-sequence protocol is stable for all number of nodes. Next, we assess the fairness of our protocols to use the channels, to discover how fair the protocols distribute
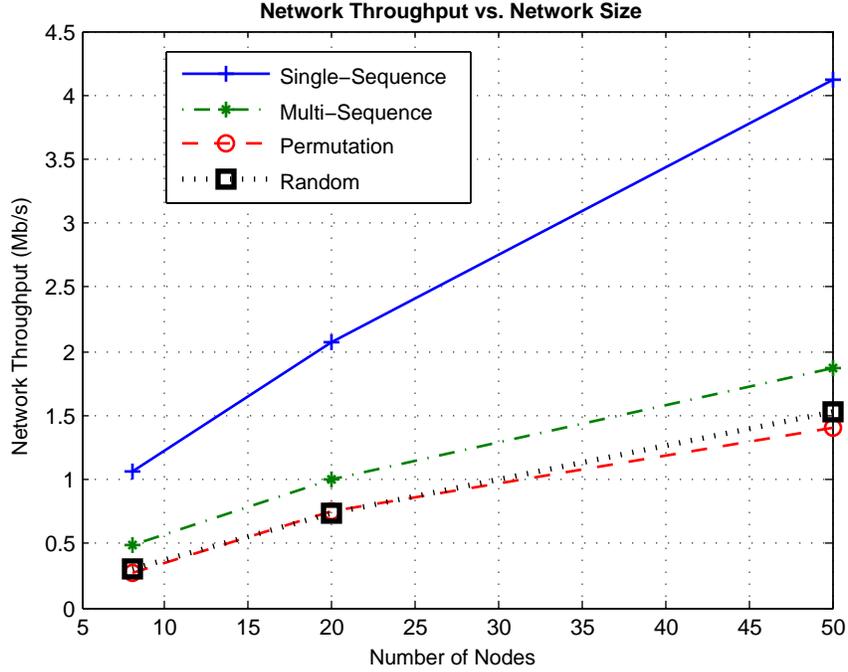
Figure 3.21: Network Throughput versus Number of Nodes

the network throughput over the channels [88]. The previous equation 3.25 becomes

$$I = \frac{(\sum Thrpt_i)^2}{C \sum (Thrpt_i)^2} \tag{3.31}$$

where $Thrpt_i$ is the network throughput over channel i, and C is the total number of channels.

The channel distribution fairness index is ploted for our protocols in Figure 3.26 for an eight-channel system ($C = 8$). The single-sequence protocol is fairer than the multi-sequence protocol. The multi-sequence protocol follows the sequence without observing other channels; it observes one channels in its current sequence.

In conclusion, we have determined that our protocols outperform than the existing protocols for all performance metrics. These metrics are time to rendezvous, channel
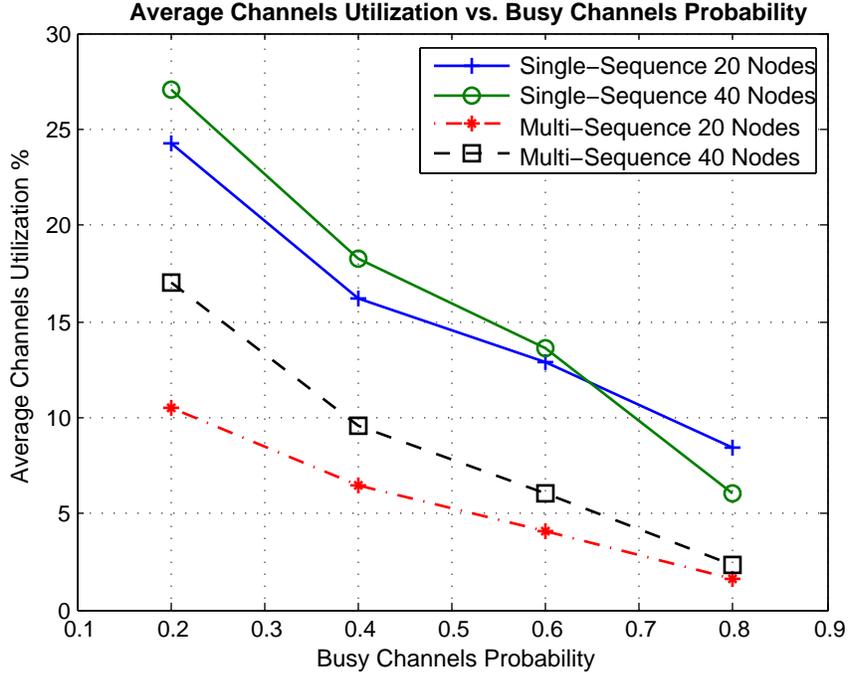
Figure 3.22: Average Channels Utilization versus Busy Channel Probability

utilization, and network throughput. The simulation results confirm this improvement.

The single-sequence protocol outperforms the multi-sequence protocol in channel utilization and network throughput because the single-sequence observes multiple channels. Observations like these support the protocol more opportunity to utilize the channels, and consequently more utilization and throughput.

However, the multi-sequence protocol outperforms the single-sequence protocol in the TTR performance. The reason is the multi-sequence protocol is designed to sense only one channel where the single-sequence protocol senses multiple channels. In fact, sensing one channel is less time-consuming than sensing multiple channels. Moreover, to sense multiple channels we have to use feature sensing, where energy sensing is enough to sense one channel. Finally, we discover both protocols have, essentially, a fair load over the
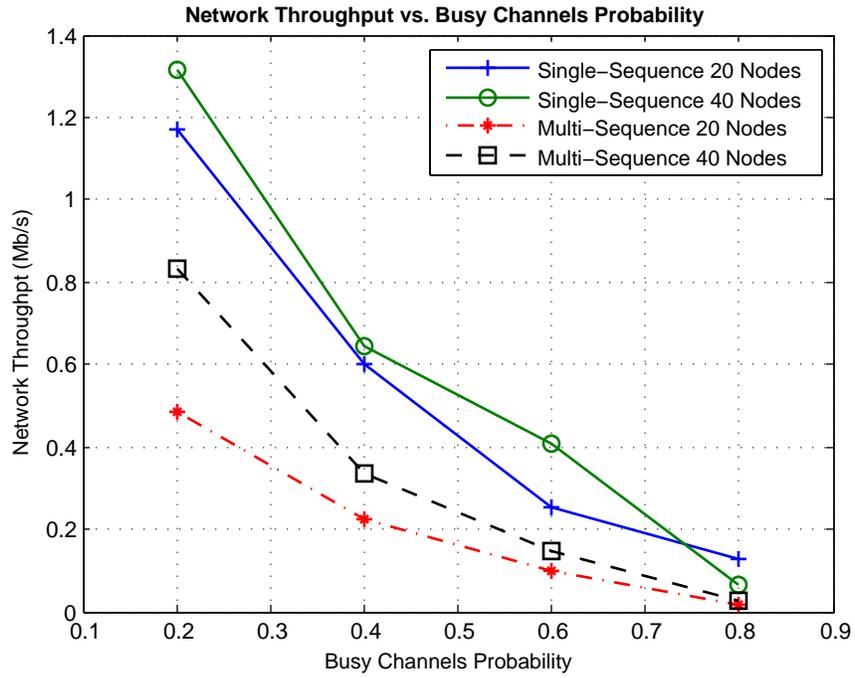
Figure 3.23: Network Throughput versus Busy Channel Probability

channels.
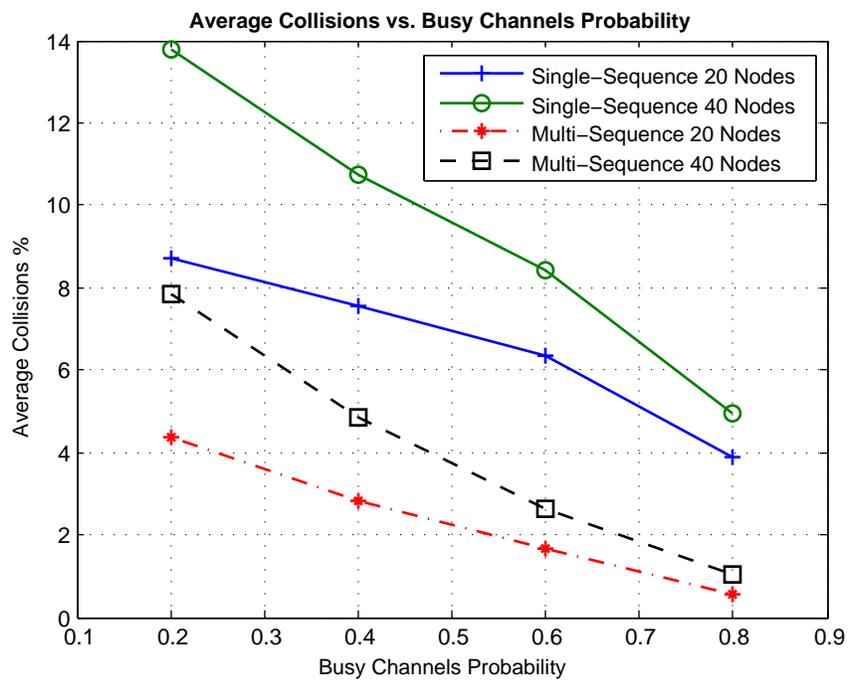
Figure 3.24: PU Collision percentage versus Busy Channel Probability
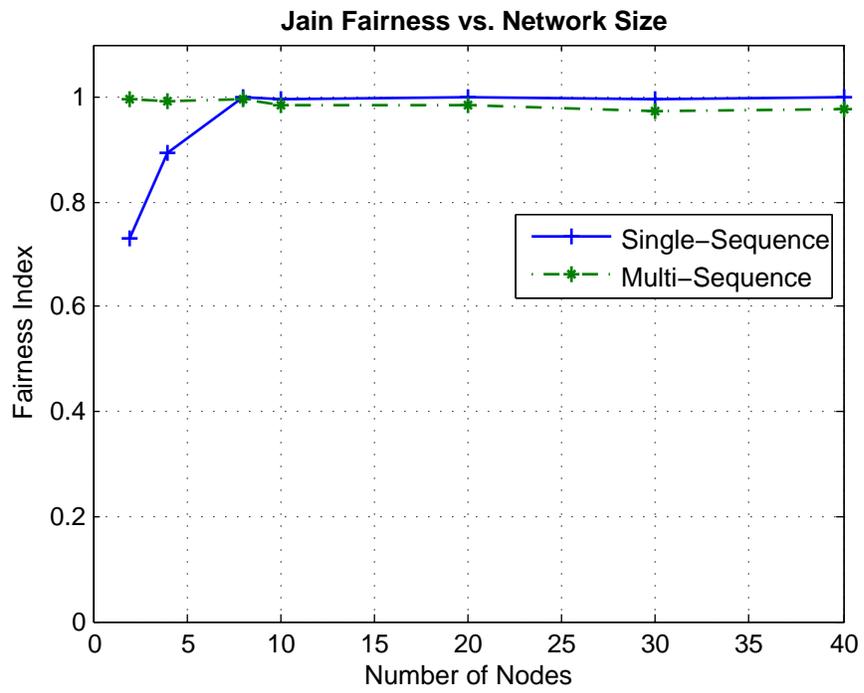
Figure 3.25: Protocols Fairness
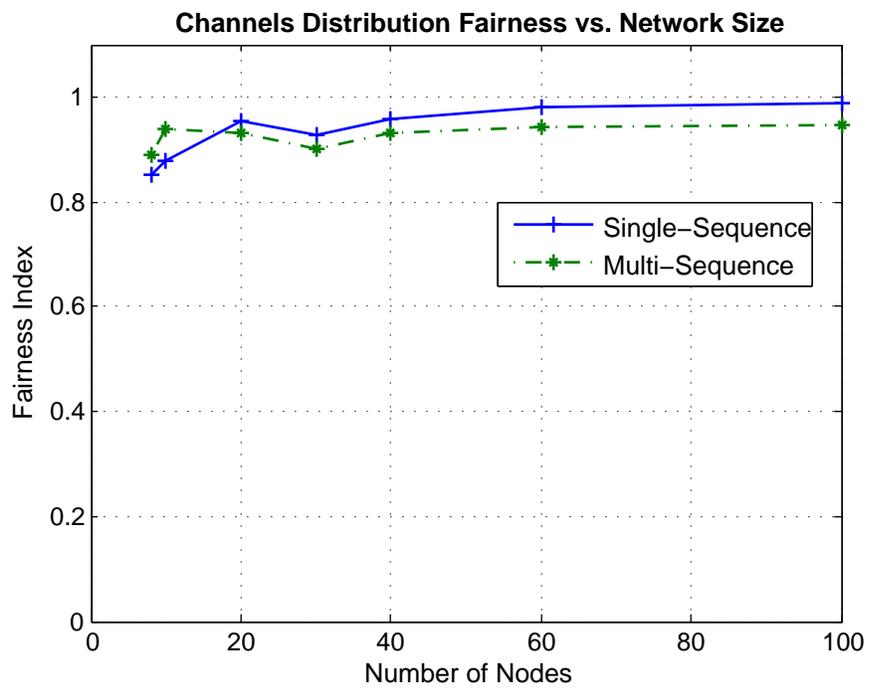
Figure 3.26: Channels Distribution Fairness

Chapter 4

Conclusions and Future Work

4.1 Conclusions

We design two distributed MAC protocols; the Balanced Incomplete Block Design (BIBD) is used in both protocols. The first protocol uses a single BIBD sequence and a multiple channels sensing. The second protocol used multiple BIBD sequences and single channel sensing. We use BIBD to provide our protocols a method to rendezvous between ad-hoc CR nodes. The BIBD guarantees there is at least one common element between any two blocks. We assign the channels to the BIBD elements and the searching sequence to the BIBD blocks. As a result, there is a guarantee of a rendezvous at least in one channel for each searching sequence. Moreover, this sequence does not need a node synchronization or an infrastructure network.

The protocols are analyzed and simulated. To analyze the single-sequence protocol, the discrete Markov Chain is used. In the multi-sequence protocol, we use the sequence structure of the BIBD to drive the maximum time to rendezvous. The simulation results

indicate that our protocols outperform other existing protocols in all performance metrics: the time to rendezvous, channels utilization, network throughput, and percentage of collisions between the SU and the PU network. Additionally, the multi-sequence protocol outperforms the single-sequence protocol in the TTR. Both protocols distribute the network load fairly on channels.

4.2   Future Work

This research opens new issues in the field of the cognitive radio. There are several aspects to designing a distributed MAC protocol that remain available. The following directions are important to the contribution for this topic:

- Adaptive Channel Selection: In reality, the PU tends to use certain channels more than others. It is worth skipping the channels that are used by the PU with a high probability, and select the channels that are most likely to be idle.

- Nodes Clustering: The rendezvous between a small number of nodes is much faster than in the case using a large number. As a solution, the node clustering is based on a geographical area, available spectrum, the PU coverage could improve the SU network performance.

- Learning Algorithm: Future spectrum availability could increase the MAC efficiency if the next available spectrum can be predicted.

- Adaptive Sensing Time: Sensing more channels means more time is required. When the sensing time is adaptive, the TTR, and consequently, more network throughput will improve.

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