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**MAC Protocols Design for Multiple Antenna Based Cognitive
Radio Wireless Mesh Network**

By

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ABSTRACT

Different measurements show that most of the time, most of the usable spectrum bands are underutilized. To improve the utilization efficiency of this natural resource (spectrum), Cognitive Radio (CR) system has been proposed. One of the key elements of CR systems is the Dynamic Spectrum Management Unit (DSMU). The DSMU improves the performance of wireless systems by providing additional spectrum bands in an opportunistic manner from the legacy spectrum users. Whereas, the cognitive radio users should not produce a significant interference to these legacy users (Primary users) and must evacuate itself seamlessly from the spectrum band in the appearance of the primary user (s). Integrating the CR system with Wireless Mesh Network (WMN) alleviates the spectrum scarcity mindset that surfaces on the traditional WMN which operates in unlicensed spectrum band.

Assimilating multiple antenna system with CR based WMN results multiple antenna based Cognitive Radio Wireless Mesh Network (CRWMN). In this dissertation, we design medium access control (MAC) protocols for CRWMN using both omnidirectional and directional multiple antenna technology. The design of MAC protocol for CR requires the integration of the physical layer (spectrum sensing) with the MAC layer. After developing the closed form expressions for the saturated throughput and average packet delay for the proposed MAC protocols, MATLAB software is used to simulate and evaluate the proposed random access MAC protocols.

There are three main contributions in this dissertation work. The first contribution is to examine the impact of multiple antenna systems on the performance of CRNS in terms of capacity, spectrum sensing and spectrum sharing. The investigation revealed that multiple antenna has significant advantages in terms of capacity improvement, range extension, energy efficiency, interference reduction, shorter spectrum sensing time, and better spectrum sharing efficiency.

The second contribution of this dissertation is proposing an improved medium access mechanism called M-CTS (Modified Clear to Send) which eliminate one RTS frame and one SIFS slot from the RTS/CTS access mechanism during a successful transmission, and based

on this access mechanism, a new random access MAC protocol called an enhanced random access MAC protocol for CRN (ECR-MAC) is proposed. The system model is developed for CRWMN using omni-directional antenna; and the performance of ECR-MAC has been analyzed using analytical model and simulated using MATLAB. Its performance in terms of throughput and average packet delay is evaluated for different number of secondary users, contention window size, and probability of transmission. The performance evaluations shows that ECR-MAC protocol exhibits good performance improvement compared with random access cognitive radio MAC protocols designed based on basic access and RTS/CTS access mechanisms. Compared with RTS/CTS based random access CR-MAC, ECR-MAC protocol shows at least five percent performance improvement.

The third contributions of this dissertation work are proposing directional random access MAC protocols for CRN called DCR-MAC protocols. The proposed DCR-MAC protocols make use of three access mechanisms; these are BASIC, RTS/CTS, and M-CTS access mechanisms. The proposed DCR-MAC protocols use beamwidth, number of secondary users, contention window size, and probability of transmission as key parameters to evaluate the performance of the proposed directional MAC protocols in terms of average throughput and average packet delay. Closed form expressions for average throughput and average packet delay are developed for the DCR_MAC protocols. The performance investigation of the proposed DCR-MAC protocols (particularly M-CTS access) using simulations show good throughput performance improvement, which is more than 475% on average, in relative to omni-directional CR-MAC protocol (ECR-MAC). However, the DCR-MAC with M-CTS access mechanisms still shows a superior performance among the remaining two access mechanisms implemented in the DCR-MAC protocols.

In general, the use of multiple antenna system for CRWMN improves the overall performance of the system. The proposed ECR-MAC protocol is promising for CRN in general and for CRWMN in particular in terms of throughput and average packet delay. The proposed directional CR-MAC protocols show remarkable performance improvement, however, equipping client nodes with multiple antenna is still a big challenge.

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List of Publications

- 1) Mulugeta Atlabachew, Jordi Casademont, and Yalemzewid Negash, ***Challenges, Opportunities and Research Direction on the Use of Multiple Antenna for CRWMNs***, 5th International Conference on Communication and Broadband Networking (ICCBN2017), Bali, Indonesia, February 20-22, 2017. (Accepted)
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- 3) Mulugeta Atlabachew, Jordi Casademont, and Yalemzewid Negash, ***Design and Performance Analysis of Directional Random Access MAC protocol for Cognitive Radio Network***, IEEE International Conference on Information Communication Technology and Society (IEEE ICTAS2018), Durban, South Africa, March 8-9, 2018. (Accepted for Publication)
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List of Acronyms

AAA -Adaptive Array Antenna	CRWMN -Cognitive Radio Wireless Mesh Network
ACS -Adaptive Cross-Self-Coherence-Restoral	CSI -Channel State Information
AP -Access Point	CSMA - Carrier Sense Multiple Access
AWGN -Additive White Gaussian	CSMA/CA -Carrier Sense Multiple Access with Collision Avoidance
BC -Backup Channel	CUL -Current Usage List
BEB -Binary Exponential Backoff	CWMN -Cognitive Radio Wireless Mesh Network
BER -Bit Error-Rate	DCA -Distributed Channel Assignment
BMRC -Blind Maximum Ratio Combining	DCF -Distributed Coordinated Function
BP -Beacon Period	DCR-MAC - Directional Random Access MAC protocol for Cognitive Radio Network
BWRC -Berkely Wireless Research Center	DIFS -DCF Inter Frame Space
CCC -Common Control Channel	DOF -Degree of Freedom
CCRN -Cooperative Cognitive Radio Network	DOSS -Dynamic Open Spectrum Sharing
CDMA -Code Division Multiple Access	DPTS -Directional Prepare to Send
C-MAC -Cognitive MAC	DSA -Dynamic Spectrum Access
CR-ALOHA -Cognitive Radio based ALOHA	DSMU -Dynamic Spectrum Management Unit
CR -Cognitive Radio	ECR-MAC -Enhanced Random Access MAC protocol for Cognitive Radio Network
CR-CSMA/CA - Cognitive Radio based Carrier Sense Multiple Access with Collision Avoidance	ED -Energy Detector
CR-CSMA -Cognitive Radio based Carrier Sense Multiple Access	FBFN -Fixed Beamforming Network
CRMAC -Cognitive Radio MAC	FCC -Federal Communications Commission's
CRN -Cognitive Radio Network	

FCL-Free Channel List

FDMA-Frequency Division Multiple Access

FFT-Fast Fourier Transform

GLRD-Generalized Likelihood Ratio Detector

GLR-Generalized Likelihood Ratio

GLRT- Generalized Likelihood Ratio Test

HC-MAC-Hardware Constrained MAC

LRT-Likelihood Ratio Test

MAC-Medium Access Control

MCHTP-Multi-Channel Hidden Terminal Problem

MC-Mesh Client

M-CTS-Modified Request-to-Send/Clear-to-Send

MIMO-BC-Broadcast MU-MIMO

MIMO-MAC-Multiple Access Channel MU-MIMO

MIMO-Multiple Input Multiple Output

MISO-Multiple Input Single Output

MME-Minimum Mean Squared Error

MRMC-Multi-Radio Multi-Channel

MR-Mesh Router

MSDF- Modified Cyclic Spectral Density Function

MU-MIMO-Multi-User MIMO

NHTP-New Hidden Terminal Problem

OFDMA-Orthogonal Frequency Division Multiple Access

OFDM-Orthogonal Frequency Division Multiplexing

OSA-opportunistic Spectrum Access

PBS-Primary User Base Station

PCF-Point Coordination Function

PIFS-PCF Inter Frame Space

POMDP-Partially Observable Markov Decision Process

PR-Primary Receiver

PSD-Power Spectral Density

PT-Primary Transmitter

PTS-Prepare to sense

PU-Primary User

QoS-Quality of Service

RA-MAC-Random Access MAC

RC-Rendezvous Channel

RF-Radio Frequency

RMT-Random Matrix Theories

RTS/CTS-Request-to-Send/Clear-to-Send

SBS-Secondary User Base Station

SCA-MAC-Statistical Channel Allocation based MAC

SCF-Cyclic Spectral Coherence Function

SDF- Cyclic Spectral Density Function

SDR-Software Defined Radio

SIFS-Short Inter Frame Space

SIMO-Single Input Multiple Output

SIMO-Single Input Multiple Output

SINR-Signal-to-Interference-Plus-Noise Ratio

SISO-Single Input Single Output

SISO-Single Input Single Output

SLC-Square Law Combining

SNR-Signal-to-Noise Ratio

SRDOF-Spatial Receive Degree of Freedom

SRMC- Single-Radio Multi-Channel

SRSC- Single-Radio Single-Channel

SR-Secondary Receiver

SS-Spectrum Sensing

STDOF-Spatial Transmit Degree of Freedom

ST-Secondary Transmitter

SU- Secondary User

SU-MIMO-Single User MIMO

TDMA-Time Division Multiple Access

Wi-Fi-Wireless Fidelity

WiMAX-

WMN-Wireless Mesh Network

ZFBF-Zero Forcing Beamforming

INTRODUCTION

1.1 General Background

Capacity, security, and reliability are the fundamental limitations of the wireless communication networks. Wireless mesh network (WMN) is a class of multi-hop wireless network with better network paradigm in terms of reliability. WMN is a dynamically self-organized and self-configured network where nodes in the network automatically establish and maintain mesh connectivity/topology among themselves to create an adhoc network. These features bring many advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage in relatively low power [1] - [4].

The nodes of WMN are classified into three major categories based on their roles in the network: mesh clients (MCs), mesh routers (MRs), and mesh gateway (MG). The MGs connect the WMN to the internet; the MRs manage a number of MCs in its cell and connects them with the backbone network over multiple hops of MRs; and the MCs are end-users' equipment which could be mobile or stationary and are connected to the network through MRs. Besides to its normal routing duties and capability to form the backbone WMN, the MRs have extra capacity to support mesh routing operation and they are assumed to have minimal mobility [1], [2].

In the initial design of WMNs, the traditional wireless network paradigm is followed, where only one radio (wireless interface) is equipped at each node and all nodes share a single channel. However, the capacity per node drops significantly with the increase of the network size which degrades the network performance. Due to the above observation, the single-radio single-channel (SRSC) architecture is evolved to the single-radio multi-channel (SRMC) architecture. Although SRMC architecture overcomes the limitations of SRSC architecture, the increasing demand for better broadband services cannot tolerate channel

switching delay, low connectivity and disconnectedness, and synchronization and channel assignment due to multi-channeling. To alleviate those problems, as well as to increase the **capacity** and **spectrum usage** of WMNs, multi-radio multi-channel (MRMC) radio interface where each node is equipped with multiple radios and can use multiple non-overlapping channels have been proposed. Therefore, almost all the current WMNs adopt the MRMC architecture [5].

One of the key advantages of WMNs over other wireless networks is that mesh nodes are relatively inexpensive to provide broadband internet service. Hence, it is economically feasible to spread mesh nodes at a high enough density to provide high data rates to a dense user population. Specifically, the high node density results in a short distance between receivers and transmitters, and hence high signal to noise ratio (SNR) channels and high bit-rates are possible. Unless otherwise the deployed high node density is not properly managed, the network performance will degrade due to interference. Generally, the capacity of WMNs is affected directly or indirectly by many factors such as network architecture, network topology, traffic pattern, network node density, number of channels and interface used per node, types of radio interface, transmission power level, and node mobility [1], [4], [5], and [7].

WMNs operate in the unlicensed band and this band is shared by many other wireless networks, as a result, there will be high node density in this unlicensed band. As the node density becomes higher, the interference will be large which significantly deteriorate the network capacity. Different analytical results show that the throughput capacity per node reduces significantly when the node density increases. Specially, urban areas are affected most by this channel congestion, and thus there is a strong motivation to identify unused portions of the spectrum (both from licensed and unlicensed) so as to transmit their traffic in an opportunistic manner. This mechanism effectively reduces the node density per transmission channel, thus improves the network throughput [4] - [7].

To solve the spectrum scarcity, a new wireless paradigm is coined by Joseph Mitolla and it is called Cognitive radio (CR). CR technology uses a dynamic spectrum management strategy to maximize the spectrum utilization efficiency. In general, CR refers to an intelligent wireless system that senses and is aware of its operational environment; Does

not operate in a fixed assigned band but it rather dynamically searches an appropriate spectrum band for the secondary user (opportunistic user) to operate without creating significant interference to the primary user (licensed user) without any user intervention; Can be trained to dynamically and autonomously adjust its radio operating parameters accordingly; Can learn from experience, plans based on knowledge, and decides based on reasoning [8]-[15].

Cognitive radio network (CRN) is promising technology that enables next generation wireless communication networks by improving the spectrum utilization efficiency in an opportunistic fashion without creating significant interference to the primary users (PUs). The emergence of CR technology could be a revolution for those wireless networks requiring large spectrum resources. CR technology can improve the network capacity of WMNs by reducing network congestion through the dynamic spectrum management strategy. WMN equipped with CR is a natural choice to improve the capacity of WMN by mining and availing additional spectrum holes in an opportunistic manner [15]-[18].

However, CRs also introduce additional complexities to bandwidth/channel allocation. In a traditional 802.11- based WMN, a set of homogeneous channels are always available to every MR; whereas in a CR-based WMN (CRWMN), each node can access a large number of heterogeneous spectrum bands, which may spread over a wide range of frequencies. Moreover, the detected vacant channels (spectrum holes) can support different transmission ranges and data rates due to spectrum diversity. This dynamicity will have a significant impact on route selection and channel assignment/spectrum allocation CRWMNs. Most of the capabilities of CR like spectrum sensing, spectrum sharing, spectrum allocation, spectrum access, and spectrum mobility are main parts of the dynamic spectrum management process of CR system which is managed at the medium accesses control (MAC) layer.

The work of this dissertation focuses on the design of *an efficient MAC Protocol for CRWMN in terms of*

- I. ***Connectivity and***
- II. ***Interference.***

1.2 Motivation of the Dissertation

CRWMNs bring paradigm shift to the conventional WMNs by introducing cognitive capabilities. It basically reduces the bottle neck observed due to spectrum scarcity. More importantly, the integration of multiple antenna system to the CRWMN improves the network capacity; with respect to spectrum sensing multiple antenna reduces the spectrum sensing time (shorter sensing time), gives robustness to noise uncertainty, and it results better detection performance (better probability of detection, reduced probability of false alarm) in relative to single antenna detection techniques used in CRN. When multiple antenna system is used with any of the spectrum sharing techniques it gives better performance [22] – [61].

Besides to the advantages of multiple antenna system, lack of MAC protocol for CRWMN has motivated us to come up with better random access MAC protocols that show good performance in terms of throughput and average packet delay. The impacts of multiple antenna system on the performance of MAC protocol for the conventional wireless network have been dealt very well. However, the impact of multiple antenna system, particularly directional antenna, on the performance of cognitive radio MAC protocol is not well explored. In this dissertation work, we design, analyze, and propose random access MAC protocols using multiple antenna technology for CRN in general and to the CRWMN in particular.

1.3 Objectives of the Dissertation Work

2.1.1 General Objective

The main objective of this dissertation work is to propose random access MAC protocols for CRWMN which show better throughput and lower average packet delay compared with the conventional CSMA/CA MAC protocol such that the overall performance of the network should be improved in terms of network capacity and connectivity by reducing interference.

2.1.2 Specific Objectives

More specifically, this dissertation work assumes the following objectives.

- I. **Improving Network Capacity**- the capacity of wireless network is mainly affected by the available bandwidth for communication. In this regard, this thesis work designs, analyzes, and proposes an improved random access MAC protocol for WMN which improves the network capacity by making use of CR technology that brings additional bandwidth to the conventional WMN. Number of secondary users, contention window size, and probability of transmission are used as key parameter to compare the performance of the proposed protocol with the other random access MAC protocols.
- II. **Improving Connectivity and Reducing Interference**-connectivity and interference are the other two important issues that are considered in the design of MAC protocol particularly in this dissertation. Connectivity in wireless network could be addressed from network topology and coverage area perspective. From network topology point of view, mesh network address well the issue of connectivity; moreover, it is possible to equip the MRs with multiple antenna technology so as to improve the capacity and connectivity by extending the coverage area of the network. The challenge associated with interference can be alleviated by using multiple antenna technology (beamforming) with CRWMN. Therefore, this thesis work also designs, analyzes, and proposes directional random access MAC protocols for CRWMN by addressing the above problems.

1.4 Methodology

The methodologies used to achieve the stated objectives in this dissertation work are mainly literature review, developing mathematical model for the proposed MAC protocols, and evaluating the performance of the proposed protocols by using simulation. The methodologies could be elaborated in more detail as follows

- 1) First, we have done an extensive literature review in order to understand state of the art of CRWMN, MAC protocol, and multiple antenna technology.
- 2) Second, following the literature review we have proposed an enhanced random access MAC protocol for CRN (ECR-MAC) based on our modified clear to send (M-CTS) access technique.

- 3) Third, we have derived a closed form expression for the saturated throughput and average packet delay to evaluate the performance of the proposed ECR-MAC protocol.
- 4) Fourth, we have identified the following parameters to evaluate the performance of ECR-MAC protocols: Number of secondary user (SU), contention window size, and probability of transmission. Using these parameters, we have simulated the throughput and average packet delay for the proposed MAC protocol using MATLAB simulator (version R2013b) to examine the performance.
- 5) Fifth, we have designed Directional random access MAC protocols for CRN (DCR-MAC), and we have developed closed form expressions for throughput and average packet delay to evaluate the performance of the proposed protocols.
- 6) Finally, using number of SU, beamwidth size, contention window size, and probability of transmission, we have simulated to examine the performance of the proposed protocols.

1.5 Dissertation Outline and Contributions

In this section, the organization and contributions of the thesis are presented.

1.5.1 Dissertation Contributions

The contributions of this dissertation work are summarized as follows.

- a) This thesis proposes an improved medium access mechanism called M-CTS access mechanism which shows better performance with respect to the performance of the Basic and request to send (RTS)/ clear to send (CTS) access mechanisms.
- b) Closed form expression for saturated throughput and average packet delay is developed for the proposed enhanced random access MAC protocol for cognitive radio network (ECR-MAC) which uses modified clear to send (M-CTS) access mechanism.
- c) The performance of the proposed ECR-MAC protocol is evaluated using simulation by considering number of secondary user (SU), contention window size, and probability of transmission as key performance evaluating parameters.

- d) This thesis proposes three directional random access MAC protocols for CRWMN based on multiple antenna technology. These directional random access MAC protocols are developed based on the three access mechanisms, namely: directional basic access mechanism, directional RTS/CTS access mechanism, and M-CTS access mechanism.
- e) Closed form expressions for the average throughput and average packet delay are developed for the three proposed directional random access MAC protocol to be used for CRWMN.
- f) The performances of the three directional MAC protocols are evaluated by using simulations. Beamwidth, number of SU, contention window size, retry limit, and probability of transmission are used as essential parameters to evaluate the performance.
- g) This thesis work investigates the benefits of CRWMN; it explores the benefits of multiple antenna technology and it extends these benefits to the CRWMNs; and it analyzes the performance of distributed coordinated function (DCF) MAC protocol in terms of throughput and average packet delay to validate our works.

1.5.2 Dissertation Outline

The thesis is organized in to seven chapters; the first chapter gives the overall ideas of the research and the road map to solve the research problems. In chapter two, fundamental concepts related to CR, WMN, and CRWMN are presented. In chapter three, the benefits and challenges of multiple antenna systems are analyzed. In chapter four, the performance of random access MAC protocol are investigated. In chapter five, a new random access MAC protocol for CRN called ECR-MAC protocol is proposed, and its performance in terms of saturated throughput and average packet delay is analyzed. In chapter six, three new directional random access MAC protocols for CRWMN are proposed and their closed form expressions for saturated throughput and average packet delay are developed; their performance using beamwidth, number of SUs, contention window size, and probability of transmission are investigated using simulations. Finally, in chapter seven, conclusions and possible future research directions are presented.

Chapter-2

STATE OF THE ART & RELATED WORK

2.1. Cognitive Radio

Wireless communication is proving its importance in the day to day life of human being and researchers are also working day and night to make a significant advancement. One revolutionary idea which has brought a paradigm shift to the wireless communication system was coined by Joseph Mitola in 1999, and it is called **cognitive radio** [11].

Generally speaking, in wireless communication system, spectrum is one of the key natural resource on which the technological advancement in the area relies on. However, the users' increasing demand for new service with good quality is being restricted by the scarcity of spectrum bands, because all important spectrum bands are already occupied. This due to the existing spectrum allocation strategy, that is, spectrum bands are being utilized in a fixed manner like legacy. Moreover, the American's Federal Communications Commission's (FCC) frequency allocation chart, fig. 2.1, indicates overlapping allocations over all of the frequency bands, which reinforce the spectrum scarcity mindset.

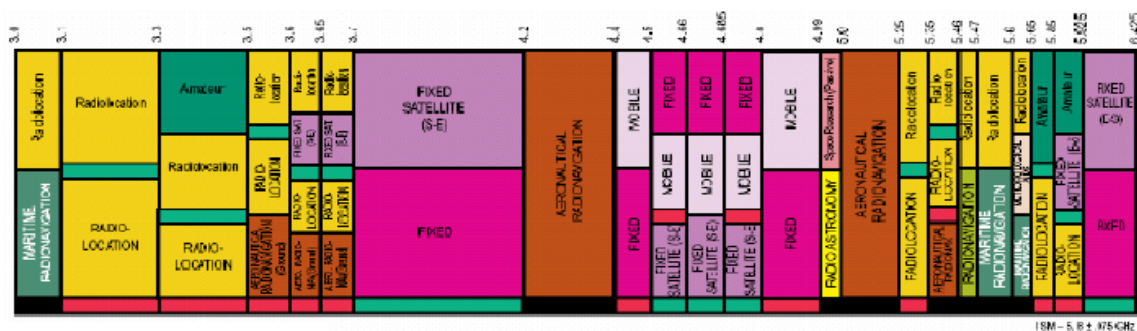


Fig. 2. 1 The FCC frequency allocations from 3-6GHz

Despite the scarcity mindset, actual spectrum measurements taken at Berkeley indicate low utilization of the allotted spectrum, especially in the 3-6 GHz frequency range [9]. Fig. 2.2 shows the power spectral density (PSD) measurement of the received 6 GHz wideband signal.

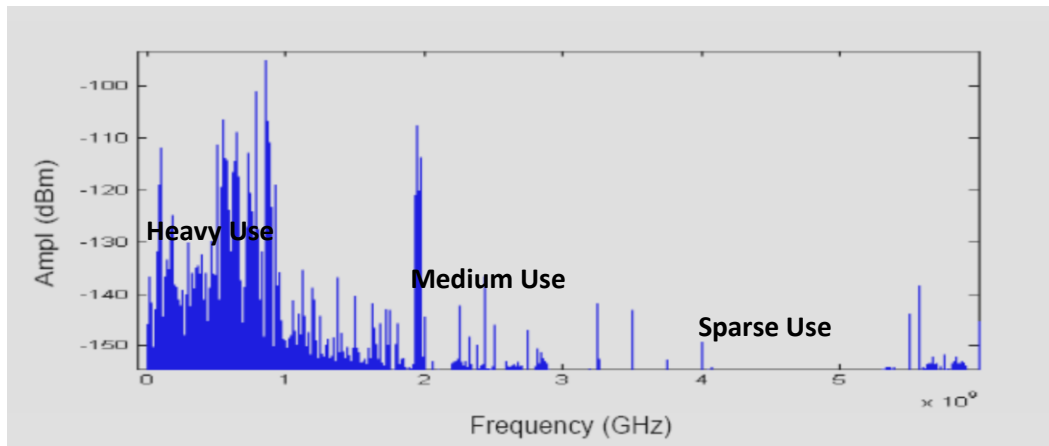


Fig. 2. 2 *Spectrum Utilization Measurements taken at Berkeley Wireless Research Center (BWRC)*

Indeed, if we see the scanned portions of the radio spectrum shown above, we observe three spectrum usages:

- 1) Some frequency bands in the spectrum are largely unoccupied most of the time (**sparse use**);
- 2) Some other frequency bands are only partially occupied (**medium use**);
- 3) The remaining frequency bands are heavily used (**heavy use**).

From the above chart, we can see that nearly 90% of the spectrum ranging from 3-6GHz is not utilized most of the time and the spectrum range from 1-3GHz is mostly occupied. Moreover, other measurements were taken by Shared Spectrum Company [13] at Gravelly Point Park, located next to National Airport in Washington, DC, offers one of the densest RF environments, show that even large fraction of the spectrum portions in the range of 1-3GHz are not being utilized most of the time. From the measurement we can observe that the existing spectrum allocation strategy is not fair enough to make distribution of this natural resource among wireless users. Therefore, there must be a fair and dynamic spectrum allocating strategy which maximizes the spectrum utilization efficiency.

To maximize the spectrum utilization efficiency a dynamic spectrum allocation strategy has been proposed and **cognitive radio technology** is among these technologies which uses dynamic spectrum allocation technique. Different literatures give different definition for cognitive radio. However, we found the definition given in [11] comprehensive enough to use in our work, which says

“Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g. transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

✚ Highly reliable communications whenever and wherever needed;

✚ Efficient utilization of the radio spectrum.”

The underutilization of the electromagnetic spectrum leads us to think in terms of *spectrum holes*, which has the following definition:

A spectrum hole is a band of frequency assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user.

Spectrum utilization can be improved significantly by making it possible for a secondary user (unlicensed user) to access a spectrum hole unoccupied by the primary user (licensed user) at the right location and time in request. In general, CR refers to wireless architectures in which a communication system does not operate in a fixed assigned band, but rather searches an appropriate band to operate. Therefore, CR is viewed as a novel approach for improving the spectrum utilization in a dynamic way.

2.1.3 Evolution of Radio

Like other technologies the radio technology has made a big evolution in the history of wireless communication. The evolution of radio can be broadly classified as [8]

1. **Hardware driven radios:** Transmit frequencies, modulation type and other radio frequency (RF) parameters are determined by hardware and cannot be changed without hardware changes.
2. **Digital radios:** A digital radio performs part of the signal processing or transmission digitally, but is not programmable in the field.
3. **Software Defined Radios (SDR):** All functions, modes and applications can be configured and reconfigured by software.
4. **Cognitive Radios (CRs):** A radio or system that senses and is aware of its operational environment and can be trained dynamically, and autonomously adjusts its radio operating parameters accordingly. CR is simply SDR plus intelligence.

2.1.4 Common Feature of Cognitive Radio

CR uses SDR's features and it has many additional functions which improves the intelligence of the system/radio. These functions are spectrum sensing, environmental awareness, adaptability, real-time processing, learning from its experience and the like. These terms can be explained in brief as follows [8], [9]

Spectrum Sensing: - it is the foremost operation of CR system. The CR senses/ scans the operating frequency bands, from the scanned portions it detects the unused portions of spectrum in the form of spectrum holes and assigns an adequate amount of spectrum for the requested service autonomously. This sensing process is a dynamic process which is expected to be made periodically for the sake of smooth transition from one spectrum hole to the other while a need to use the spectrum from the primary user arises.

Environmental Awareness :- CR has awareness about its operating environment such as the fading, interference, temperature, user needs and preferences, radio capabilities and performance limits, interoperability with other services, co-existence of several services on

common bands, policies, existence and location of licensed users, your own location, routing paths and conflicts, and it knows that the received radio energy is a measure of how much a section of spectrum is occupied in space, time and frequency.

Adaptation: - since CR is intended to work in different scenario like providing different services in any band available it is expected to adapt its parameters to enhance the overall performance of the radio. The adaptation includes modulation, power, coding and the like.

Intelligence: - The radio is capable of applying information/knowledge towards a purposeful goal.

2.2. Wireless Mesh Networks (WMN)

Flexibility, coverage, capacity, and reliability are the most fundamental features of the wireless networks. To respond to the increasing demand of affordable broadband services, the WMN is a much better networking paradigm which increases the spectrum usage efficiency, increases the coverage area, increases the network capacity, and network reliability. WMN is a family of multi-hop wireless network including adhoc network. In many respect WMN is a better network paradigm because it is a dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves (creating, in effect, an adhoc network). Generally, the architecture of WMNs can be classified into three types: Infrastructure/Backbone WMNs, Client WMNs, and Hybrid WMNs.

2.2.1 Infrastructure/Backbone WMNs

In this architecture, mesh routers form an infrastructure for clients, as shown in Fig. 2.5, where dashed and solid lines indicate wireless and wired links, respectively. The WMN infrastructure/backbone can be built using various types of radio technologies, in addition to the mostly used IEEE 802.11 technologies. The mesh routers form a mesh of self-configuring, self-healing links among themselves. With gateway functionality, mesh routers can be connected to the Internet. This approach, also referred to as infrastructure meshing, provides a backbone for conventional clients and enables integration of WMNs with

existing wireless networks, through gateway/bridge functionalities in mesh routers. Conventional clients with an Ethernet interface can be connected to mesh routers via Ethernet links. For conventional clients with the same radio technologies as mesh routers, they can directly communicate with mesh routers. If different radio technologies are used, clients must communicate with their base stations that have Ethernet connections to mesh routers [1].

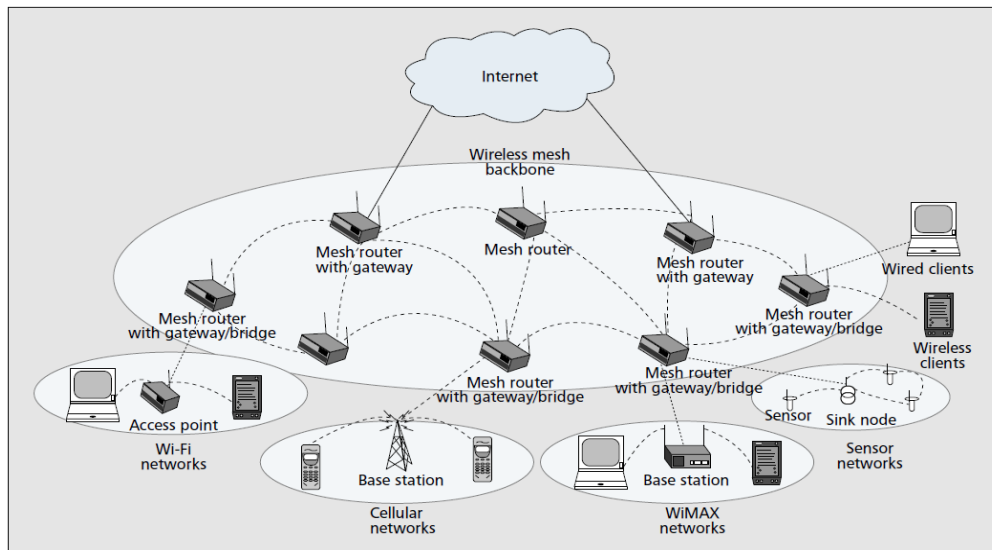


Fig. 2. 3 Infrastructure/Backbone WMNs

2.2.2 Client WMNs

Client meshing provides peer-to-peer networks among client devices. In this type of architecture, client nodes constitute the actual network to perform routing and configuration functionalities as well as providing end-user applications to customers. Hence, a mesh router is not required for these types of networks. Client WMNs are usually formed using one type of radios on devices. Thus, a Client WMN is actually the same as a conventional ad hoc network. However, the requirements on end-user devices is increased when compared to infrastructure meshing, since in Client WMNs the end-users must perform additional functions such as routing and self-configuration.

2.2.3 Hybrid WMNs

This architecture is the combination of infrastructure and client meshing, as shown in Fig. 2.4. Mesh clients can access the network through mesh routers as well as directly meshing with other mesh clients. While the infrastructure provides connectivity to other networks such as the Internet, Wi-Fi, WiMAX, cellular, and sensor networks, the routing capabilities of clients provide improved connectivity and coverage inside WMNs [1].

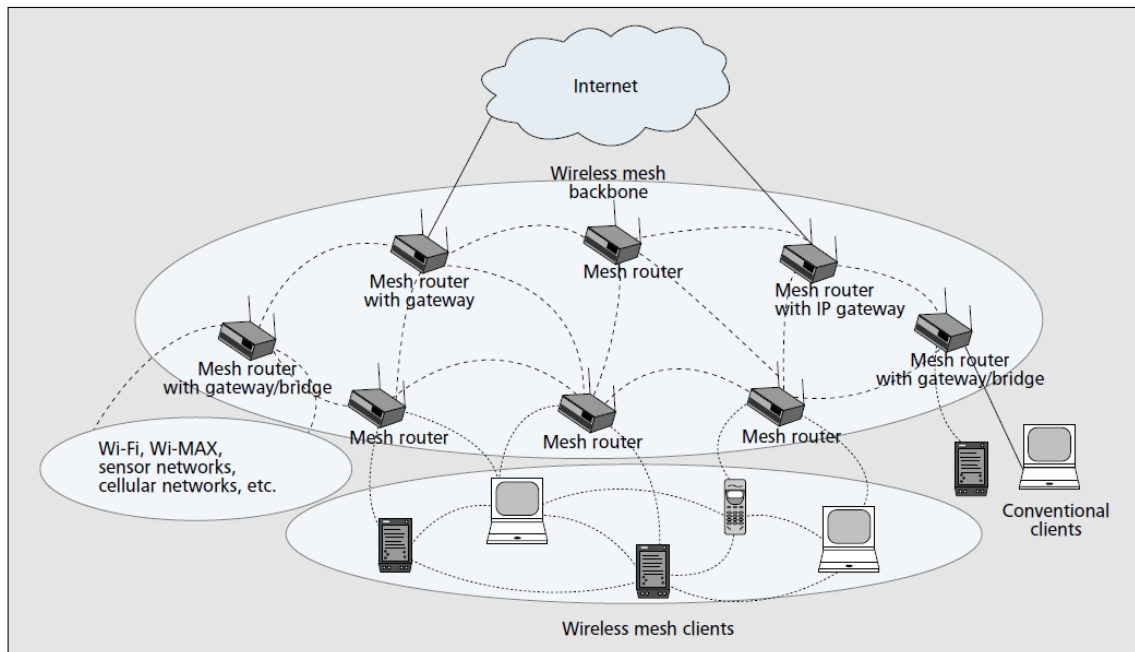


Fig. 2. 4 Hybrid WMNs Architecture

2.3. Types of Radio Interface in WMNs

In the initial design of WMNs, the traditional wireless network paradigm is followed, where only one radio (i.e., wireless interface card) is equipped at each node and all nodes share a single channel [1]. However, several research findings gradually revealed that the capacity per node in such solutions drops significantly with the increase of the network size. An intuitive interpretation of the above phenomenon is as follows: in a single channel multi-hop network, interference can occur not only between nearby flows (known as inter-flow interference) but also between the nearby hops in a single flow (known as intra-flow interference), thus significantly degrading the network performance.

Due to the above observation, the SRSC architecture is not appealing. SRMC architecture is then proposed as a solution but this architecture introduced channel switching which involves non-negligible delays, node disconnectedness is observed due to synchronization difficulty, and inefficient spectrum utilization. To overcome the fundamental limitations of SRMC architecture and to increase the capacity and spectrum usage of WMNs at large, MRMC interface, where each node is equipped with multiple radios and can use multiple non-overlapping channels have been proposed. Therefore, almost all the current WMN deployments and proposals adopt the MRMC architecture.

Basically, the capacity of WMNs is affected by many factors such as network architecture, network topology, traffic pattern, network node density, number of channels used for each node, transmission power level, and node mobility. A clear understanding of the relationship between network capacity and the above factors provides a guideline for protocol development, architecture design, deployment and operation of the network. Therefore, before a network is designed, deployed, and operated, factors that critically influence its performance need to be considered. For WMNs, the critical factors are Radio Techniques, Scalability, Mesh Connectivity, Broadband and QoS, Security, Ease of Use, and Compatibility and Inter-operability.

Many approaches in the radio techniques have been proposed to increase capacity and flexibility of wireless systems in recent years. Typical examples include directional and smart antennas, multiple input multiple output (MIMO) systems, and multi radio/multi-channel systems. To improve the performance of a wireless radio and control by higher layer protocols, more advanced radio technologies, such as reconfigurable radios, frequency agile/cognitive radios, and software radios, have been proposed for wireless communication networks. These days, the marriage of these radio technologies with WMN becomes hot research areas. The marriage of smart antenna and WMNs produced directional wireless mesh networking, whereas, the marriage of MIMO and WMNs produced MIMO based WMNs, likewise the marriage of CR and WMNs produced CRWMN.

2.4. Cognitive Radio Wireless Mesh Networks (CRWMNs)

CRWMN has the same principle of operation with the conventional WMN, except its empowerment with CR capabilities. In short, CRWMN is a mesh network formed by CR nodes. It has the same network architecture like the conventional mesh network having either a SRMC interface or MRMC interfaces but it operates in licensed bands in an opportunistic fashion [15]-[23].

The motivation for CRWMNs is the spectrum scarcity mindset on both licensed and unlicensed bands. CR capabilities leverage the capacity of wireless network by supplying additional spectrum bandwidth so that it can use the available bandwidth in an opportunistic manner without producing a significant interference to the primary users. WMNs are designed to provide broadband service with reliable network connection. By designing an opportunistic spectrum access mechanism, the bandwidth limitation observed in WMNs can be reduced in a significant way, thus the idea of CRWMN is the right forward step in designing energy efficient, reliable, flexible, dynamic, and intelligent wireless networks[15]-[23].

2.5. Literature Survey

In this section different literature works are reviewed, most of which are related with multiple antenna, and medium access control protocols that are associated with cognitive radio networks. First literatures which are related with capacity gain of multiple antenna technology, then impact of multiple antennas on spectrum sensing and sharing are survived in details. MAC protocols for CRNs, particularly for multi-hop CRNs are explored.

2.5.1. Capacity of CRN, and WMNs using Multiple Antenna

In the wireless domain the impact of multiple antennas on the conventional wireless network performance is huge. Now we shall examine the influence of multiple antennas on the performance of CRNs in general and on the CRWMN in particular.

In [22] the authors developed an upper and lower bounds for multiple antennas based CRs where both the primary and secondary transmitters and receivers may have multiple antennas. They have assumed that the primary transmitter knows the message of the primary transmitter a prior to help the primary transmitter adjust all its transmission parameters and strategies to assume the secondary transmitter transmitted with the optimum transmission capacity.

In [23] the authors analyzed the sum throughput of an underlay multiuser CR system with multiple antenna base stations operating either in the multiple access channel or broadcast (BC) mode where the cognitive or primary users may be equipped with multiple antennas. They have assumed that the primary and secondary networks have N and n users, respectively, and their base stations have M and m antennas, respectively. For primary broadcast network with a set of interference power constraints on the primary, the maximum throughput of the secondary multiple access channel grows as $\frac{m}{N+1} \log n$ and for primary multiple access channel it grows as $\frac{m}{M+1} \log n$. For the case of secondary multiple access channel, it is possible to reduce the interference on the primary to zero by maintaining the throughput growth rate to $\Theta(\log n)$. Whereas, for the secondary broadcast channel they have showed that the throughput can grow as $m \log \log n$ in the presence of primary broadcast or multiple access channel, thus the growth rate of the throughput is unaffected by the presence of the primary system.

In [24] they have shown that the use of multiple antennas specially the directional antennas improves the performance of WMNs in comparison to the omnidirectional antennas. It is also observed that increasing the number of antennas and decreasing the beam width increases the capacity of the WMN. Moreover, in [25] it is also shown that there is a capacity gain by using directional antennas in random ad hoc network both at the transmitter and receiver. In [26] it is also shown that using directional antennas in MRMC WMN improves the throughputs by up to 231% and reduces packet delay drastically compared to omnidirectional MRMC WMN. In [27] the advantages of smart antennas/adaptive arrays to the WMNs are explored and it is noted that the use of smart antennas enhances the capacity of WMNs with a proper design of MAC protocol.

2.5.2. Spectrum Sensing Using Multiple Antennas for CRNs

Spectrum sensing in CR is a process of detecting the primary transmitter. It is the foremost step that needs to be performed in the CR system. Probability of false alarm, probability of detection, probability of miss detection, sensing time, and system complexity can be used to evaluate the performance of different spectrum sensing techniques. Moreover, the sensing performance can also be affected by the signal-to-noise-ratio (SNR), fading and multipath, and noise/interference level (since it changes over time and becomes difficult to obtain accurate noise power it is also called noise uncertainty).

There are different spectrum sensing methods which are proposed for CRNs; these are Likelihood Ratio Test (LRT), Matched Filter, Energy Detection(ED), and Cyclo-Stationary feature Detection. These algorithms have different advantages and disadvantages. Although LRT is proven to be optimal, it is very difficult to use, because it requires exact channel information and distributions of the source signal and noise, which are practically intractable. The matched filter technique is an optimal spectrum detector with best performance and low complexity but it requires accurate prior knowledge about the primary user signal, e.g. modulation type, pulse shaping, channel equalization and timing and frequency synchronization, for these reasons it is also impractical spectrum detection technique. Whereas, ED is a sub-optimal spectrum detector which does not require prior knowledge about the primary signal and has the least computational complexity but it is not robust in low SNR environment, it cannot distinguish users sharing the same channel (primary user and interference) and it requires noise power. The cyclo-stationary detector is robust in low SNR environment and it can distinguish primary signal from interference so that it could be beneficial in the coexistence scenario however, it requires partial information of the primary user and it is computationally more complex.

In different literatures the use of multiple antennas for spectrum detection has been explored and found to be a promising candidate in the spectrum detection process of CRNs. It provides additional spatial degree of freedom that has a significant gain of spectrum sensing performance in relative to the performance of a CR system which is equipped with single antenna element. In addition to the conventional benefits obtained from the use of multiple antennas technology in the wireless communication systems, a CR equipped with

multiple antennas benefits much in the spectrum detection process by providing better detection performances and shorter sensing time among others. Therefore, we have explored different literatures on the use of multiple antennas in CRNs as follows.

In [28], the authors proposed a spectrum sensing algorithms using multiple antennas receiver. It is a statistical covariance based spectrum detection algorithm which compensate for the noise level uncertainty at the detector. Generally, they have extended the covariance-based detector for multiple antennas receiver, they have derived the decision variable distribution for the case of signal in noise, and they have investigated the noise uncertainty impact to the detector's performance and gave guidelines of how to control the detection probability in case of noise uncertainty. However, they have made no performance comparison to show the proposed algorithm performs better than other alternative spectrum detection techniques and they have considered large sample which results longer sensing time.

In [29], the authors presented spectrum sensing with multiple antennas where the noise and the PU signal are assumed to be independent complex zero-mean Gaussian random signals. They have made the performance comparison for Rayleigh fading and AWGN channel. They have considered Generalized Likelihood Ratio (GLR) detectors by driving different cases. Case 1: when channel gains are unknown (GLRD1), Case 2: when channel gains and PU variance are unknown (GLRD2), and Case 3: when channel gains, PU and noise variances are unknown (blind GLR detector). It is shown that high SNR improves the performance of all spectrum detectors and in this general scenario the performance of ED is better than the performance of the blind GLR detector. It was also shown that increasing number of antennas increase the performance of the detectors which is due to the spatial diversity gain of the multiple antennas used at the SU, and also increasing number of samples do improves the performance but it is at the expense of longer sensing time. They have also shown that the optimal detector can outperform the GLR detectors provided that the optimal detector knows the noise variance accurately. Moreover, it was shown that the GLR detectors are more robust to the noise uncertainty than the optimal detector and ED, and in fact under noise variance mismatch, the optimal detector performs similar to the GLRD1. Also, the blind GLRD performs slightly better than the GLRD1. When the PU signal is not a Gaussian signal, the performance of the proposed detectors, i.e., blind detector and

GLRD1, are acceptable, and the blind detector performs like and even slightly better than the cyclo-stationary based detector. Generally the simulation results revealed that the proposed GLR detectors perform better than the ED and almost identical to the optimal detector under noise variance mismatch. In terms of computational complexity the proposed detectors complexity is M (number of antennas) times that of the ED.

In [30], the authors studied the performance of energy detector using multiple antennas at the CR receivers. They have considered two multiple antenna processing methods and analyzed their detection performance i.e. the achieved probability of detection for a pre-specified probability of false alarm and given signal-to-noise ratio. They have also derived closed form expressions for the probabilities of detection and false alarm for multiple antenna processing based energy detection under maximum ratio processing and selection processing. They have shown that using multiple antennas for spectrum sensing improves the probability of detection. Moreover, from the two multiple antennas processing techniques maximum ratio processing performs better than the selection processing. Generally, in the presence of unknown parameters, the GLRT is optimal in detecting the primary user, with a finite number of signal samples.

In [31], the authors investigated the PU signal detection performance in a CRN where the secondary user receiver is equipped with multiple antennas. Both the primary and secondary networks are based on OFDM system. They have showed that by using square law combining scheme in ED based multiple antennas spectrum sensing, high PU detection probability is achieved even at low SNR. It is also shown that increasing number of symbols increases the detection performance with higher sensing time. As the ratio of symbol period of the primary to the secondary subcarriers increase the probability of detection starts to decline and generally the performance of primary user signal detection of multiple antennas is much more better than single antenna ED based OFDM cognitive radio network.

In [32], the authors proposed an ED spectrum sensing which is a parallel, multi-resolution spectrum sensing techniques that uses multiple antennas for the CR users. They have managed to reduce the spectrum sensing time in a significant way with respect to the serial, fixed-resolution technique by first sensing the system bandwidth using a coarse resolution and then by performing fine resolution sensing over a small range of frequencies

which eliminates the necessity of sensing the entire system bandwidth at the maximum resolution. They have revealed that increasing number of antennas decreases the sensing time approximately by a factor of the number of antennas on the receiver (faster sensing time), whereas it is observed that number of antennas and the total number of blocks to be sensed at a fine resolution (α) are inversely related. i.e. for small number of antennas large α is best and vice-versa. For the number of points in FFT (N), there is a tread-off between system flexibility and sensing time and they have exposed that sensing time decreases almost linearly with N until a point at which it begins to increase that point is at N=4, which is the optimum number of points for the FFT. Generally, they have proposed a sensing method that reduces the sensing time and increases the average data throughput of the CRN.

In [33], the authors proposed multiple antenna based spectrum sensing using the generalized likelihood ratio test (GLRT) paradigm that make use of eigenvalues of the sample covariance matrix of the received signal vector. They have derived two algorithms that do not require prior knowledge of the primary user signals, or the channels from the primary users to the CR. By making different assumptions on the availability of the white noise power value at the CR receiver, they have derived two algorithms that are shown to outperform the conventional ED with or without noise power uncertainty. In comparison to the conventional ED, the proposed algorithms are computationally complex but it has shorter sensing time for a given probability of detection and false alarm.

In [34], the authors proposed a suboptimal multiple antennas detector under unknown noise which does not require obtaining the eigenvalues of the spatial correlation matrix. The performance of the proposed detector is better than many eigenvalue based detectors. However, its performance also degrades when the noise variance is not uniform across the antenna elements. They have also proposed another multiple antennas detector based on Generalized Likelihood Ratio (GLR) which performs better for two number of antenna elements.

In [35], the authors proposed spectrum detection techniques based on GLRT using multiple antennas for vehicular application that needs short sensing time. They have considered the scenario where multiple receiver antennas are used, and there is only one primary transmitter to be detected. They have made performance comparison between the

proposed GLRT method and others like multichannel ED, eigenvalue-based methods. The results show that for small number of samples the proposed GLRT performs better than others, which makes it suitable for vehicular applications.

In [36], the authors proposed an affordable cyclo-stationary based spectrum sensor using smart antenna which is less computationally complex than the conventional cyclo-stationary spectrum detector but it is still computationally complex than ED. It is assumed that the SUs have limited priori knowledge of the PUs' signal characteristics. They have used an adaptive beamforming algorithm for the proposed spectrum sensing, and it is called the adaptive cross-self-coherent-restoral (ACS) algorithm. They have proposed a universal spectrum sensor that uses ACS algorithm to extract the desired signal from the antenna array measurement and able to decide whether the spectrum is occupied by the PU or by the SU or vacant which is not possible for ED.

In [37], the authors proposed cyclo-stationary based spectrum detectors using multiple antennas which work well under spatially and temporally correlated noise environments in a licensed network where the primary user is equipped with single antenna. They have used cyclic spectral coherence function (SCF) and modified cyclic spectral density function (MSDF) as cyclo-stationary features in the signal detection process. Pre-combining detectors based on the blind maximum ratio combining (BMRC), called the BMRC-SCF and BMRC-MSDF detectors, are proposed. To estimate channel coefficients, the eigenvalue-based blind channel estimation exploiting the cyclic autocorrelation function is considered. For post-combining detectors, linear combiner is incorporated with the considered features to provide the Linear Combining-SCF and Linear Combining-MSDF detectors. All detectors have shown to be effective in both uncorrelated and correlated noise scenarios, however Pre-combining detectors perform better than post-combining ones since the channel knowledge is exploited. It is observed that detectors using the modified cyclic SDF can achieve comparable performance with less computational complexity compared to those using the cyclic SDF.

In [38], the authors studied the effect of correlated channel gains (antenna correlation) among the antenna elements of the receiving SU on the performance of ED based spectrum sensing using multiple antennas. They have derived the detection and false-alarm probabilities for EDs with correlated multiple antennas. They have shown that the

presence of antenna correlation decreases the performance of the spectrum detection by increasing the false-alarm probability, however they have also shown that even if the antenna correlation degrades the performance of the spectrum detection, it can be compensated by increasing the number of antennas of the SUs since increasing number of antennas decreases the false-alarm probability.

In [39], the authors investigated the performance of PU signal (OFDM) detection using OFDM based multiple antennas SU receiver. They have used square-law-combining (SLC) based ED to detect the presence of PU. The investigation revealed that the SLC based ED provides high detection probabilities even at low to moderate SNRs. Besides, it is observed that probability of detection increases as number of CR-OFDM symbols increase but in contrary it increases the spectrum sensing time.

In [40], the authors proposed spectrum detection technique that overcomes the noise uncertainty problem observed in ED while maintaining its advantages. The proposed spectrum detection method is based on eigenvalues of the covariance matrix of the received signal. It is the ratio of the maximum eigenvalue to the minimum eigenvalue that is used to detect the signal existence. Based on random matrix theories (RMT), they have quantized the ratio and find the threshold. In general, the method can be used for various sensing applications without knowledge of the signal, the channel and noise power using multiple antennas receiver.

In [41], the authors proposed a simple non-iterative GLRT sensing algorithm which is obtained based on a fast-fading signal model, offers the best performance in all systems under considerations, including slow-fading channels, fast-fading channels, MIMO systems, and OFDMA systems. This sensing algorithm significantly outperforms several state-of-the-art spectrum sensing methods in the presence of noise uncertainty for small number of signal samples (i.e., fast spectrum sensing). Its complexity is very small in relative to the computational complexity of the iterative GLRT sensing algorithms.

The use of multiple antennas in spectrum sensing for CRN brings many advantages such as shorter sensing time, robustness to noise uncertainty, and better detection performance (better probability of detection, reduced probability of false alarm) in relative to single antenna detection techniques.

Therefore, multiple antenna based spectrum sensing could be one possible spectrum sensing technique for CRWMN. Among the different spectrum detection techniques, GLRT detector is a promising candidate for CRWMN particularly the non-iterative-GLRT detector.

Generally, the use of multiple antennas for spectrum sensing in CRN brings many advantages such as shorter sensing time, robustness to noise uncertainty, and better detection performance (better probability of detection, reduced probability of false alarm) in relative to single antenna detection techniques.

2.5.3. Spectrum Sharing Using Multiple Antennas for CRNs

Spectrum sharing is an authoritative allocation of the opportunistically available spectrum to the SUs in such a way that the efficiency of the spectrum usage would be maximized and the interference produced to the PUs must be less than the predefined threshold level. In CRNs, spectrum could be shared mainly in five different fashions, namely: interweave, underlay, overlay, hybrid, and beamforming [42, 43, 44, and 45].

Interweave spectrum sharing is the first spectrum sharing model coined with CR. In the interweave spectrum sharing, the SU finds an idle spectrum hole and use opportunistically without the knowledge of the PU. When the PU appears the SU must evacuate the spectrum hole immediately and hop to another vacant spectrum hole. Therefore, forced termination is one of the drawback of interweave spectrum sharing.

Underlay spectrum sharing allows concurrent transmission of PU and SU on the same spectrum band by controlling the level of interference radiated to the primary receiver by the secondary transmitter to be lower than the noise floor of the PUs. Thus, the most important issue in underlay spectrum sharing model is to come up with an efficient interference management/mitigation system.

Overlay spectrum sharing allows the SU to coexist with the PU in the same band, but unlike underlay model it impose no power limit on the SU transmitter so as not to produce interference to the PU, rather the SU is assumed to have prior knowledge of the PU's transmissions (codebook). Overlay spectrum sharing can be further classified in to selfish and selfless. A SU that assumes to use part of their power to transmit its own data and the

remaining power to relay the message of the PU is called selfless. Whereas, a SU that uses all of its power to transmit only its own message by making use of the knowledge obtained from primary message so as to effectively null the interference to the secondary receiver is called selfish approach.

Hybrid Spectrum Sharing is commonly known as a marriage of interweaves and underlay spectrum sharing. That is, if the SU finds an idle spectrum it establish its communication in an interweaves mode, and when it cannot find spectrum hole it will establish the communication using underlay mode. Some literatures consider hybrid spectrum sharing as a marriage of overlay and underlay spectrum sharing models.

The last but not the least spectrum sharing techniques in CRN is beamforming. Some literatures classify beamforming to be part of underlay spectrum sharing since it concurrently transmit signal with PUs by controlling its power but it requires information about the location of the PUs and SU receiver. By using beamforming it is possible to let the SUs to coexist with PUs on the same spectrum band but unlike overlay spectrum sharing no secondary transmitters has access to primary users' codewords.

However, there are two major challenges in using beamforming for spectrum sharing, first it should maintain the interference generated by the CRN to the primary network below an acceptable threshold level (it could be by null placing), and second it should maximize the sum-rate of the CRN. To exploit efficiently the benefits of beamforming in CRNs, transceiver beamforming should be used because, if the primary network users are equipped with non-beamforming antenna then, the secondary receiver may experience interference coming from the primary transmitted unless the secondary receivers uses beamforming which degrades the network performance and spectrum usage efficiency. Moreover, so as to place nulls to all the interferers the SUs must be equipped with more number of antenna elements than the total number of interferers.

Different research works have been conducted to show the comparative performance advantages of these fundamental spectrum sharing techniques for single antenna and multiple antennas systems which could be summarized as follows.

In [44] the authors presented performance comparison between underlay and overlay spectrum sharing for MISO system. The study takes in to account the rate loss exhibited

due to primary message learning phase. The study shows that in most cases the overlay performs better than underlay spectrum sharing.

In [46] the authors presented a performance comparison for underlay and interweave spectrum sharing. The achievable SU ergodic capacity and the PU outage probability are used to compare the two detection techniques. The study shows that as the probability of spectrum usage of the PU becomes larger and larger the underlay starts to outperform the interweave spectrum sharing but in all other scenarios the interweave spectrum sharing shows clear SU capacity gain for all PU outage probability.

In [47], the performance of hybrid spectrum sharing is investigated. In this model the activity of PUs, the distance between SUs and primary transmitter and the distance between secondary transmitter and primary receiver are considered as factor affecting system capacity. The study shows that hybrid spectrum sharing has better performance in terms of achievable capacity over the other spectrum sharing models.

In [48] the authors proposed a hybrid spectrum sharing approach for CRNs. However, this work is different from the other similar work in that if the primary network satisfies the required quality of service (QoS), an underlay approach can be applied for the secondary network; Otherwise, the secondary network must help primary network obtain the QoS and hence it must operate on overlay mode not in interweave mode.

In [49] the authors proposed a hybrid spectrum sharing scheme based on power control. They combined underlay and interweaves, and modeled the behavior of the primary network using a discrete-state Markov process in order to determine the fraction of time that the SUs operates. The proposed hybrid spectrum sharing which uses optimal power allocation scheme maximized the capacity of the CRN in comparison to CRNs that uses interweaves and underlay spectrum sharing systems.

In [50], in contrary to the conventional cooperative cognitive radio networks (CCRN) that operates only in temporal domain, the authors considered CCRNs which operates both in the temporal and spatial domain. In the conventional CCRNs the PU gives portion of the channel access time to the SUs to transmit secondary data and in exchange to this the SUs' cooperate in relaying the PU data. In this spectrum sharing strategy (cooperative/overlay) both the PU and SUs will be restricted to the given spectrum access time and this scenario will limit the performance of both PUs and SUs (i.e. it introduces higher overhead to the

PU's communication and in the secondary spectrum access time there will be multiple secondary links competing for spectrum access which will make this access time very crowded). To alleviate the limitations of this chronic assumption of CCRNs, the authors proposed the use of Multiple Input Multiple Output (MIMO) techniques in CCRNs which uses zero forcing beamforming (ZFBBF) and it requires instantaneous channel coefficient matrix. This novel approach (MIMO-CCRN) enables the SUs to utilize the capability provided by the MIMO to cooperatively relay the traffic for the PUs while concurrently accessing the same channel to transmit their own traffic. They have shown using analysis and Simulation that both the primary and the secondary network achieve higher utility in MIMO-CCRN than in the conventional schemes.

In [51], the authors proposed an overlay spectrum sharing scheme to improve the performance of both the PUs and SUs networks. They have considered a CRN which consists of a primary transmitter-primary receiver pair, and a secondary base station-secondary receiver pair. The PU leases half of its time slots to the SU in exchange for the SU cooperatively relaying the PU's data using the amplify and forward scheme. All except the secondary base station are equipped with single antenna; whereas the secondary base station is equipped with multiple antennas. The authors proposed two time slots transmission scheme to enable spectrum sharing between primary and secondary users. In the first time slot, the primary transmitter (PT) transmits its signal to the primary receiver (PR), which is also received by the secondary (ST) and the secondary receiver (SR). In the second time slot, the ST amplifies and forwards the PT's signal, and at the same time, transmits its own signal while the PT remains silent. Then the PR applies maximum ratio combining to retrieve the transmitted signal by PT. In this paper the authors provided analytical expression and simulation to show that cooperative overlay spectrum sharing performs better than non-cooperative underlay spectrum sharing in terms of BER and rate performance. Moreover, increasing the number of antenna at the secondary user base station has also increased the rate performance of both the primary and secondary networks compared with the non-cooperative underlay spectrum sharing.

In [53], the authors proposed the use of beamforming technique to manage the spectrum sharing among the secondary and primary users without spectrum sensing. They have proposed the use of adaptive beamforming technique both at the secondary transmitter

and receiver. It is used at the transmitter side to make null to the direction of primary receiver and to produces narrow beam to the direction of the intended secondary receiver, whereas, it is used at the secondary receiver to cancel interference that comes from the primary transmitters. It is shown that a CR that uses adaptive beamforming shows better performance than the non-beamforming CR system. The limitation of the proposed technique is that it cannot operate in multi-bands, because it performs channel estimation only for one channel at a time. The authors did nothing to compare the performance of the proposed scheme with other variant of spectrum sharing models.

In [54], the authors investigated joint transceiver beamformer design for the cognitive radio MIMO system where perfect, partial and no information cases are considered. They have presented a spectrum sharing MIMO cognitive radio network, in which multiple PUs coexist with multiple SUs. The joint transceiver beamformer is designed to minimize the transmit power of the SU base station (SBS) while simultaneously targeting lower bounds on the received signal-to-interference- plus-noise ratio (SINR) for the SUs and imposing upper limits on the interference temperature to the PUs. Simulation results show that the proposed joint transceiver design has the ability to minimize the total transmit power while efficiently controlling the interference temperatures to the PUs.

In [55], the authors investigated the spectral efficiency gain of an uplink cognitive a radio MIMO system which combines both orthogonal (interweave) and non-orthogonal (underlay) CR spectrum sharing transmission modes for cellular network with common receiver. The SU is allowed to share the spectrum with the PU using a specific precoding scheme to communicate with a common receiver in an uplink MIMO communication. They have studied the SU achievable rate which increases significantly when the SU exploits the unused eigenmodes of the PU and share the used ones by respecting both total power and interference temperature constraints.

In [56], the authors considered spectrum sharing in massive MIMO systems where, a multiuser MIMO primary network with N_P -antenna PU base station (PBS) and K single-antenna PUs, and a MISO secondary network with N_S -antenna SBS and a single-antenna SU. They have proposed and analyzed the performance of underlay spectrum sharing in massive MIMO cognitive network. In this paper the authors shows that by using massive antenna arrays at the PBS and the SBS, it is possible to cut the transmit powers of PBS and

SBS proportionally to $1/N_P$ and $1/N_S$, respectively, while maintaining a given QoS. They have shown that the secondary network's performance is equivalent to a SISO AWGN channel with no interference and transmit power E_s . They have shown that increasing number of antenna on SBS increases the achievable rate however; increasing number of antennas of PBS has negligible impact on the average achievable rate.

In [57], the authors study the optimal secondary link beamforming pattern that balances between the SU's throughput and the interference it causes to PUs in such a way that it maximizes the throughput of the SU, while keeping the interference temperature at the primary receivers below a certain threshold.

In [58], the authors considered an underlay CRN with the primary transmitter, primary receiver, and secondary receiver equipped with single antenna and the secondary transmitter equipped with N antennas. They have proposed an antenna selection scheme that ensures the instantaneous interference caused by the ST to the PR is below an acceptable level while maximizing the instantaneous SINR at the SR. This is achieved by choosing the 'best' ST antenna, in terms of achieving the highest SINR at the SR that satisfies the instantaneous interference power constraint at the PR. If none of the antennas satisfies the interference power constraint at PR then it holds the transmission for a channel coherence time and check the channel condition again. They have showed that the proposed antenna selection scheme outperforms the existing antenna selection schemes in terms of ergodic capacity.

In [59], the author presented the capacity of spectrum sharing (beamforming) for adhoc network with multiple antennas. The system considered assumes that each secondary transmitter has N antennas, while each secondary receiver has M antennas. Each secondary transmitter is assumed to send a single data stream through its multiple antennas. Multiple antennas at each secondary transmitter are used for partial nulling, where some spatial transmit degrees of freedom (STDOF) are used for nulling its interference towards the primary receivers, and the rest of the STDOF are used for beamforming towards its corresponding secondary receiver. Similarly, multiple antennas at each secondary receiver are used for partial interference cancelation, where some spatial receive degrees of freedom (SRDOF) are used for canceling the interference from both the primary and secondary transmitters, and the rest SRDOF are used to increase the strength of the signal

of interest. In contrary to the SIMO system used in non-cognitive network, it is shown that employing multiple antennas only at the secondary receivers does not yield any gain, rather to exploit the multiple antenna gain, either the multiple antennas should be employed at the secondary transmitters only, or at both the secondary transmitters and receivers. Moreover, they have shown that with multiple antennas only at the secondary transmitters, the intensity of the secondary network scales sublinearly with the number of transmit antennas. The sublinear scaling of the intensity cannot be improved by employing multiple antennas at both the secondary transmitters and receivers; however, the sublinear exponent is better for path-loss exponent greater than four.

In [60], the authors studied opportunistic spectrum sharing in cognitive MIMO network in order to maximize the sum-rate throughput of the cognitive system and minimize the interference to the primary user. In the proposed approach, cognitive users whose channels are nearly orthogonal to the PU channel are pre-selected so as to minimize the interference to the PU. Then, M best cognitive users, whose channels are mutually near orthogonal to each other, are scheduled from the preselected cognitive users. A lower bound of the proposed cognitive system capacity is derived. It is then shown that opportunistic spectrum sharing approach can be extended to the MIMO case, where a receive antenna selection is utilized in order to further reduce the computational and feedback complexity. Simulation results show that our proposed approach is able to achieve a high sum-rate throughput, with affordable complexity, when considering either single or multiple antennas at the cognitive mobile terminals.

In [61], the authors considered an interweave spectrum sharing for CRWMN in which the nodes are equipped with an omni-directional radio antenna and use one common control channel. Moreover, they have assumed that all the radios have a channel switching delay equal to zero and their interference range is equal to their communication range. They have managed to improve the scalability of the network, reduce the amount of control overhead, and minimize the overall scheduling time.

CRWMN is proposed to bring additional advantages to the conventional WMNs by making use of the opportunistically available spectrum. As it is explored and understood from the above literatures Hybrid (Interweaves and Underlay) spectrum sharing brings better

capacity gain to the cognitive radio network. Therefore, we propose hybrid spectrum sharing for CRWMNs.

The study on the different spectrum sharing revealed that hybrid spectrum sharing has superior performance with over the other spectrum sharing techniques (interweave, underlay, and overlay) mainly in terms of capacity gain, bit error rate, and spectrum efficiency. However, a comprehensive performance comparison among these spectrum sharing is not available, for example comparing overlay with underlay, interweave with overlay, a hybrid (which combine interweave with underlay, and overlay with underlay) with others, and beamforming with the others.

For CRWMN, depending on the available spectrum the mesh router will make a prioritization depending on the location of the SU, the QoS demanded by the SU, the requested service types by the SU, the number of antennas used on the SU terminal and other parameters could be used in the sense of maximizing the overall spectrum utilization efficiency in a well-coordinated fashion.

The most common assumption of hybrid spectrum sharing is the switching of the SU from interweaves to underlay spectrum sharing mode while the PU appears. What would be the network performance if the SU who is operating in the interweave mode remains in interweave by hopping to another spectrum hole than switching to the underlay mode without compromising the interest of SU unless it loss the option of operating in the interweave mode? For example, a SU which is located in shorter distance with the other communicating end and may be equipped with multiple antenna may be placed to operate in the underlay mode, moreover an SU which is located far from the communicating end but has small bandwidth and reasonable QoS demand and might be forced to switch to the underlay mode than an SU whose bandwidth and QoS demand is higher.

2.5.4. MAC Protocols for Multi-Hop CRNs Using Multiple Antenna

Most of the protocols proposed for multi-hop CRNs do not have a central entity that controls the network operation; such types of MAC protocols are called distributed MAC protocol. A distributed MAC protocols are scalable, flexible, and dynamic than the centralized MAC protocols. However, the distributed spectrum sensing, sharing and access process of CRNs necessitate increased cooperation with the neighboring nodes. Therefore,

maintaining time synchronization and obtaining spectrum information from surrounding nodes with minimum overhead are some of the factors that must be considered in the designing of MAC protocol for multi-hop CRN.

In general, multi-channel networks and multi-hop CRNs share a plenty of common features. In both networks, each user has a set of channels available for communication. When two users want to communicate, they negotiate possibly via a common control channel (CCC). Furthermore, the CCC and MCHTPs, which are related to a multi-channel network, are common to a multi-hop CRN. Therefore, many multi-hop CRN MAC protocol proposals in the literature are inspired by the design of MAC protocols for multi-channel networks. There are two major differences between these two networking environments. First, the number of channels available at each node is fixed in a multi-channel network, while it is variable in a multi-hop CRN. Hence, it is probable that a SU in a multi-hop CRN has no available channels owing to the complete occupancy of the spectrum by the PUs. Second, the channels in a multi-channel network generally have equal bandwidths and transmission ranges; however, the environment is heterogeneous in a multi-hop CRN. In this respect, a multi-hop CRN may be considered as an opportunistic multi-hop and multi-channel network.

Some of the most common and recent types of MAC protocols proposed for multi-hop CRNs in general and directional MAC protocols proposed for multi-hop CRN are summarized.

In [62], the authors proposed the first cognitive radio MAC protocol for non-infrastructure CRNs. The proposed MAC protocol is called dynamic open spectrum sharing (DOSS) MAC protocol. The proposed protocol adaptively selects and combines available vacant spectrum bands in arbitrary fashion. Three radios per node are assumed for control, data, and busy tone signaling. The strength of this MAC protocol are managing hidden node and exposed terminal problems, it offers real-time dynamic spectrum allocation, and it provides high spectrum utilization. The drawbacks are use of separate and out-of-band spectrum for issuing the busy tones and for exchanging control messages which reduces the spectrum utilization efficiency; it resulted low radio interface utilization efficiency; higher system

complexity (costly); and the task of spectrum sensing with respect to which radio interfaces is not justified.

In [63], the authors proposed a distributed channel assignment (DCA) MAC protocol for multi-hop CR emergency network. It basically adopted the IEEE 802.11 CSMA/CA protocol by adding a distributed channel assignment algorithm. It uses multiple transceivers, a dedicated out-of-band common control channel for signaling, and utilizes spectrum pooling technique. Each node maintains spectrum information using two data structures called the current usage list (CUL), and the free channel list (FCL). In the data transfer process the FCL is matched at both the sender and receiver nodes using the RTS-CTS handshake using the dedicated CCC. As limitations the use of CCC could be considered, and it lacks specific support for spectrum sensing or PU related adaptation that is required for CR networks.

In [65], the authors proposed a hardware constrained MAC (HC-MAC) protocol for multi-hop CRNs. The proposed MAC protocol assumes single radio interface and a dedicated CCC. The constraints imposed on the hardware of the node emanates from the tradeoff between spectrum sensing time and sensing outcome accuracy, and from the tradeoff between number of scanned bands and maximum number of subscribers based on OFDM system with the time required to scan large number of spectrum bands. To overcome this limitation they have proposed a stopping rule to decide how many channels should be scanned and for how long using low computational algorithm for large number of channels. The proposed protocol has three phases: the contention, the sensing, and the transmission phases. In every phase there is an RTS/CTS frame exchange. Cost effectiveness could be considered as strength of this work. However, use of CCC, the efficiency of the messaging mechanism, the appropriateness of the contention phase before the spectrum sensing phase could be taken as limitations of the work. In the operation of the protocol the contention phase comes before the spectrum sensing phase but if no user win the contention phase, the efficiency of the protocol in identifying and using the vacant channel might be affected.

In [66], the authors proposed a distributed multichannel MAC protocol for multi-hop CRNs. They have proposed an energy efficient MAC protocol which uses a dedicated CCC, and it

uses two radio interfaces per node due to this spectrum sensing and communication can be performed concurrently. It assumes low power software defined radio (SDR) radio frontend. The limitations of this work are it does not take in to account the spectrum sensing time, the drawback of a dedicated CCC exist, and cost of the system.

In [67], the authors proposed a distributed MAC protocol with no dedicated communication or control channel for multi-hop CRNs assuming transmitter-receiver synchronization. SUs are not forced to monitor/scan all the spectrum bands when they have no data to transmit by taking the hardware and energy constraints. They have proposed an optimal strategy using partially observable Markov decision process (POMDP) assuming a cross-layer approach design by integrating the spectrum access (from physical layer) and spectrum sensing (from the MAC layer) mechanisms, and a suboptimal distributed MAC protocol using greedy algorithm. They have integrated sensing error in the design of MAC protocol. However, the complexity of the system grows with the number of channels, and it assumes that PU's usage statistics remain unchanged simplifies the protocol design.

In [68], the authors proposed a cognitive MAC protocol using statistical channel allocation strategy (SCA-MAC) for multi-hop wireless networks. It is a CSMA/CA empowered protocol which uses the statistics of spectrum usage to make the decision of opportunistic channel access by the SUs. It assumes CCC for signaling and channel bonding for data communication. They have used operating range and channel aggregation as parameters. They have shown that due to statistical spectrum usage the throughput of the proposed MAC protocol outperforms the throughput of the generic MAC protocol.

In [69], the authors proposed a random access MAC protocols for CRNs using a two-level opportunistic spectrum access (OSA) strategy. They have considered no CCC and assumed single transmission channel for both PUs and SUs. They have proposed a two-level OSA strategy where the first level performs the spectrum sensing which is arranged to operate at the beginning of the MAC frame before data transmission then the second level which is the conventional slotted ALOHA or the CSMA MAC protocol is operated. When it operates in

slotted ALOHA mode it is called CR-ALOHA, and when it operates in CSMA mode it is called CR-CSMA.

In [70], the authors proposed a new MAC protocol based on asynchronous spectrum sensing and RTS/CTS mechanism called CR-based carrier sense multiple accesses with collision avoidance (CR-CSMA/CA). They have compared the performance of slotted CR-ALOHA, and CR-CSMA MAC protocol with the performance of CR-CSMA/CA MAC which is a random access protocol. The proposed CR-CSMA/CA MAC protocol illustrated better performance in terms of throughput and average packet delay.

In [72], the authors presented a hybrid MRMC MAC protocol for multi-hop CRNs. They have proposed two radio interfaces, the first one is used for listening on the channel for control messages, and the second interface is used for data traffic. This protocol does not use a dedicated CCC, and the dedicated listening also addresses the multi-channel hidden terminal problem. However, this approach does not guarantee protection to the PUs, as their arrivals are notified only in specific time slots to the neighbors. In addition, the channel may not be utilized efficiently, as it can be used only once in a given cycle.

In [73], the authors proposed a synchronized and time slotted multi-channel cognitive MAC (C-MAC) protocol. C-MAC includes two key concepts: the rendezvous channel (RC), and the backup channel (BC). The RC is selected as the channel that can be used for the longest time throughout the network, and it is assumed for node coordination, PU detection, as well as multi-channel resource reservation. The BC, determined by out-of-band measurements, is used to immediately provide a choice of alternate spectrum bands in case of the appearance of a PU. In C-MAC, each spectrum band has recurring super frames composed of a beacon period (BP) and a data transfer period (DTP). The RC is used on a network-wide communication, neighbor discovery, and sharing of load information for each band. Moreover, this is also used to exchange the schedules for the BP, so that the beacons are not simultaneously sent over all the spectrum bands. Upon power-up, each CR user scans all the available spectrum bands to determine the vacant spectrum resource. In these bands, if it hears a beacon, then it may choose to join that specific band and also set the global RC to the band specified in the beacon. The limitations are low scalability, the spectrum

switching is not instantaneous, and the information must first be disseminated to the other CR users in the beacon period of the RC.

In [71], the authors proposed a hybrid MAC protocol for multi-hop cognitive radio networks called opportunistic cognitive MAC. The opportunistic cognitive MAC uses two transceivers, one for a dedicated CCC, and the other that can be dynamically tuned to any chosen spectrum. The time is slotted for the data transfer over the licensed channels, while the CCC operation is partly slotted, followed by a random access negotiation phase. Thus, it is a hybrid protocol. The CCC has two phases the reporting and negotiation. The reporting phase is composed of min-slots which is equal to the number of sensed channels. So at the beginning of every time slot the SU sends beacon over the common control channel if it senses the channel idle. During the negotiation phase the SUs negotiate based on the IEEE 802.11 and p-persistent carrier sense multiple access mechanism. Synchronization, use of multiple transceivers, and overhead of the MAC protocol could be taken as limitations for the proposed MAC protocol.

The literature review made on the impact of multiple antenna on spectrum sensing and spectrum sensing revealed that multiple antenna have significant contribution in terms of better probability of detection, reducing the spectrum sensing time, reducing the bit error rate (BER), and improve the spectrum utilization like in multi-user MIMO systems. From the literature review on MAC protocols for multi-hop cognitive radio network, different protocols have been proposed by different authors but none of these protocols assume multiple antenna systems. For these reasons MAC protocol design using multiple antenna system for CRNs in general and to the CRWMNs in particular is an interesting research area.

MULTIPLE ANTENNAS FOR COGNITIVE RADIO WIRELESS MESH NETWORK

3.1. Introduction

CRWMN is a good solution to the problem of network capacity, network flexibility, and network reliability which are the fundamental problems of the current wireless network. The integration of multiple antenna systems to the CRWMNs would further improve the overall network performance of the CRWMN by reducing the spectrum sensing time, by increasing the primary user detection probability, by improving the spectrum utilization efficiency, by significantly increasing the network capacity, by reducing the amount of radiated power, and by decreasing the level of interference to the direction of unintended users.

Our main interest in this dissertation work is to propose MAC protocols for multiple antenna based cognitive radio wireless mesh network. The impact of multiple antenna system on the performance of cognitive radio wireless mesh network has been overlooked. It is therefore, a gap for researchers like us who would like to work on part of a cognitive radio wireless mesh network that makes use of multiple antenna at the physical layer.

In this chapter, for the fulfillment of our finding, multiple antenna technologies from the point of view of capacity, interference, and spectrum sensing are evaluated both analytically and by using simulations.

3.2. Multiple Antenna Technology

The multiple antennas have three fundamental benefits which are array gain, diversity gain and multiplexing gain. Multiple small antenna elements can be arranged in space and interconnected to produce a high directional radiation than the individual antenna element does which is called array gain. The elements of the array antenna may have any number of different antenna apertures/elements (i.e. dipoles, loops, microstrips and others) [75], [80]. Spatial diversity and multiplexing gain are obtained by taking advantage of the spatial signature and sending a replica of the same message by all the antenna elements (spatial diversity gain), and by sending different messages concurrently (spatial multiplexing gain). Generally, spatial multiplexing brings capacity advantage and spatial diversity brings reliability advantage by reducing the bit error rate (BER) of the wireless system [83]-[88].

3.2.1. Array Gain

Array antenna technology is a more practical way of producing highly directive radiation pattern than producing the required radiation by using single and large antenna. Besides, it has the following advantages: narrow beams, low side lobes, steerable beams, tracking multiple targets, it can be conformed to surface, it scans/steers electronically and the like. As given in [78], a reference antenna which is located at the origin radiates an electromagnetic field with far field components that are proportional to

$$F_0 = I_0 \frac{e^{-jkr}}{r} f(\theta, \phi) \quad \dots (3.1)$$

Where: I_0 is complex amplitude, $f(\theta, \phi)$ is the radiation pattern, r is the observation point distance from the origin, and k is the propagation constant in free space (wave number) and it is equal to $2\pi/\lambda$.

Now consider an N number of identical radiating elements placed in parallel to each other within a volume of radius a , which is much smaller than the distance r ($a/r \ll 1$). The far

field components of the i^{th} antenna element, whose position vector with respect to the origin \vec{r}_i is proportional to

$$F_i = I_i \frac{e^{-jkR_i}}{R_i} f(\theta_i, \phi_i) \quad \dots (3.2)$$

Where $R_i = |\vec{r} - \vec{r}_i| = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}$.

The overall field of the array is determined by the vector addition of the fields radiated by the individual radiating elements. However, in order to render a very directive pattern, it is essential that the fields from the elements of the array interfere constructively in the required directions and interfere destructively in the remaining space. The far field due to all of the antenna elements by using superposition principle becomes

$$S(\theta, \phi) = \sum_{i=1}^N F_i = I_0 \frac{e^{-jkr}}{r} f(\theta, \phi) \sum_{i=1}^N \frac{I_i}{I_0} e^{j\psi_i(\theta, \phi)} = F_0 AF(\theta, \phi) \quad \dots (3.3)$$

where $AF(\theta, \phi) = \sum_{i=1}^N \frac{I_i}{I_0} e^{j\psi_i(\theta, \phi)}$ is the array factor (pattern),

$\psi_i(\theta, \phi) = 2\pi d_i / \lambda$, Where d_i is the projection of \vec{r}_i on \vec{r} , and λ is wave length.

Therefore, the array radiation field is equal to the product of the field of an array element (usually located at the origin), and the array factor. The above expression shows that the characteristic of array of identical elements is mainly controlled by the array factor which is a function of the number of elements, the geometrical arrangement, their relative phase, and spacing between elements. Thus, varying any of these parameters would affect the characteristics of the array factor and of the total radiation characteristics of the array [75], [78].

If we consider uniform linear antenna (ULA) with N number of elements and uniform distance of separation d with phase $\psi_i(\theta, \phi) = (i-1)kd \cos \theta$, and the exciting current $I_i = I_0 e^{-j\beta_i}$ at the i^{th} element the array factor expression could be rewrite as

$$AF(\theta) = \sum_{i=1}^N e^{j(i-1)(kd \cos \theta - \beta)} \quad \dots (3.4)$$

Using Taylor Series and trigonometric identity, we can have a closed form expression for the array factor expression which is given by

$$AF(\theta) = e^{j(N-1)\frac{\xi}{2}} \frac{\sin(N\xi/2)}{\sin(\xi/2)} \quad \dots (3.5)$$

Where $\xi = kd \cos \theta - \beta$ and β is the current phase reference.

The array factor is periodical for $\xi = 0, \pm 2\pi, \pm 4\pi, \pm 8\pi, \dots$. Therefore, the array pattern maxima (main beam peaks) occur periodically at these values of ξ . For example, the maximum that corresponds to $\xi = 0$ be therefore designated as the peak of the main beam, this peak occurs at angle $\theta_0 = \cos^{-1}(\frac{\beta}{kd})$. This angle is used to determine the direction of the main beam which dependence on the constant phase displacement between adjacent elements. Thus, if the phase difference between adjacent elements changes, then the beam will move to a new position [74]-[80].

Below the effect of varying array parameters on the radiation pattern of ULA which holds true for other variants of array antenna is presented below. The number of array element variation on the radiation patter is shown in Fig. 3.1. The simulation was carried out for $\beta = 0^0$ and $d = 0.5\lambda$. The simulation is presented both in rectangular and polar plot, where the x-axis and the y-axis represent the direction (in degree) and the normalized values of the array factor respectively. In the simulation increasing the number of array element results narrower beam, increased number of side lobes and nulls of the radiation pattern proportionally.

The effect of varying distance of separation on the behavior of radiation pattern is shown below in Fig. 3.2. In the simulation increasing distance of separation results in a narrower beam but it is obtained at the cost of large array antenna size. Therefore, the designer need to compromise between number of elements and distance of separation to obtain a main

beam with a reasonable beam width and also to protect the appearance of grating lobes at all (for this simulation the grating lobes appeared for $d=0.5\lambda$). The simulation was carried out for $\beta = 0^0$ and $d = 0.5\lambda$.

Unlike the other parameters of array factor which are used to control the radiation pattern, variation of excitation phase has no effect on the beam width (an exception may be when changing from broadside to end-fire) rather it controls the direction of the main beam. This is shown in Fig. 3.3.

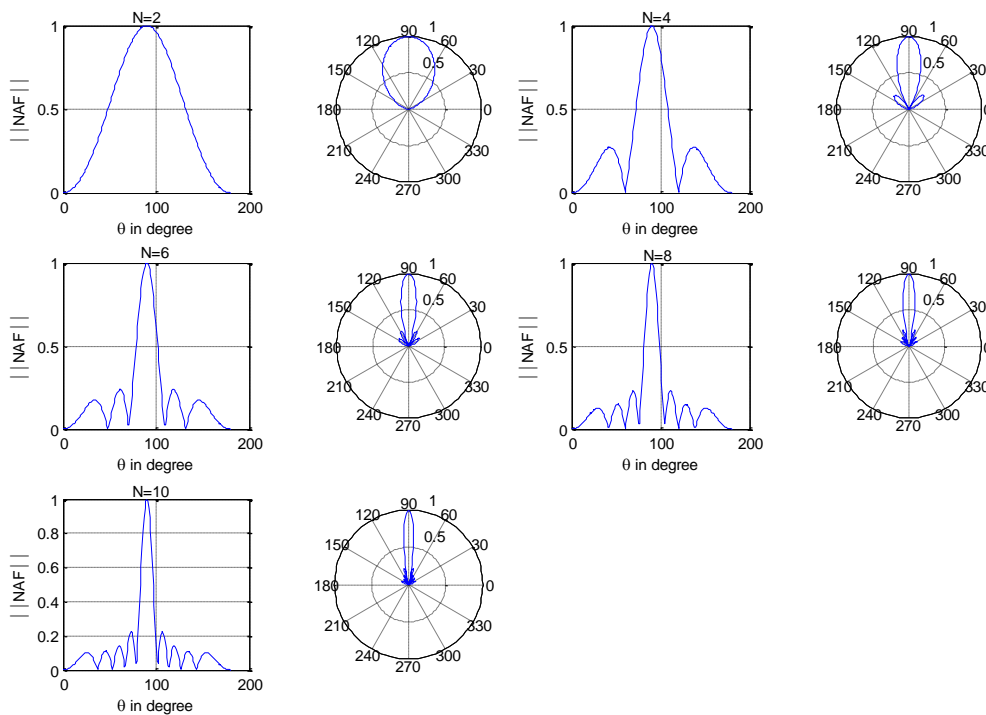


Fig. 3.1 Simulation for array factor (both in rectangular and polar plot) to illustrate the effect of varying number of array elements for $\beta = 0^0$ and $d = 0.5\lambda$.

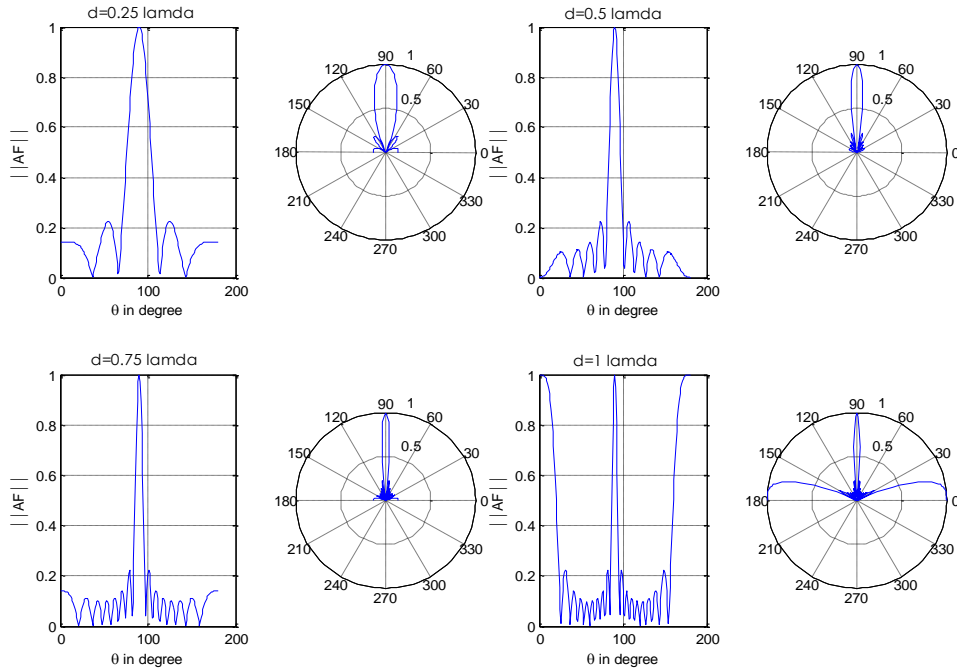


Fig. 3. 2 Simulation for array factor (both in rectangular and polar plot) to illustrate the effect of varying distance of separation for $\beta = 0^0$ and $n=10$.

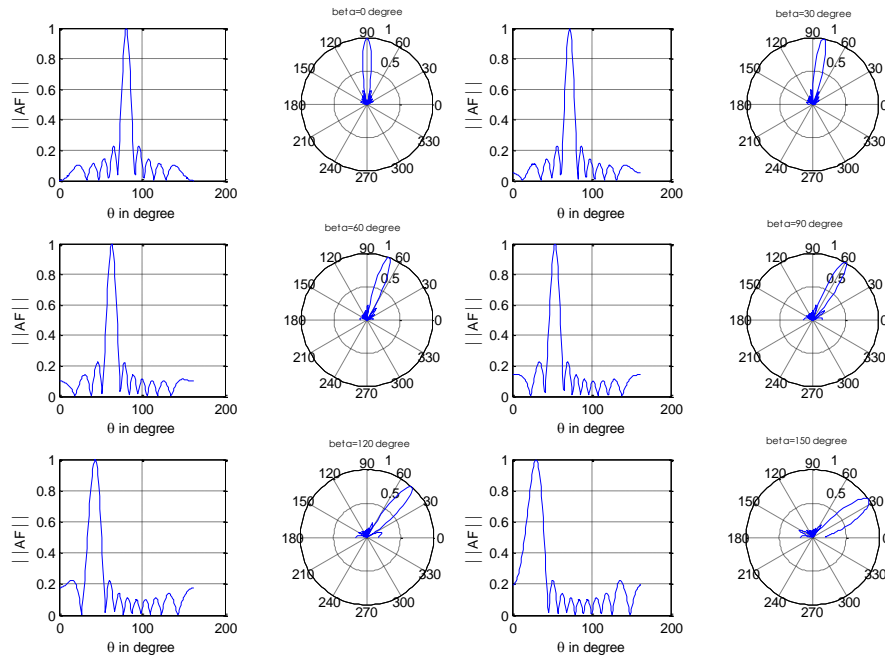


Fig. 3. 3 Simulation for array factor (both in rectangular and polar plot) to illustrate the effect of varying excitation phase between adjacent elements (for $0^0, 30^0, 60^0, 90^0, 120^0, 150^0$), $d = 0.5\lambda$ and $n=10$.

3.2.2. Spatial Multiplexing and Spatial Diversity Gains

A multiple antenna technology which use multiple antennas at both transmitter (TX) and receiver (RX) known as Multiple-Input Multiple-Output (MIMO) systems, are a promising way to enhance data rates of the wireless systems without requiring additional spectrum. The multiple antennas in MIMO systems can be used to achieve diversity and/or multiplexing gains by taking multipath fading as an opportunity and by transmitting or receiving multiple data streams respectively. Basically, unlike time and frequency diversity, space diversity does not induce much delay and any loss in bandwidth efficiency, and it is this property that makes spatial diversity attractive for high data rate wireless communication. In spatial multiplexing also there is a linear increase in channel capacity with the minimum number of transmit (N) and receive (M) antennas i.e. the spectral efficiency grows linearly with number of parallel N and M antennas at a fixed power [81] - [83].

3.3. Multiple-Input Multiple-Output (MIMO) Systems

Based on diversity, MIMO systems can be grouped into two groups [84]. The first group requires the channel state information (CSI) at the receiver, but not at the transmitter or example space-time (ST) codes. The second group requires CSI both at the transmitter and the receiver ends. This approach is known as beamforming. In beamforming, the array pattern (beam) at the transmitter and the receiver can be formed in such a way that the average SNR is increased. In MIMO systems, beamforming separates the MIMO channel into parallel independent subchannels. When the best subchannel is used, the technique is called single beamforming; and if more than one subchannel is used, the technique is called multiple beamforming [83]-[88].

The output of a general MIMO channel is modeled by

$$Y = HX + n \quad \dots (3.6)$$

Where X is the transmitted signal, H channel transition matrix and n is additive Gaussian noise.

The capacity of MIMO channel is an extension of SISO (single input single output) channel capacity to a matrix form which is given by

$$C = \max_{p(x)} I(X, Y) \quad \dots (3.7)$$

The maximization of $I(X, Y)$ for full channel state information (CSI) only at the receiver with uniform power allocation yields the capacity expression

$$C = w \log_2 \det \left(I_m + \frac{P}{N\delta^2} Q \right) \quad \dots (3.8) \quad \square$$

Where $Q=HH^*$, for $M<N$ and H^*H for $M \geq N$, P it the total transmitted power, w is the bandwidth.

Using singular value decomposition (SVD) we can write H as

$$H = UDV^* \quad \dots (3.9)$$

Where D is $M \times N$ diagonal matrix whose entries are the non-negative square roots of the eigenvalues (λ) of matrix HH^* . U and V are $M \times M$ and $N \times N$ unitary matrices respectively. The number of non-zero eigenvalues of a matrix HH^* is equal to the rank(r) of a matrix H [79]. For $M \times N$ matrix H , the rank is at most equals to $m = \min(M, N)$. This implies that there are at most m non-zero eigenvalues. The capacity expression then reduces to

$$C = w \sum_{i=1}^r \log_2 \left(1 + \frac{P_{ri}}{\delta^2} \right) = w \log_2 \prod_{i=1}^r \left(1 + \frac{\lambda_i P}{n_T \delta^2} \right) \quad \dots (3.10)$$

Where $p_{ri} = \frac{\lambda_i P}{n_T}$.

Whereas SISO's channel capacity is given by

$$C = w \log \left(1 + \frac{P}{\delta^2} |h|^2 \right) \quad \dots (3.11)$$

Where $|h|^2$ is the path gain.

Therefore, MIMO's channel capacity can be interpreted as the sum of the channel capacities of the sub-channels with channel path gain λ_i , $i = 1, 2, \dots, r$. i.e. we can have a maximum of $\min(M, N)$ independent paths through which independent information can be sent [78].

If the channel coefficients are random variables, the above channel capacity expressions give instantaneous capacity values and the ergodic channel capacity becomes

$$C = E[w \log_2 \det(I_m + \frac{P}{N\delta^2} Q)] \quad \dots (3.12)$$

Where E is an expectation operator.

The simulations shown below in fig. 3.4, fig. 3.5, and fig. 3.6 show the capacity gain for transmitter diversity (MISO), receiver diversity (SIMO), and MIMO system for different SNR values.

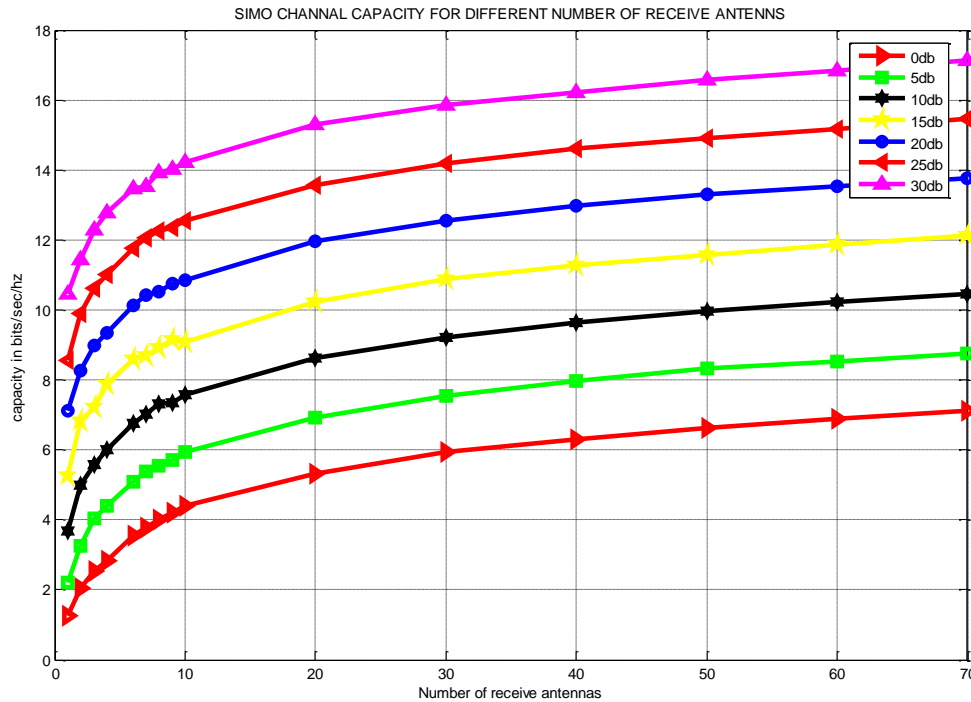


Fig. 3. 4 Capacity of receiver diversity for different SNR values.

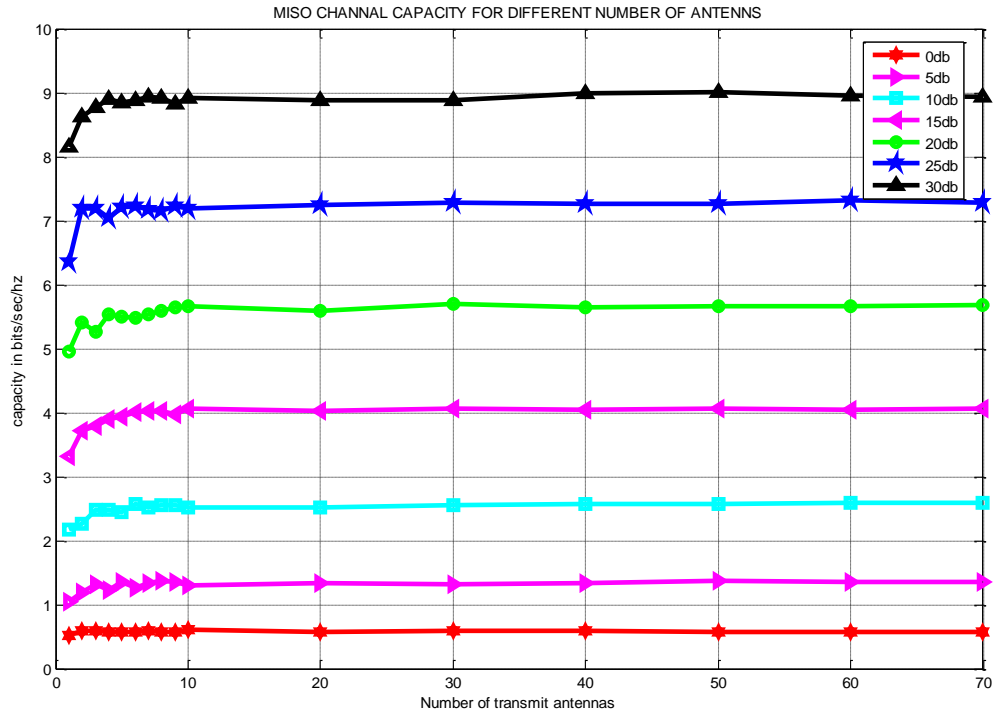


Fig. 3. 5 Capacity of transmitter diversity for different SNR values.

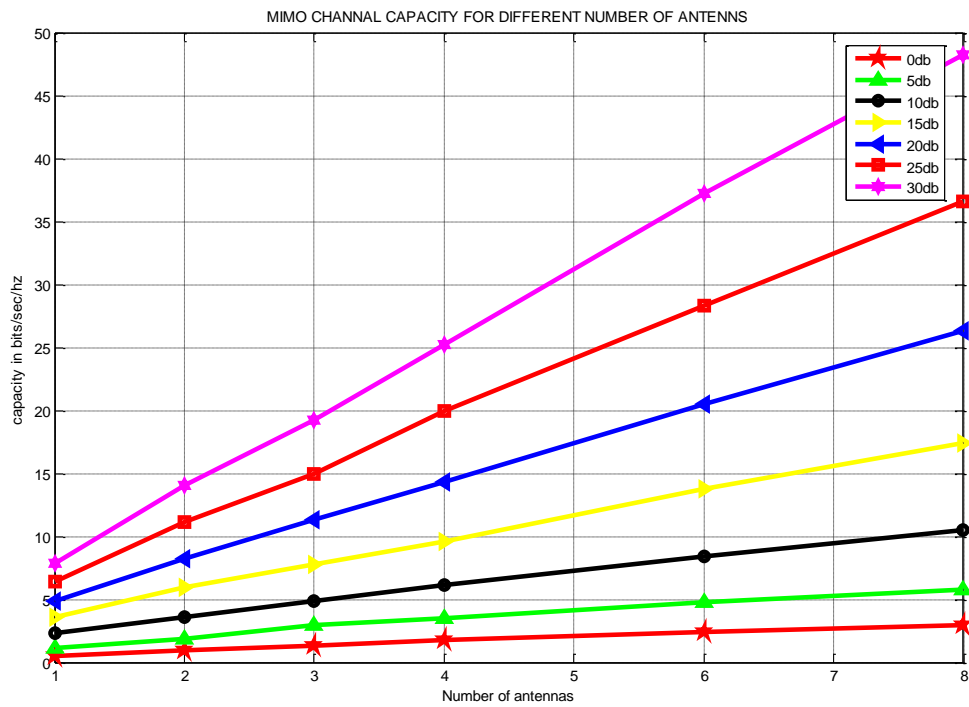


Fig. 3. 6 Capacity of MIMO channel for different SNR values.

3.4. Multi-User MIMO System (MU-MIMO)

The conventional MIMO systems which involve a communication link between two users equipped with multiple antennas is known as single user MIMO (SU-MIMO). SU-MIMO is advanced to a new concept to fully realize the benefits of MIMO systems which is called multi-users MIMO, in some literatures it is considered as an extension of Space-Division Multiple Access (SDMA). Unlike SU-MIMO, in multi-user MIMO (MU-MIMO) the access point communicates with multiple users simultaneously on a single conventional channel where the different users are identified by their spatial signature, which maximizes the spectral efficiency. MU-MIMO is all about equipping the access point with more number of antennas which brings more degrees of freedom and hence, more users can be scheduled on the same time-frequency resource. Unlike SU-MIMO, the users in the MU-MIMO systems may or may not be equipped with multiple antenna elements [89]-[95].

MU-MIMO systems are capable of achieving the overall multiplexing gain which is equal to the minimum of the number of antennas on the access point and the sum number of antennas on all of the users which are in communication, as a result of which it brings huge MIMO capacity gain and superior spectrum usage efficiency. To enjoy the huge capacity gain of the MU-MIMO systems, it is essentially important to have perfect channel state information (CSI) and deploy pre-coding/beamforming techniques to help the receiver cancel the interference caused by other users to support multi-stream transmission. There are two schemes in MU-MIMO systems, the Uplink and the Downlink schemes. The Uplink scheme is called Multiple Access Channel MU-MIMO (MIMO-MAC) and the Downlink scheme is known as Broadcast MU-MIMO (MIMO-BC). Now let's see each one of them in brief respectively.

3.4.1. MIMO-MAC system

Assume we have K users which are equipped with M_k number of antenna elements where $k=1,2,\dots,K$ and we have an access point which is equipped with N antennas where N is greater than or equal to $\sum_{k=1}^K M_k$. Let $\mathbf{X}_k \in \mathbb{C}^{M_k \times 1}$ be the transmit signal vector of user \mathbf{U}_k . Let's assume that data streams associated to user \mathbf{U}_k are zero mean white random vectors where

$E\{X_k X_k^*\} = I_{M_k}$. $\mathbf{H}_k \in \mathbb{C}^{N \times M_k}$ is a complex channel matrix relating user \mathbf{U}_k to the access point. In presence of Additive White Gaussian noise signal, the received signal vector by the access point in a slow fading channel for an uplink MU-MIMO system is given by:

$$\begin{aligned} \mathbf{y} &= \mathbf{H}_1 \mathbf{X}_1 + \mathbf{H}_2 \mathbf{X}_2 + \dots + \mathbf{H}_K \mathbf{X}_K + \mathbf{b} \\ \mathbf{y} &= \sum_{k=1}^K \mathbf{H}_k \mathbf{X}_k + \mathbf{b} \\ \mathbf{y} &= [\mathbf{H}_1 \quad \dots \quad \mathbf{H}_K] \begin{bmatrix} \mathbf{X}_1 \\ \vdots \\ \mathbf{X}_K \end{bmatrix} + \mathbf{b} \end{aligned} \quad \dots (3.13)$$

Where, $\mathbf{y} \in \mathbb{C}^{N \times 1}$ and $\mathbf{b} \in \mathbb{C}^{N \times 1}$ are the received signal vector by the access point and the AWG noise vector respectively.

For an uplink MU-MIMO system, the number of antennas on the access point must not be less than the total sum of antennas on all of the users, and every user must have at least equal number of antennas to the number of data streams it wants to transmit. In the MIMO-MAC system each user is subjected to an individual power constraint P_k , such that $\text{Tr}(\mathbf{Q}_k) \leq P_k$ where $\mathbf{Q}_k \triangleq E\{\mathbf{X}_k \mathbf{X}_k^\dagger\}$ is the transmit covariance matrix of user k . If all users are equipped with single antenna the covariance matrix of each transmitter reduce to a scalar value which is equal to the transmitted power.

The uplink MU-MIMO system includes a joint linear pre-coder and decoder. Linear pre-coders associated to users $\mathbf{U}_1, \mathbf{U}_2, \dots, \mathbf{U}_K$ will be respectively denoted by $\mathbf{F}_1, \mathbf{F}_2, \dots, \mathbf{F}_K$. The received signal vector at the access point is given by:

$$\mathbf{y} = \sum_{k=1}^K \mathbf{H}_k \mathbf{F}_k \mathbf{X}_k + \mathbf{b} \quad \dots (3.15)$$

An estimate of the transmitted signal vectors denoted by \mathbf{Y}_k ; $k = 1, \dots, K$ are obtained by using the linear decoders $\mathbf{G}_1, \mathbf{G}_2, \dots, \mathbf{G}_K$. The decoder at the access point for the k^{th} user is designed such that the decoder output gives a good estimate of the k^{th} user transmitted signal which is given by

$$\mathbf{Y}_k = \mathbf{G}_k \mathbf{y} = \mathbf{G}_k \left[\sum_{k=1}^K \mathbf{H}_k \mathbf{F}_k \mathbf{X}_k + \mathbf{b} \right]$$

$$Y_k = \underbrace{\mathbf{G}_k[\mathbf{H}_k \mathbf{F}_k \mathbf{X}_k]}_{\text{desired signal vector}} + \underbrace{\mathbf{G}_k[\sum_{j=1, j \neq k}^K \mathbf{H}_j \mathbf{F}_j \mathbf{X}_j]}_{\text{interferers}} + \underbrace{\mathbf{b}_k}_{\text{noise}} \quad \dots (3.16)$$

The most common combining filters used at the access point in order to eliminate the interference and maximize the SNR are the Zero-Forcing (ZF) and the Maximum Ratio Combining (MRC)[89]-[95].

3.4.2. Channel Capacity of MIMO-MAC

Obtaining a closed form expression for the capacity of MU-MIMO system is still an open problem. Rather, we analyze the performance of the system in terms of the achievable rate with arbitrary small amount of error. The capacity of any MIMO-MAC can be written as the convex closure of the union of rate regions corresponding to every user input distribution satisfying the user-by-user power constraints. For the Gaussian MIMO-MAC, however, it has been shown that it is sufficient to consider only Gaussian inputs and that the convex hull operation is not required [89].

$$\mathbf{C}_{MAC}(P_1, P_2, \dots, P_K; \mathbf{H}^\dagger) = \mathbf{C}_{MAC}(\mathbf{P}; \mathbf{H}^\dagger) \triangleq \bigcup_{\{\mathbf{Q}_i \geq 0, \text{Tr}(\mathbf{Q}_i) \leq P_i \forall i\}} \left\{ (\mathbf{R}_1, \dots, \mathbf{R}_K): \sum_{i \in S} \mathbf{R}_i \leq \frac{1}{2} \log |\mathbf{I} + \sum_{i \in S} \mathbf{H}_i^\dagger \mathbf{Q}_i \mathbf{H}_i| \quad \forall S \subseteq \{1, 2, \dots, K\} \right\} \quad \dots (3.17)$$

The capacity region for K user MIMO-MAC where each of the K users is equipped with single antenna becomes the set of all vectors $(\mathbf{R}_1, \dots, \mathbf{R}_K)$ satisfying

$$\sum_{i \in S} \mathbf{R}_i \leq \frac{1}{2} \log |\mathbf{I} + \sum_{i \in S} \mathbf{H}_i^\dagger P_i \mathbf{H}_i| \quad \forall S \subseteq \{1, 2, \dots, K\} \quad \dots (3.18)$$

For MIMO-MAC with K number of users each equipped with M number of antennas and an access point equipped with N number of antennas, might be modeled as KMxN single user MIMO systems. Therefore, the sum capacity of MIMO-MAC can loosely be approximated (upper bounded) by [90]

$$\min(KM, N) \log(\text{SNR}) \quad \dots (3.19)$$

From the above expression we can understand that by increasing the number of users in MU-MIOM increase the system capacity by increasing the number of antennas on the access point, and the total data stream for the K users is $\min(KM, N)$.

3.4.3. MIMO-BC System

Now let's consider a downlink MU-MIMO system, where the access point is simultaneously transmitting to K different users (K users are simultaneously receiving). The transmitted signal vector $\mathbf{x} \in \mathbb{C}^{N \times 1}$ from the access point is expressed as the sum of signals intended to the K users.

$$\mathbf{x} = \sum_{k=1}^K \mathbf{X}_k \quad \dots (3.20)$$

The channel matrix between user \mathbf{U}_k and the base station is denoted by $\mathbf{H}_k \in \mathbb{C}^{M_k \times N}$. At each user, received signal vector of dimension $\mathbf{y}_k \in \mathbb{C}^{M_k \times 1}$ is given by:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x} + \mathbf{B}_k \quad \dots (3.21)$$

Where $\mathbf{B}_k \in \mathbb{C}^{M_k \times 1}$ is an Additive White Gaussian noise vector.

We can rewrite the received signal vector at each user as follows

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{X}_k + \sum_{j=1, j \neq k}^K \mathbf{H}_k \mathbf{X}_j + \mathbf{B}_k \quad \dots (3.22)$$

The second term (the sum) in the above equation represents the interference signals to user k but coming for the other users from the base station (Access Point). The effect of these interfering signals can be reduced by introducing pre-coding techniques at the access point. Using linear pre-coding technique, the pre-coded transmitted vector signal for the kth user could be given by

$$\mathbf{X}_k = \mathbf{T}_k \mathbf{S}_k \quad \dots (3.23)$$

Therefore, the transmitted vector from the access point to the K different stations after the pre-coding is given by

$$\mathbf{x} = \sum_{k=1}^K \mathbf{T}_k \mathbf{S}_k$$

$$\mathbf{x} = \mathbf{T}_k \mathbf{S}_k + \sum_{j=1, j \neq k}^K \mathbf{T}_j \mathbf{S}_j \quad \dots (3.24)$$

Where, $\mathbf{s}_k \in \mathbb{C}^{M_k \times 1}$ and $\mathbf{T}_k \in \mathbb{C}^{N \times M_k}$ are the transmitted symbol vector and the linear precoding matrix for user k respectively.

$$\mathbf{T}_k = [T_{k1}^T T_{k2}^T T_{k3}^T \dots T_{kN}^T]^T$$

Where $T_{ki} \in \mathbb{C}^{1 \times M_k} \forall i \subseteq \{1, 2, \dots, N\}$

Then the received signal vector at the kth user becomes

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{T}_k \mathbf{s}_k + \sum_{j=1, j \neq k}^K \mathbf{H}_k \mathbf{T}_j \mathbf{s}_j + \mathbf{B}_k \quad \dots (3.25)$$

The rank of \mathbf{H}_k becomes $rank(\mathbf{H}_k) = \min(M_k, N)$. To eliminate the interference and maximize the SNR different processing techniques such as Zero-Forcing (ZF) or beamforming, and Maximum Ratio Transmission (MRT) should be introduced in the block diagram of the MU-MIMO system for mitigating the effect of interference and improving the system performances. Like MIMO-MAC, the transmitter in the downlink MIMO is subjected to an average transmit power constraint P , such that $Tr(\mathbf{Q}) \leq P$ where $\mathbf{Q} \triangleq E\{\mathbf{x}\mathbf{x}^\dagger\}$.

3.4.4. Channel Capacity of MIMO-BC

Obtaining a general channel capacity expression for MIMO-BC system with multiple antenna receivers is difficult; rather in [90] it is shown that by using the duality concept, under the same power constraint if we exchange the input and output, and transpose the channel matrix, the capacity of the MIMO-BC and MIMO-MAC will be the same. The dirty paper rate region of the multiple antenna MIMO-BC with power constraint P is equal to the union of capacity regions of the dual MAC, where the union is taken over all individual power constraints that sum to P is given by [90]-[93]

$$\begin{aligned} C_{dirtypaper}(\mathbf{P}; \mathbf{H}) &= C_{BC}(\mathbf{P}; \mathbf{H}^\dagger) \\ &\triangleq \bigcup_{\sum_i^K P_i = P} C_{MAC}(P_1, P_2, \dots, P_K; \mathbf{H}^\dagger) \end{aligned} \quad \dots (3.26)$$

The simulation in fig. 3.7 below shows the capacity improvement for MU-MIMO system. In relative to the conventional SU-MIMO system the performance improvement that comes due to MU-MIMO systems is astonishing which is for the same spectrum band used in the

SU-MIMO system which maximizes the spectrum utilization efficiency, for the same power, but for larger number of antenna elements.

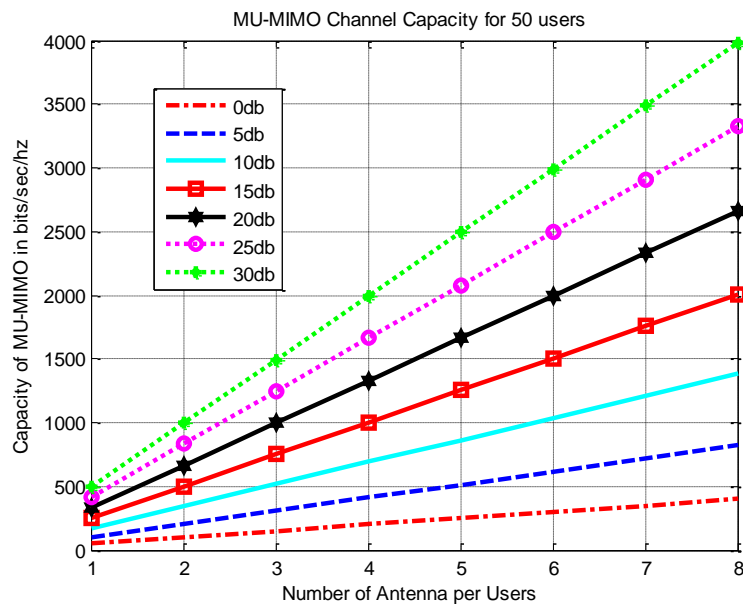


Fig. 3. 7 Capacity of MU-MIMO for different SNR values.

3.5. Massive MIMO System

It is also possible to increase the number of antenna elements to a very large number so as to increase the system capacity and the system is called massive MIMO which uses the same concept like MU-MIMO except the number of antenna element used per base station[94]-[95].

3.6. Smart Antenna

A smart antenna is defined as an array of antennas with a digital signal processing unit that can change its pattern dynamically to suppress noise, interference and reject multipaths. In other words, smart antenna may be considered as a marriage of array antenna and digital signal processing (DSP) to improve the performance of wireless communications technology. Generally, smart antenna systems can be implemented in two different ways either as switched beam antennas or adaptive array antennas.

The most major benefits of smart antenna are reduction in co-channel interference by producing narrow beams only to the direction of the intended user and producing nulls to the direction of interferences; communication range extension; increases channel capacity as well as spectrum utilization efficiency; reduction in transmitted power and handoff; Mitigation of multipath effects, and compatibility with any modulation and multiple access techniques such as TDMA, FDMA, and CDMA [79], [80], [96]- [102].

3.6.1. Switched Beam Antennas

Switched beam systems are considered to be an extension of the cellular sectoring schemes, with cell sectors basically further subdivided to form micro-sectors. The switched beam approach is simpler compared to the fully adaptive approach. It provides a considerable increase in network capacity when compared to traditional omni-directional antenna systems or sector-based systems. In this approach, an antenna array generates overlapping beams that cover the surrounding area as shown in fig.3.8. When an incoming signal is detected, the base station determines the beam that is best aligned with the direction of signal-of-interest and then switches to that beam to communicate with the user [79].

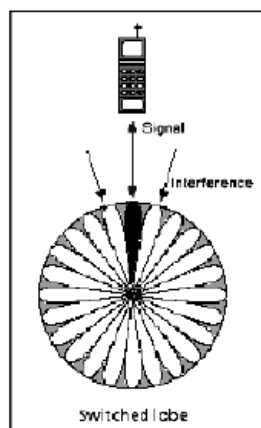


Fig. 3. 8 Beams generated by switched beam antennas.

3.6.2. Adaptive Array Antennas (AAA)

An *adaptive array* fundamentally has the ability to control its own beam pattern dynamically in order to track the location of the users as well as the fast time-varying

environment. This is possible by using adaptive signal processing technology, which enables the array to adapt the time-varying environment very quickly and steer the new beams electronically to the users' new locations.

For fixed array weights value, the antenna array cannot adapt to changing conditions. However, by using feedback control mechanism to adjust the amplitude and phase of the array weights it is possible to produce a beam pattern that is capable of tracking the time-varying environment. Fig. 3.9 shows block diagram of an AAA system.

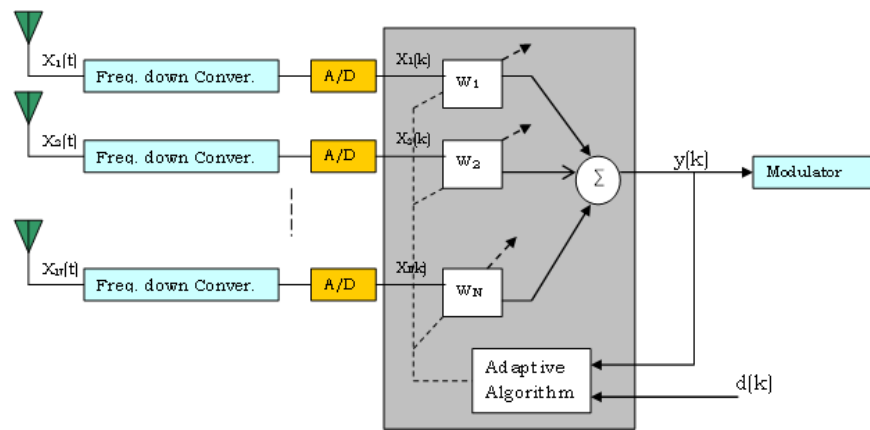


Fig. 3. 9 Block diagram of an Adaptive Array system

The output of any beamformer is given by the following relation [101], [102]

$$y(t) = \sum_{n=1}^N w_n^* x_n(t) \quad \text{----- (3.28)}$$

Where: w_n is a complex weight applied to the n^{th} element

$x_n(t)$ is the signal received by the n^{th} element at time t

(.)* signifies complex conjugate

In vector form

$$y(t) = \overline{W}^H \overline{X}(t) \quad \dots (3.29)$$

Where: $\bar{W}=[w_1, w_2, \dots, w_N]^T$

$$\bar{X}(t)=[x_1(t), x_2(2), \dots, x_N(t)]^T \text{ ,and}$$

$(.)^H$ Signifies Hermitian transpose or complex conjugate transpose

For digital beamformer, the inputs to the beamformer are fed in digital form as shown in fig. 3.9. Therefore, the output of the beamformer at the k^{th} sample is given by [96], [101]

$$y(k)=\sum_{n=1}^N w_n^* x_n(k) \quad \dots (3.30)$$

$$y(k)=\bar{W}^H \bar{X}(k) \quad \dots (3.31)$$

The objective of the antenna array system is then finding weight vector \bar{W} such that the following conditions are satisfied [101]

$$\bar{W}^H a(\theta_1)=1, \bar{W}^H a(\theta_2)=0, \dots, \bar{W}^H a(\theta_M)=0 \quad \dots (3.32)$$

$$\bar{W}^H \bar{b}_1=1, \bar{W}^H \bar{b}_2=0, \dots, \bar{W}^H \bar{b}_M=0 \quad \dots (3.33)$$

Eqn.3.32 and Eqn.3.33 are the two conditions used for the LOS and multipath environment respectively to find the array weight vector which produces main beam to the direction of the intended user and place nulls to the direction of interferers. The above conditions are taken for one intended user in the direction of θ_1 and M-1 unintended users (interferers or noise sources) in the other direction. Under these conditions, the output of the array for LOS and multipath environment respectively becomes [96], [98]

$$y(t)=\gamma_1 s_1(t) \quad \dots (3.34)$$

$$y(t)=\bar{b}_1 s_1(t) \quad \dots (3.35)$$

In matrix form Eqn.4.21 can be rewritten as

$$\begin{bmatrix} a^T(\theta_1) \\ a^T(\theta_2) \\ \vdots \\ a^T(\theta_M) \end{bmatrix} \begin{bmatrix} w_1^* \\ w_2^* \\ \vdots \\ w_N^* \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad \dots(3.36)$$

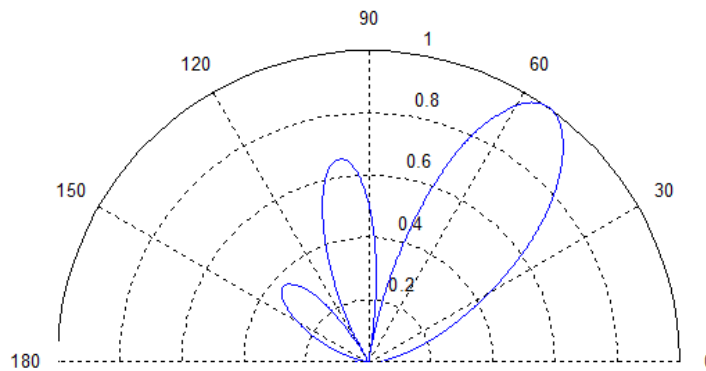
Or it can be represented as

$$A^T \bar{W}^* = \bar{C} \quad \dots (3.37)$$

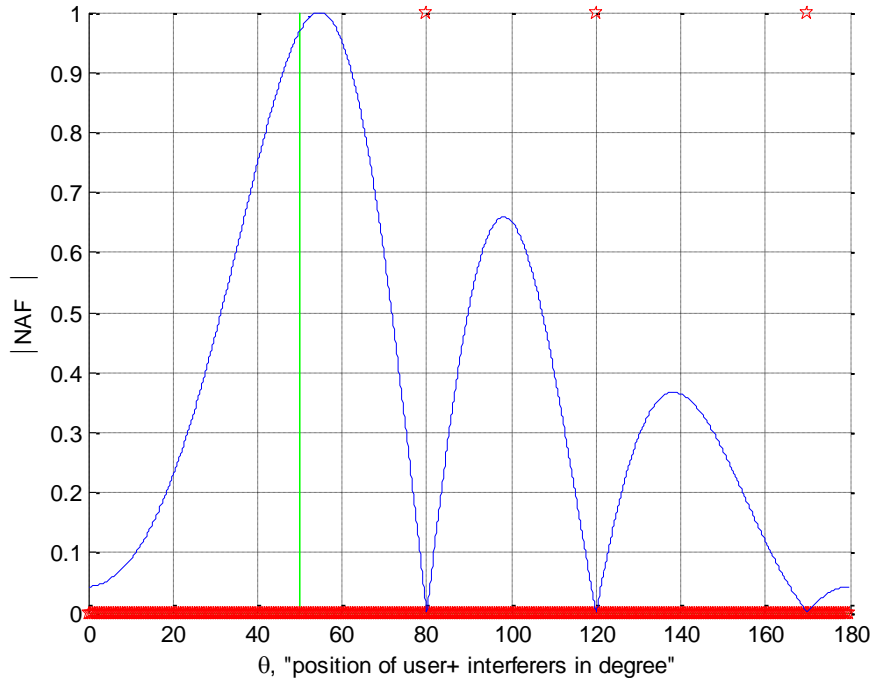
Where: A is NxM matrix, and \bar{C} is a constant vector

Therefore, finding array weights is the same as finding solution(s) of linear algebra problem. Depending upon the properties of the matrix A, there can be one solution, no solution, or infinite solutions.

The simulation in fig. 3.10 carried out for 4 array elements and 4 numbers of users. The first user is the desired user having an angle of arrival of 50° , and the remaining are interferers having angles of arrival of 80° , 120° , 170° . The location of the interferers are represented by asterisks (*) in the simulation and the solid line represents the location of the desired user.



a) Polar plot of normalized Array Factor



b) Rectangular Plot of normalized Array factor

Fig. 3. 10 Simulation of nulls formation at 80° , 120° , 170°

From the simulation we can understand that smart antenna can eliminate the effect of interference due to other users and it can dynamically change its beam direction by tracking the intended users and it can place null to the direction of the other users not to produce any signal to that directions. The integration of smart antenna and cognitive radio system is very fascinating but the complexity of the system becomes very high. This area is still a highly researchable area.

The finding in this chapter shows that multiple antenna has meaning full impact on the performance of cognitive radio network. Therefore, designing an efficient MAC protocol by using multiple antenna technology for cognitive radio wireless mesh network is crucial. In the next chapter we present the fundamental elements of cognitive radio MAC protocols and we analyzes and simulates the performance of random access MAC protocol in terms of throughput and average packet delay.

Chapter-4

MEDIUM ACCESS CONTROL PROTOCOLS FOR COGNITIVE RADIO NETWORKS

4.1 Introduction

Wireless medium is one of the most precious natural resource in the domain of wireless communication. Therefore, a fair and efficient way of distributing/allocating this natural resource among different wireless competitors becomes mandatory issue [9]-[13]. Medium Access Control (MAC) protocol in wireless network is meant to control and maximize the utilization of the wireless medium. The essential element of cognitive radio network is the dynamic spectrum management unit which is responsible to design and implement a better spectrum management system so as to respond to the ever increasing huge bandwidth demanding services/technologies. The main functions of the MAC protocol in cognitive radio networks (CRNs) are identifying the available spectrum resource through spectrum sensing, selecting the best available channels, coordinating users to access the available channels, and vacating the channel when a licensed user is detected. In general it is responsible to decide on the optimal sensing and transmission times so as to maximize the spectrum utilization efficiency [103]-[105].

Cognitive radio MAC (CR-MAC) protocols could be classified based on different parameters, among others it can be classified depending on the spectrum sensing techniques, spectrum sharing techniques, the spectrum handoff techniques, spectrum access techniques, spectrum allocation techniques, the nature of control channel used, the amount of transmission channel and radio interface used, the nature of network architecture. The

above mentioned parameters could be further clustered in to a more holistic classification. We can classify CR-MAC based on the characterizing nature of the dynamic spectrum management functionalities or based on the nature of network architectures. The classification based on the network architecture is no more different from the conventional wireless networks (software defined radio) however, the main characterizing nature of CRN comes from the dynamic spectrum management functionalities like spectrum sensing, access mobility, sharing, and allocation, which is well organized and presented in Fig4.1 [103],[104].

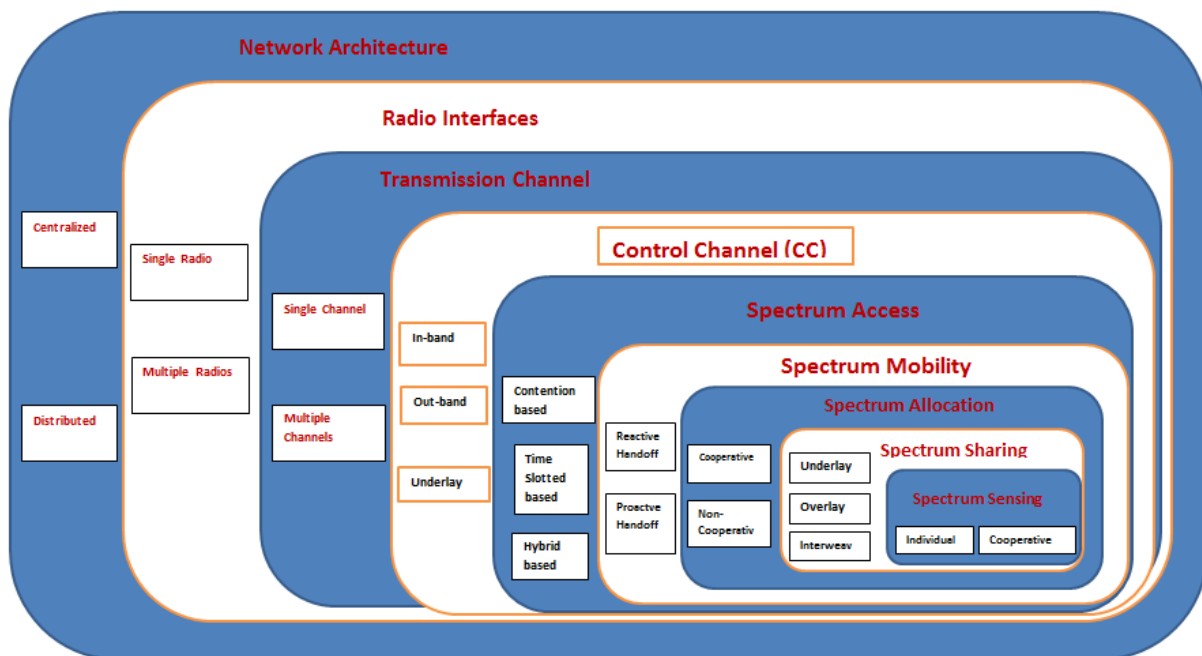


Fig.4. 1 Classification of CR-MAC protocols

4.2 Dynamic Spectrum Management Unit (DSMU)

The main functionalities of DSMU in CR systems are

- a) Spectrum sensing,
- b) Spectrum sharing,
- c) Spectrum allocation,
- d) Spectrum access, and
- e) Spectrum mobility.

Each of these components is briefly summarized below [8], [11], and [12].

i) Spectrum sensing functionality allows CR networks to discover spectrum holes by observing spectrum environment. Spectrum sensing could be conducted in both individual and cooperative manners among cognitive radio users.

ii) Spectrum sharing functionality defines how the spectrum resource is shared among primary and secondary users, or among heterogeneous CR systems (networks). The most common spectrum sharing techniques are underlay, interweave, and overlay.

iii) Spectrum allocation functionality is a dynamic component of the DSMU which is responsible for the allocation of opportunistically detected spectrum holes. Spectrum allocation can be classified in to either a cooperative or a non-cooperative depending on how the CRN announces the other CR users about the allocated spectrum holes.

iv) Spectrum access functionality enables to coordinate multiple CR users to share the vacant spectrum band detected by deciding who and when to access such that access collision is minimized. There are three fundamental mechanisms by which a CR user may access the detected spectrum hole, these are random access mechanism, time slotted mechanism, and hybrid mechanism. MAC protocols defined based on any one of these mechanisms are called random access MAC protocol, or slotted MAC protocol, or hybrid MAC protocol.

Random access/Contention based MAC protocols do not need time synchronization, and are generally based on the collision sense multiple accesses with collision avoidance (CSMA/CA) principle. Whereas, Time slotted MAC protocols need network wide synchronization, where time is divided into slots for both the control channel and the data transmission. The hybrid MAC protocols use a partially slotted transmission, in which the control signaling generally occurs over synchronized time slots, however, following the control signaling the data transmission phase will have random channel access schemes.

v) Spectrum mobility functionality allows a secondary user to vacate its channel, when a primary user is detected, and hop to another idle channel in order to reestablish the communication link. It aims at providing a seamless communication during transition to other spectrum band due to the presence of primary users.

The design of CR-MAC protocol will be affected by both dynamic spectrum access (***DSA***) ***functions*** and ***network infrastructure***. Therefore, from network infrastructure point of view, a designer must answer the following questions while designing CR-MAC protocols: does the network organize in centralized or distributed paradigm? How many channels are used for data transmission? How to manage the control channel? How many radio units are equipped for each device?

Moreover, from DSA functionality point of view, a designer must also considered the overall DSA functions except spectrum sensing while designing a CR-MAC protocol. Even if the spectrum sensing function does not belong to CR-MAC protocol, the schedule as well as the cooperation between users in a network for spectrum sensing is the responsibility of CR-MAC protocol, it is shown in fig. 4.2.

In multi-channel communication scheme, each pair of transmitter and receiver is allowed to transmit data through multi-channel simultaneously. Depending on the number of radio equipped on devices, there are two subclasses for multi-channel protocol, i.e., MRMC protocol and SRMC protocol.

In SRMC protocol, a CR device equipped with single radio will transmit data through multiple channels by using channel aggregation techniques. However, it is difficult to perform the aggregation for non-contiguous channels with a single radio. In contrast, MRMC protocol can be adopted for networks which are equipped with multiple radio CR users.

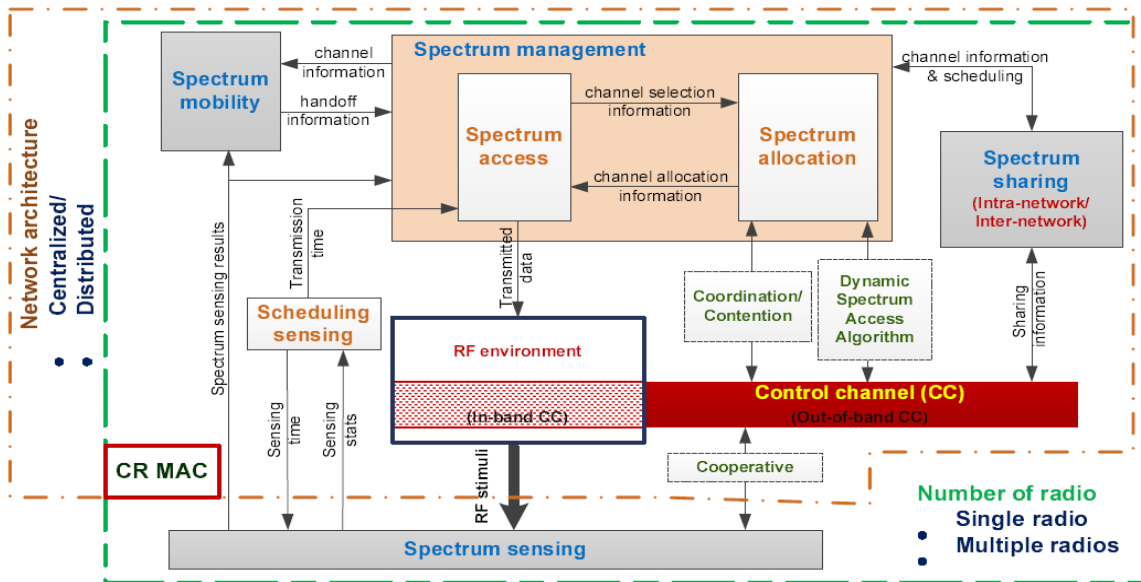


Fig.4. 2 Components of CR-MAC Scheme

4.3 Factors that influence the design of MAC protocol in CRN

The CR users are allowed to use the spectrum holes under two constraints: the secondary users (SUs) should not produce interference to the primary users (PUs), and they must evacuate the spectrum hole when the PU is detected. Therefore, SUs should be intelligent enough to control the dynamic behavior of the PUs and to be able to adjust their operating parameters to the newly available spectrum hole that it would be hopping to continue its communication. Thus, the design of MAC protocol for CRN is a very challenging task.

The most common factors that affect the design of MAC protocol for CRN in general to the multi-hop network in particular are common control channel (CCC), transceiver synchronization, CTS timeout and undecodable CTS, multi-channel hidden terminal problem (MCHTP), number of transceivers, and MAC layer authentication [103], [104].

4.4 Random Access Medium Access Control (RA-MAC) Protocol

The most popular random access MAC protocol in the domain of multi-hop wireless networking is a carrier senses multiple accesses with collision avoidance protocol (CSMA/CA). In CSMA/CA medium access control protocol a transmitting node is

responsible to monitor the shared wireless medium (sense the wireless medium); it only transmits when it detects an idle channel. Distributed Coordinated Function (DCF) is a well-known MAC technique that deploys CSMA/CA with binary exponential algorithm. The IEEE 802.11 standard employs two medium access techniques which are DCF (mandatory) and Point Coordination Function (PCF) which is optional. The PCF is suitable for centralized operation like in the access point (AP), the AP always scans the channel for PCF Inter frame Space (PIFS) duration to decide whether it is idle or not. Basically, the DCF Interframe Space (DIFS) duration is greater than PIFS duration so as to give priority for point to point communication. DCF is an asynchronous data transmission function, which best suits delay insensitive services which can be implemented in both ad-hoc and infrastructure network configurations and can be either used exclusively or combined with PCF in an infrastructure network. PCF, on the other hand, best suits delay sensitive applications and is only available in infrastructure networks.

Two packet transmission mechanisms are used in DCF scheme, the basic access mechanism (two-way handshaking) and the Request to Send / Clear to Send (RTS/CTS) mechanism (four-way handshaking). The basic access mechanism is the default accessing scheme whereas the RTS/CTS mechanism is optional. The RTS/CTS scheme is introduced to overcome the hidden terminal (node) problem and bring fairness for long packet size transmission. Fig. 4.3 and Fig. 4.4 present how basic access and RTS/CTS mechanism operate respectively [107].

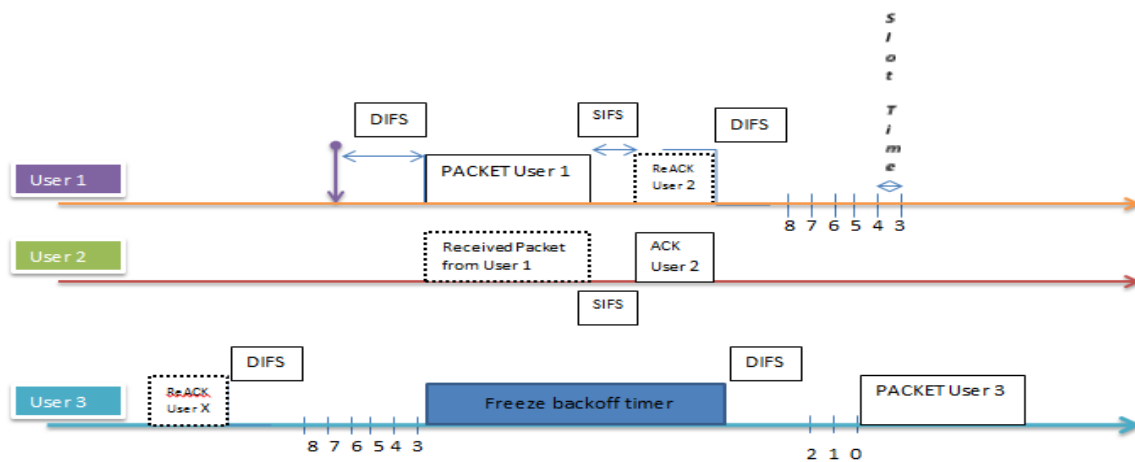


Fig.4. 3 Basic Access Mechanism

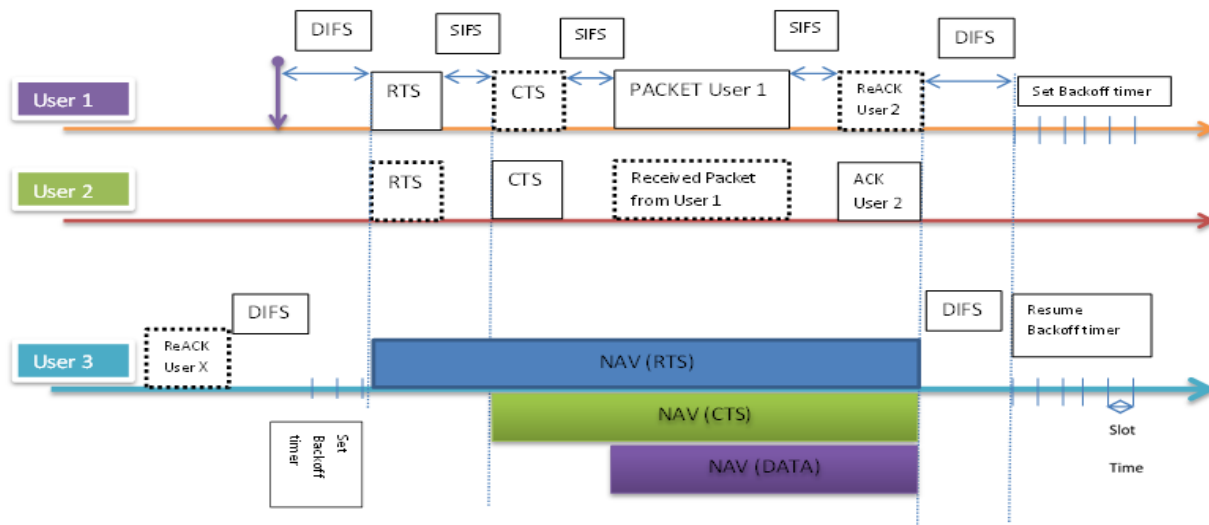


Fig.4. 4 RTS/CTS Access Mechanism

In the channel sensing process, we observe two channel state outcomes, the busy channel state or an idle channel state. In the busy channel state, a station that demands to transmit defers its transmission by setting its network allocator vector (NVA) for RTS/CTS mechanism or it monitors the channel until it becomes idle for more than DIFS period for the basic access mechanism. Station which is in backoff state freezes its backoff timer counter when the channel is sensed busy and resumes the counter at the end of a slot time when the channel is sensed idle for DIFS duration and transmit when the backoff counter becomes zero[106]-[117].

4.4.1 Throughput and Delay Analysis of IEEE 802.11 MAC Protocol

The backoff mechanism used in DCF MAC protocol is the random binary exponential backoff (BEB) technique which is a very fundamental concept to improve the performance of the random access MAC protocol by reducing the probability of collision. A station with a new packet to transmit monitors the channel and if it detects the channel idle for a period of DIFS it can start transmission. If the station makes a successful transmission and have more packet to transmit, it sense the channel and when the channel is detected idle for more than DIFS period it will choose a backoff time from the minimum contention window size and monitor the channel. By the time when the back of timer become zero it can

transmit but when the transmission is not successful for one or more reason (may be due collision) it can retransmit its packet after sensing the channel idle for more than DIFS period and waiting for random backoff time (an integer multiple) which is chosen from the interval $(0, CW-1)$, where CW is the contention window size which is dependent on the number of retransmission attempted. The station decreases the backoff timer by one for every detected idle time slot, when the backoff timer becomes zero it can transmit, but if the transmission do not succeed, then the contention window size will be doubled, and the process continue for limited/unlimited number of retransmission attempt. A station in a backoff state may sense the channel busy at any time, when it detects busy channel it freezes the backoff timer and resume when it detects the channel idle for more than DIFS and make the decrement for every idle slot detected till the counter become zero and it transmits the packet [106]-[117].

Using the two dimensional Markov chain model, the throughput and average packet delay of the DCF based MAC protocol for the IEEE 802.11 is presented as follows[107].

Let $CW_{min} = W_0$ be the minimum contention window size and CW_{max} be the maximum contention window size.

$$i = \log_2 \frac{CW_i}{CW_{min}} \text{ Where } i \text{ is the backoff stage between } 0 \text{ and } m$$

i. Transmission Probability τ

Let $b(t)$ be the stochastic process representing the backoff time counter and $s(t)$ be the stochastic process representing the backoff stage for a given station at slot time t . The bi-dimensional process $\{b(t), s(t)\}$ can be modeled with a discrete-time Markov chain. Let $b_{i,k} = \lim_{t \rightarrow \infty} p\{s(t) = i, b(t) = k\}$ be the stationary distribution of the Markov chain, where $i \in [0, m], k \in [0, W_i - 1]$. Using the Markov chain model the transmission probability τ at any random time slot is given by [107]

$$\tau = \frac{2}{\left(\frac{W_0(p-1) \cdot ((2p)^{m+1} - 1)}{(p^{m+1} - 1) \cdot (2p - 1)} + 1 \right)} \text{ for } 0 \leq i \leq m \text{ and } 0 \leq k \leq W_i - 1 \quad \dots (4.1)$$

The maximum value of τ could be obtained from eqn. 4.1. The maximum value of τ is obtained for minimum value of the denominator..

Now let's consider n number of nodes which is in saturated condition, the nodes always have packets to transmit, the probability any transmission experiences (sees) a collision which is independent of the number of collision that it has already suffered is given by

$$p = 1 - (1 - \tau)^{n-1} \quad \dots (4.2)$$

ii. Throughput Analysis

The normalized system throughput (S) is defined as the fraction of time the channel is used to transmit a successful payload bits. Let's assume that there are n nodes sharing the same channel and are in the same interference region of each other. A collision occurs when more than one station transmit at the same time in a random time slot. The channel becomes busy when there exist atleast one transmission. The probability the channel become busy is given by

$$P_{\text{busy}} = 1 - (1 - \tau)^n \quad \dots (4.3)$$

The channel becomes idle when there is no transmission from all nodes. The probability the channel becomes idle is given by

$$P_{\text{idle}} = 1 - P_{\text{busy}} = (1 - \tau)^n \quad \dots (4.4)$$

A successful transmission is detected on the channel when only one out of the n nodes transmits. The probability the channel is used for successful data transmission is given by

$$P_{\text{suc}} = \binom{n}{1} \tau (1 - \tau)^{n-1} \quad \dots (4.5)$$

Then the probability of collision is given by

$$P_{\text{coll}} = P_{\text{busy}} - P_{\text{suc}} = 1 - (1 - \tau)^n - \binom{n}{1} \tau (1 - \tau)^{n-1} \quad \dots (4.6)$$

Now we can express the throughput of the system as follows

$$S = \frac{E[\text{Payload information transmitted in a slot time}]}{E[\text{length of a slot time}]}$$

$$S = \frac{P_{\text{suc}}E[P]}{(1 - P_{\text{busy}})\sigma + P_{\text{coll}}T_{\text{coll}} + P_{\text{suc}}T_{\text{suc}}} \quad \dots (4.7)$$

Where $E[P]$ is the average packet payload size, therefore $P_{\text{suc}}E[P]$ is the average amount of payload size transmitted in a slot time, σ is the duration of an empty slot time, T_{coll} is the average slot time the channel is sensed busy due to transmission collision, T_{suc} is the average slot time the channel is sensed busy due to successful transmission. The the expression for the T_{coll} and T_{suc} for basic access mechanism become

$$T_{\text{suc}}^{\text{bas}} = H + E[P] + \text{SIFS} + \delta + \text{ACK} + \text{DIFS} + \delta \quad \dots (4.8a)$$

$$T_{\text{coll}}^{\text{bas}} = H + E[P^*] + \text{DIFS} + \delta \quad \dots (4.8b)$$

Where $H = \text{PHY}_{\text{hdr}} + \text{MAC}_{\text{hdr}}$, $E[P^*]$ is the average length of the longest packet payload involved in a collision, and δ be the propagation delay.

In a similar fashion, the expression for T_{coll} and T_{suc} of the RTS/CTS access mechanism become

$$T_{\text{suc}}^{\text{rts}} = \text{RTS} + \text{SIFS} + \delta + \text{CTS} + \text{SIFS} + \delta + H + E[P] + \text{SIFS} + \delta + \text{ACK} + \text{DIFS} + \delta \quad \dots (4.9a)$$

$$T_{\text{coll}}^{\text{rts}} = \text{RTS} + \text{DIFS} + \delta \quad \dots (4.9b)$$

Throughput expressions for basic access and RTS/CTS access mechanisms becomes

$$S^{\text{bas}} = \frac{P_{\text{suc}}E[P]}{(1 - P_{\text{busy}})\sigma + P_{\text{coll}}T_{\text{coll}}^{\text{bas}} + P_{\text{suc}}T_{\text{suc}}^{\text{bas}}} \quad \dots (4.10)$$

$$S^{\text{rts}} = \frac{P_{\text{suc}}E[P]}{(1 - P_{\text{busy}})\sigma + P_{\text{coll}}T_{\text{coll}}^{\text{rts}} + P_{\text{suc}}T_{\text{suc}}^{\text{rts}}} \quad \dots (4.11)$$

iii. *Packet Delay Analysis*

A packet in the MAC layer can be delayed for two main reasons; the first one is when the station transmits with other station at the same time slot (collision will occur), the second is when the medium becomes busy (occupied by other stations). Generally, the average packet delay, $E(D)$, for successfully transmitted packet can be defined as the amount of time it takes for a packet to reach the destination starting from the time it is being ready for transmission (at the top of the output queue of the MAC layer) till an acknowledgment is received.

Packet drop probability (P_{drop}) is the probability a packet is dropped when it reaches the retry limit or the probability a packet reaches the last stage and experiences more collision, where m is the number of stages (retry limit). The probability a packet is successfully transmitted at an arbitrary stage i is given by

$$P_{\text{suc}}(i) = p^i(1 - p) \quad 0 \leq i \leq m \quad \dots (4.12)$$

The packet is dropped when the retry limit is reached, then the packet drop probability becomes

$$P_{\text{drop}} = p^{m+1} \quad \dots (4.13)$$

The probability a packet is not dropped, means a packet do not experience more than m collision (it is transmitted at arbitrary stage before experiencing more than m number of collision) is given by

$$P'_{\text{drop}} = 1 - P_{\text{drop}} = 1 - p^{m+1} \quad \dots (4.14)$$

The probability a packet reaches in backoff stage i given that it is not dropped is given by the following conditional probability (unless the retry limit is not reached, at any stage it has the probability to experience collision or may succeed to transmit) is given by

$$p(S_i \setminus P_{\text{notdropped}}) = \frac{p^i - p^{m+1}}{1 - p^{m+1}} \quad \dots (4.15)$$

Where $p(S_i)$ is the probability a packet reach in backoff stage i , and $p(P_{notdropped})$ is the probability a packet is not dropped.

The average delay of a packet at any arbitrary backoff stage i is given by

$$W_{avg}^i = \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} = \frac{W_i + 1}{2} \quad \dots (4.16)$$

Then the average number of slot required to successfully transmit a packet becomes

$$E(X) = \sum_{i=0}^m \frac{(2^i W_0 + 1)(p^i - p^{m+1})}{2(1 - p^{m+1})} \quad \dots (4.17)$$

A station experiences an average packet delay which is given by

The average packet delay for the basic access and RTS/CTS access mechanisms can be expressed as follows

$$E(D)^{bas} = E(X).E(slot)^{bas}$$

$$E(D)^{bas} = ((1 - P_{busy})\sigma + P_{coll}T_{coll}^{bas} + P_{suc}T_{suc}^{bas}) \cdot \sum_{i=0}^m \frac{(2^i W_0 + 1)(p^i - p^{m+1})}{2(1 - p^{m+1})} \quad \dots (4.18)$$

$$E(D)^{rts} = E(X).E(slot)^{rts}$$

$$E(D)^{rts} = ((1 - P_{busy})\sigma + P_{coll}T_{coll}^{rts} + P_{suc}T_{suc}^{rts}) \cdot \sum_{i=0}^m \frac{(2^i W_0 + 1)(p^i - p^{m+1})}{2(1 - p^{m+1})} \quad \dots (4.19)$$

4.5 Discussion and Simulation

In this section the performance CSMA/CA MAC protocol is simulated. We have used an event driven simulator to examine the behavior of CSMA/CA MAC protocol. The following simulating parameters are used which are taken from Banchi's paper [107].

Table 4.1 CSMA/CA protocol simulation parameters [107]

<i>Simulation Parameters used</i>	
<i>Channel Bit Rate</i>	<i>1 Mbit/sec</i>
<i>Slot Time</i>	<i>50μsec</i>
<i>Propagation Delay</i>	<i>1μsec</i>
<i>SIFS</i>	<i>28μsec</i>
<i>DIFS</i>	<i>128μsec</i>
<i>Initial Contention Window Size (W)</i>	<i>32</i>
<i>Maximum Backoff Stage (m)</i>	<i>3</i>
<i>PHY Header</i>	<i>128 bits</i>
<i>MAC Header</i>	<i>272 bits</i>
<i>Packet Payload</i>	<i>8184 bits</i>
<i>RTS</i>	<i>160 bits + PHY Header</i>
<i>CTS</i>	<i>112 bits + PHY Header</i>
<i>ACK</i>	<i>112 bits + PHY Header</i>

Moreover, the following parameters are used in the simulations, probability of false alarm ($P_f=0.01$), probability of detection ($P_d=0.9$), and probability of vacant channel availability ($P_H=0.9$) unless otherwise.

The performance evaluation is performed in terms of throughput and average packet delay which are measured in bit per second and in second respectively. We have used the simulations to validate the output of our simulator.

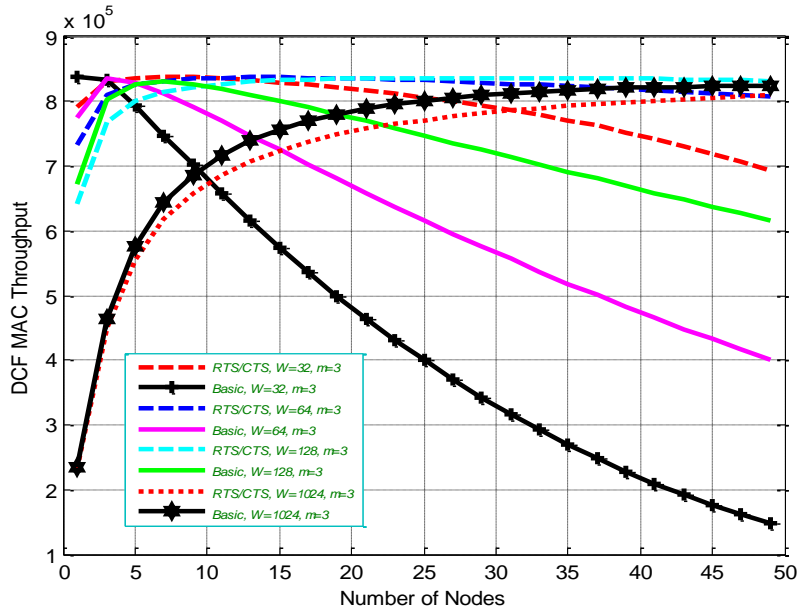


Fig. 4.6 Throughput of Basic, RTS/CTS Access Mechanisms for different number of nodes and contention window sizes (W), probability of transmission (0.01), and retry limit (3).

The simulation in fig. 4.6 shows the performance of CSMA/CA MAC protocol for both basic and RTS/CTS access mechanisms. From the simulation we can observe that as the numbers of user increase the throughput of CSMA/CA protocol start to decline especially for small contention window size, this is because as the number of contending nodes increase the probability of collision will increase. When the increased probability of collision is backed with small contention window size the performance becomes worse. Therefore, for larger window size the collision probability becomes smaller but the delay becomes very large. Moreover, the simulations also show that the basic access mechanism performs better for smaller number of nodes, however, for larger number of nodes RTS/CTS access mechanism shows better performance in terms of throughput.

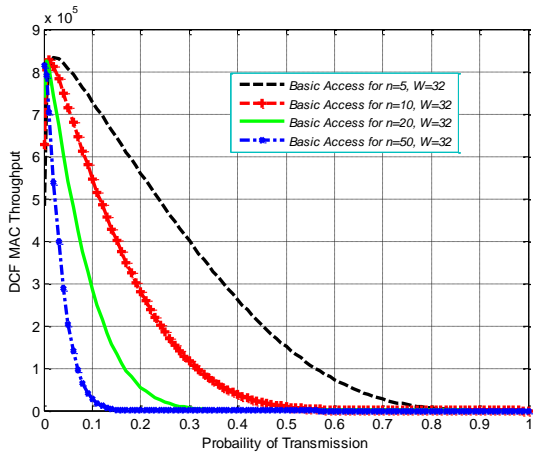


Fig. 4.7 Throughput of Basic Access Mechanism for different probability of transmission, number of nodes (n), retry limit (3), and $W=32$.

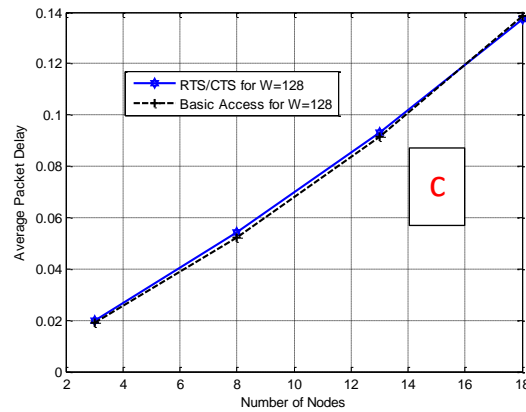
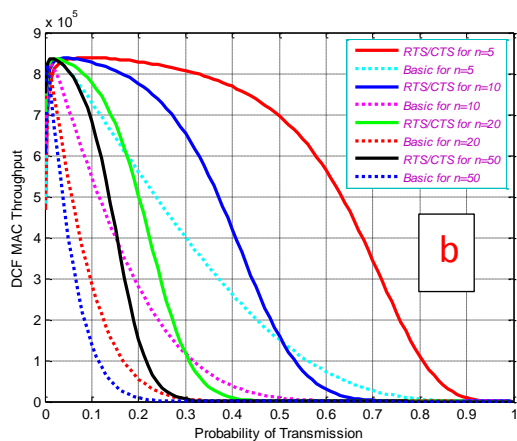
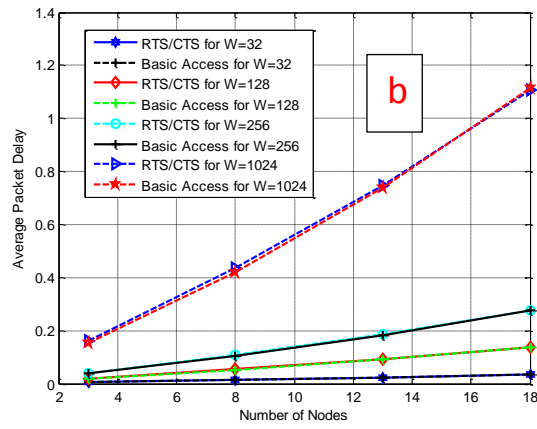
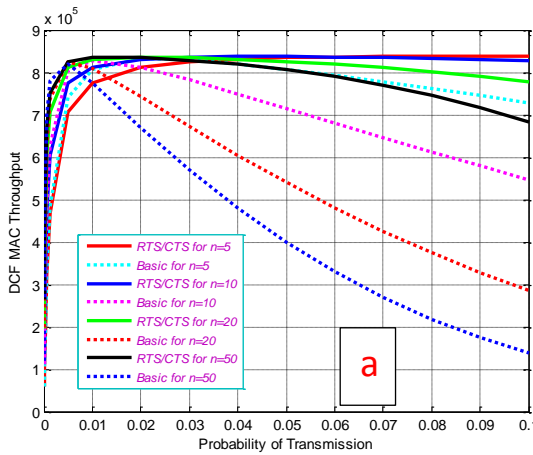
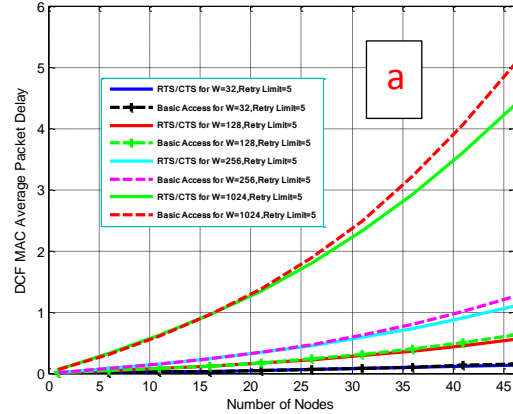
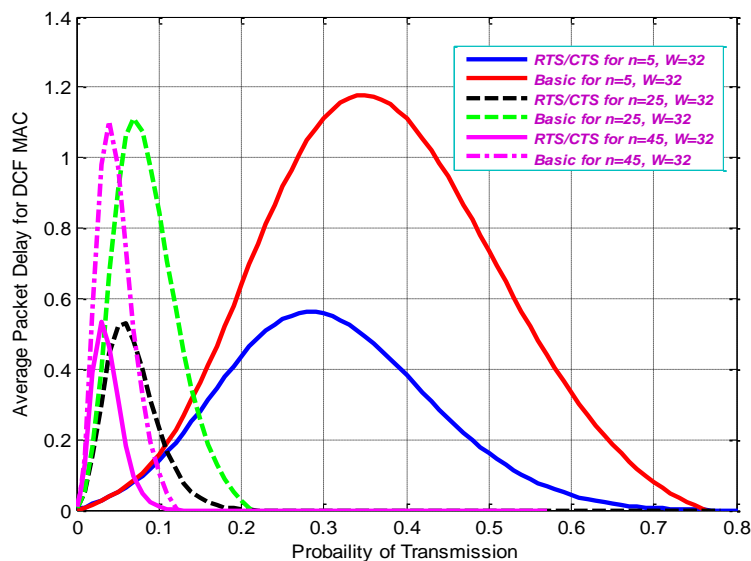


Fig. 4.9 Average packet delay vs number of nodes for Basic and RTS/CTS Access Mechanisms for $\text{thaw}=0.01$, and different contention window size.

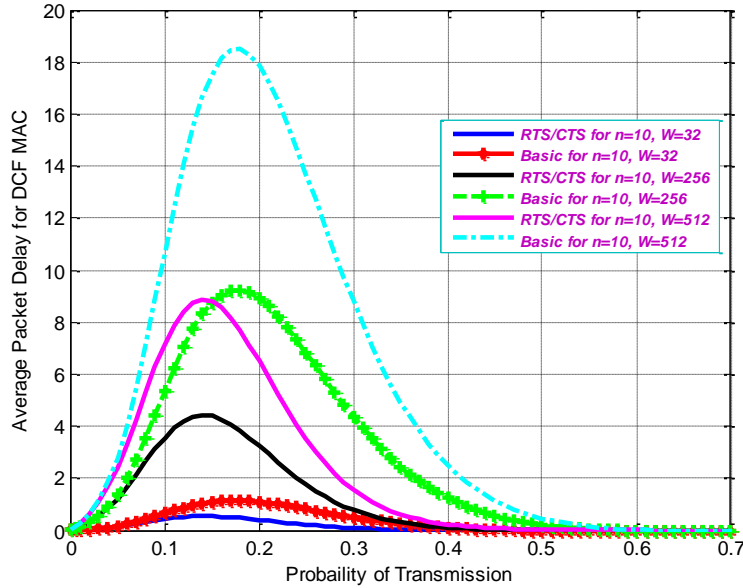
Fig. 4.8 Throughput of Basic and RTS/CTS Access Mechanism for different probability of transmission, number of nodes (n), retry limit (3), and $W=32$.

The simulations in fig. 4.7 and fig. 4.8 show the performance of basic and RTS/CTS access mechanisms for constant contention window size ($W=32$), and for variable probability of transmission and number of nodes. The performance of large number of nodes decline very quickly as the probability of transmission becomes larger and larger, this is because, as the probability of transmission becomes larger the number of colliding nodes becomes large and due to limited retry limit the packet will be dropped relatively in a short time. However, for small number of nodes the performance decline very slowly, this is because for small number of nodes the probability of collision is relatively smaller.

The simulations in fig. 4.9 show the performance of CSMA/CA MAC protocols in terms of the average packet delay. The simulations are performed for constant probability of transmission and varying number of nodes, and contentions window size except fig. 4.9 (c) which is simulated to show the performance in a visible way for contention window size of $W=128$. The simulations show that increasing number of nodes increases the average packet delay, this is due to the fact that increasing number of nodes increases the probability of collision for a given probability of transmission and constant retry limit. Especially, for the scenario where the contention window size becomes larger, the throughput becomes stable but the average packet delay becomes larger.



4.10a) Average packet delay vs probability of transmission for Basic and RTS/CTS Access Mechanisms for constant contention window size ($W=32$), and for different number of nodes.



4.10b) Average packet delay vs probability of transmission for Basic and RTS/CTS Access Mechanisms for constant number of nodes $n=10$, and different contention window size.

Fig. 4.10 Average packet delay Vs probability of transmission for Basic and RTS/CTS Access Mechanisms.

The simulations in fig. 4.10 show the average packet delay of CSMA/MA protocol for different number of nodes, constant contention window size and varying probability of transmission; and for different contention window size, constant number of nodes and varying probability of transmission. As the probability of transmission becomes larger and larger the average packet delay starts to increase and after some point it declines to zero. The average packet delay declines after some point because of the limited number of retry limit. Had the retry limit been larger and larger, the average packet delay would have been very big.

In this chapter, we have simulated the IEEE 802.11 CSMA/CA to validate our simulator and it has revealed a good performance evaluation. The performance of IEEE 802.11 CSMA/CA in terms of throughput and average packet delay has been simulated and the outputs of our simulator for the throughput and average packet delay are similar to the simulation outputs presented in [107]. In the next chapter, we have proposed a new random access MAC protocol for CRN in general and to multi-hop CRN in particular.

ENHANCED RANDOM ACCESS MAC PROTOCOLS FOR COGNITIVE RADIO NETWORK (ECR-MAC)

5.1 Introduction

In this chapter the most popular type of random access MAC protocol that uses a carrier sense multiple accesses with collision avoidance (CSMA/CA) and exponential backoff algorithm is presented in the context of CRN. In DCF MAC protocol there are two access mechanisms, the basic and RTS/CTS access mechanisms. In this chapter a new access mechanism has been proposed by modifying the existing RTS/CTS access mechanism by making use of the unique nature of CR systems.

We have made a detailed mathematical analysis for the newly proposed access mechanism called M-CTS which stands for modified RTS/CTS access mechanism. Using the proposed access mechanism, the M-CTS, a new random access MAC protocol has been designed and it is called Enhanced Random Access MAC Protocol for Cognitive Radio Network (ECR-MAC). The mathematical analysis is performed to examine ECR-MAC protocol performance in terms of throughput and average packet delay. The performance comparison of the ECR-MAC protocol with basic access based CR-MAC protocol and RTS/CTS based CR-MAC protocol shows that the proposed ECR-MAC protocol out performs the other two types of CR-MAC protocols.

To design ECR-MAC protocol we have made the following assumptions. The protocol is assumed to be random access with no central coordination unit. The nodes are empowered with cognitive capabilities, such that they are capable of observing the spectrum

environment, they are capable of learning about the behavior of the primary users, they are capable of selecting spectrum channels based on reasoning, and they are aware of the spectrum accessing mechanisms, in order to maximize the overall system performance. The nodes are equipped with multiple antennas single radio interfaces which can operate in multi-channel mode. There is no common control channel assumption, the selected channel(s) is used for both signaling and data communication.

System Model

Let's consider a cognitive radio network with N number of secondary users (SUs), and assume that the M secondary users (SUs) are under the omni-directional coverage area of any arbitrary SU. The SUs are assumed to have packet ready for transmission all the time, as a result any SUs shall be either in transmission attempt or listening mode. When it is in transmission attempt, it may experience transmitter blocking, transmission collision with other secondary user(s) or with primary user(s) transmission (due to miss detection), or successful transmission. While in listening (overhearing) mode it may detect idle channel or successful transmission among other SUs or collision among SUs transmission or the transmission of both SU(s) and PU(s). This phenomenon is presented in a diagrammatic way in fig. 5.1.

At any arbitrary time, the channel(s) can be either in busy or idle mode. These two states can be represented by using a random variable. The performance of spectrum detecting system is determined by its ability to detect the status of the channel with good precision. Since cognitive users are supposed to detect these status so as to properly use the opportunistically available spectrum for communication and it is also responsible not to produce interference to the primary user due to false alarm.

Probability of detection is the probability an arbitrary SU detects the channel busy when it is actually busy, and the probability of false alarm is the probability an arbitrary SU detects the channel busy when it is actually idle. A good spectrum detector is the one which has high probability of detection and small probability of false alarm.

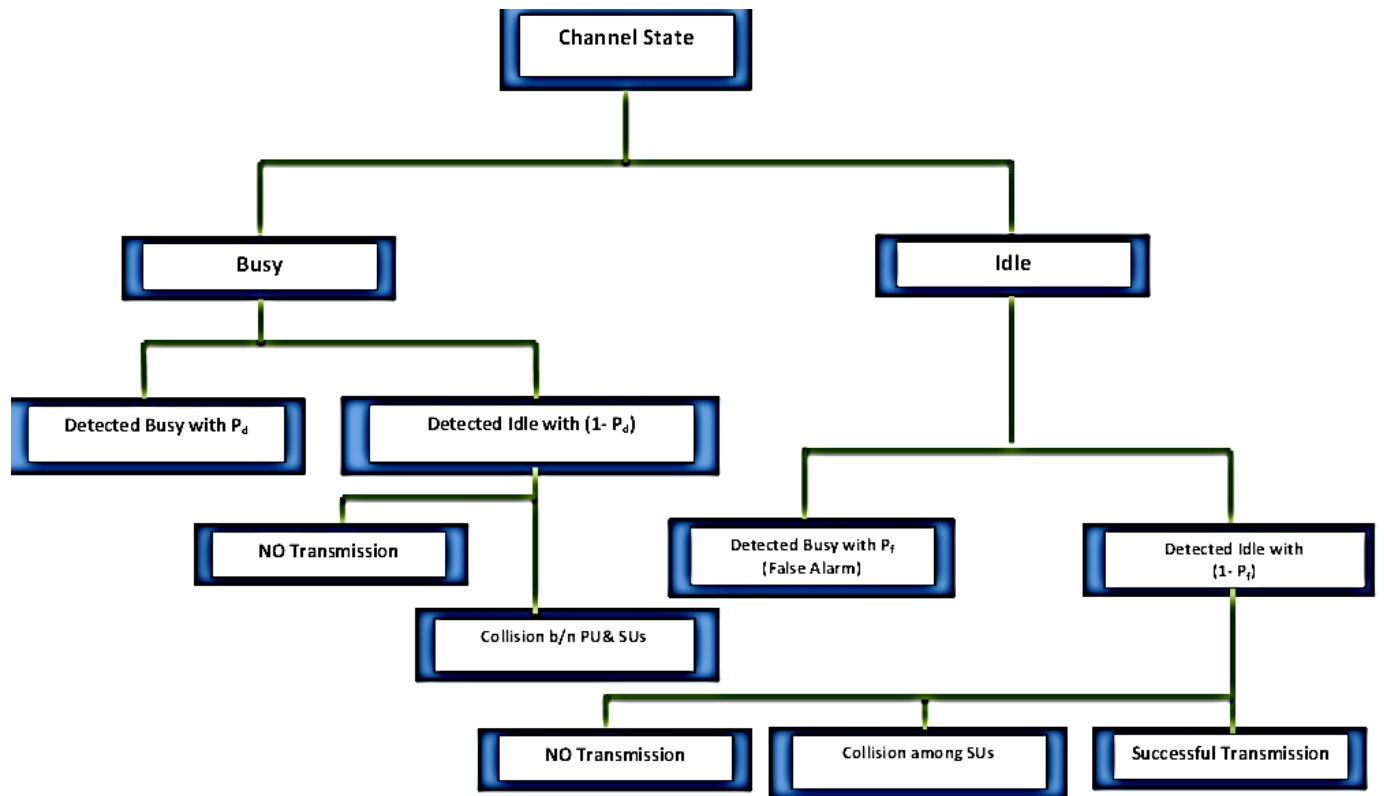


Fig. 5. 1 Channel state detection output model.

5.2 ECR-MAC Protocol for CRNs

The distributed random access MAC protocol operation is dominated by the CSMA/CA mechanism. This protocol has got wider acceptance in the wireless communication domain. It basically uses two access mechanisms, the basic access and the RTS/CTS access mechanisms [107]. The authors in [70], proposed cognitive radio based carrier sense medium access with collision avoidance using the RTS/CTS mechanism which is called CR-CSMA/CA, and they have compared the performance of CR-CSMA/CA with the slotted-ALOHA and CSMA modified to suit the behavior of CRNs. We have used this finding as a mile stone for our works. Next, the operation of the three access mechanisms with respect to CRN is modified and presented as follows.

5.2.1 Basic Access Mechanism for CRN

The basic operations of the basic access mechanism remain the same in the design of random access MAC protocol for CRN. The difference comes only due to the introduction of the spectrum sensing phase which is part of the MAC protocol in cognitive radio systems. A SU which wants to transmit perform carrier sensing and if it does not sense any carrier signal then it sends a prepare to sense (PTS) frame to the receiving node so that both of the SUs will make the spectrum sensing to make sure that the PUs in their vicinity are not using the spectrum. After the spectrum sensing time if the transmitting SU confirms the absence of PU, it proceeds with the normal operation of the basic access mechanism by sending the data packet. Fig. 5.2 shows the operation of the modified basic access mechanism for cognitive radio networks.

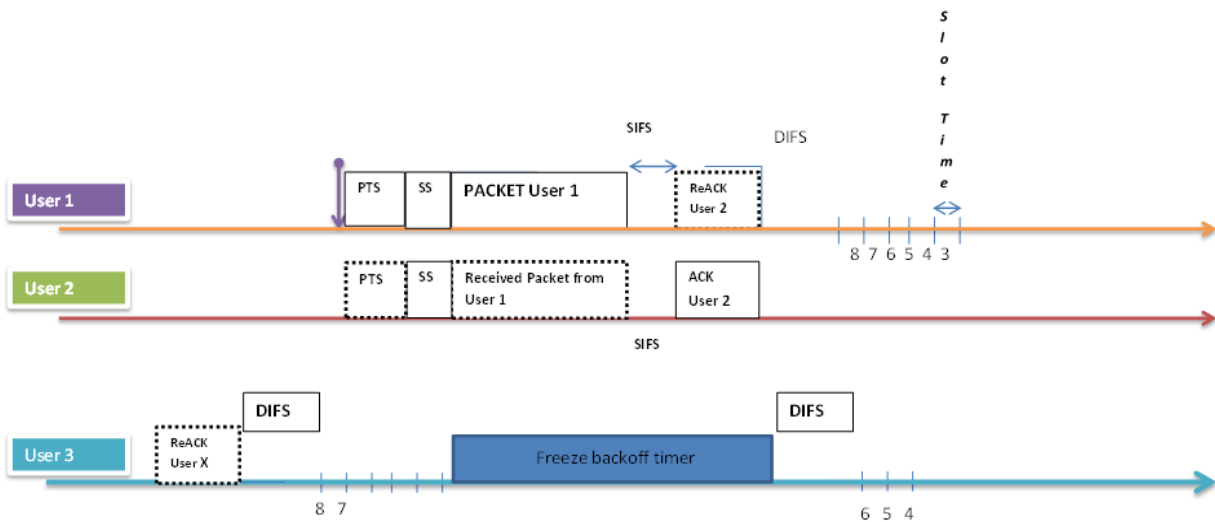


Fig. 5.2 Basic Access Mechanism for Cognitive Radio Network.

5.2.2 RTS/CTS Access Mechanism for CRN

In a similar fashion the operation of the RTS/CTS access mechanism is modified so as to suit the function of the cognitive radio network. A SU which want to transmit always makes carrier sensing to detect the presence of signal. If no signal is detected, it transmits PTS frame and both the transmitting and receiving SUs will perform spectrum sensing. If the transmitting node detects no PUs, it will send RTS frame and then the normal RTS/CTS

procedure continuous. The operation of the RTS/CTS access mechanism customized to accommodate the cognitive radio functionality is shown in fig.5.3.

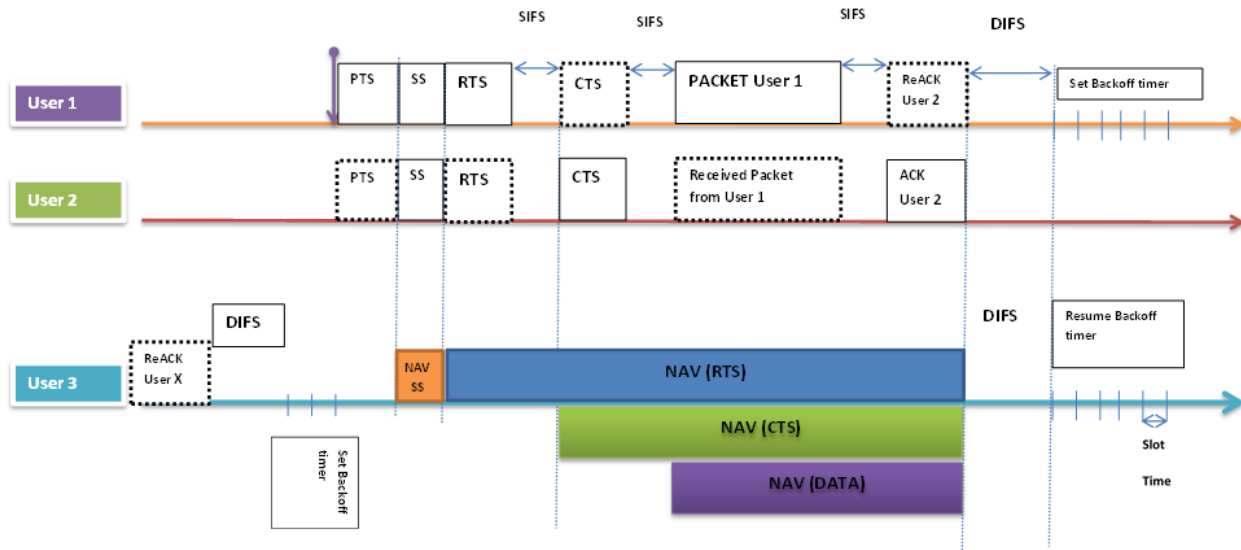


Fig. 5. 3 RTS/CTS Access Mechanism for Cognitive Radio Network.

5.2.3 Modified RTS/CTS (M-CTS) Access Mechanism

In this section the operation of the modified RTS/CTS (M-CTS) access mechanism has been presented. The M-CTS access mechanism takes advantage of the inherent behavior of CR system, which is spectrum sensing. CR system needs to control the spectrum environment by periodically performing spectrum sensing in order to utilize the unused spectrum hole or spectrum bands without creating significant interference on the primary user. The CR user needs to send prepare to sense(PTS) message to the intended receiver so as to decide on the vacant spectrum hole that the two communicating nodes can possible communicate if the transiting node does not detect carrier signal in carrier sensing mode.

In the basic access mechanism, following the PTS the secondary users perform spectrum sensing and identify if there is spectrum hole(s)/band(s) to establish communication link between the two users. If the transmitting user succeeds to identify vacant hole it transmits data packet to the intended secondary user (receiver) and the other procedure remain the same (two way handshaking). In the RTS/CTS access mechanism, following the spectrum sensing process if it manages to detect spectrum hole, it will send RTS frame and follows

the same procedure with the conventional RTS/CTS access mechanism (four way handshaking).

Whereas, the M-CTS access mechanism omit either the RTS or the CTS frame and SIFS frame following the spectrum sensing phase. Since the frame size of RTS is larger than CTS frame, we propose to omit RTS frame in the handshaking process and it is presented in fig. 5.4 below using the time axis.

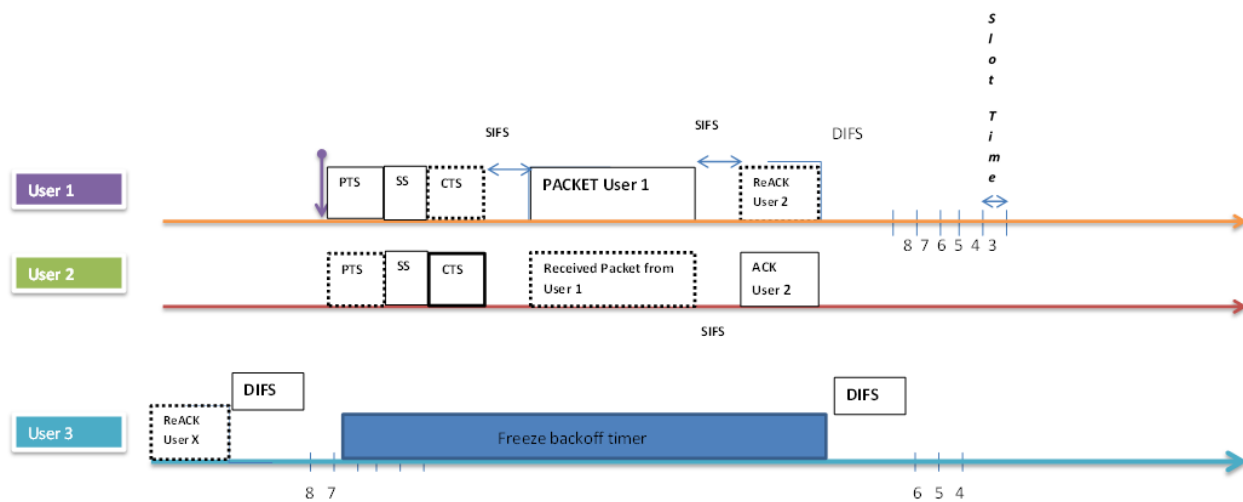


Fig. 5. 4 M-CTS Access Mechanism for cognitive radio network.

In the M-CTS access mechanism, a SU that wants to transmit makes carrier sensing and if it does not detect any signal, it sends PTS frame to the intended SU so as to reserve the upcoming slot for spectrum sensing, and both of them perform spectrum sensing to detect the PU. The intended SU receiver responds with CTS frame to the transmitting SU, after a successful reception of the CTS frame by the transmitting SU, it transmits the data packet and if the data packet is successfully received by the intended SU, the receiving SU will send an acknowledgment frame.

The M-CTS access mechanism reduces one RTS frame and one SIFS compared to the RTS/CTS access mechanism for a successful transmission process. Compared to the basic access mechanism, it introduced one CTS frame and one SIFS during a successful transmission event. When collision is detected on the channel, the amount of time an overhearing SU freezes its backoff timer will be small for the M-CTS access mechanism than

the other two types. With respect to basic access, the M-CTS access mechanism freezing time during collision is less than by the amount of time used to transmit a DATA packet minus the time it takes to transmit CTS frame, whereas with respect to RTS/CTS access mechanism the freezing time during collision is less than by the amount of time used to transmit an RTS frame and SIFS duration.

5.3 Throughput and Delay Analysis of ECR-MAC Protocol for CRN

The throughput and average packet delay are taken as performance evaluating parameters for the proposed enhanced random access cognitive radio MAC protocol. The Markov chain shown in fig.5.5 is used to drive the throughput and average packet delay expressions. Most of the terms used in the derivations are defined in chapter four, except P_{E4} , which is the probability of successful transmission. The expression for the probability of successful transmission (P_{E4}) for the case of cognitive radio network is different from the expression in the conventional wireless network using Markov chain model. We have developed the Markov chain model and it is presented in fig.5.5 for the saturated condition.

5.3.1 Throughput Analysis of ECR-MAC protocol

The transmission probability expression can be expressed using the above Markov chain model as follows, the probability $b_{i,k}$ is given by

$$b_{i,0} = (1 - P_{E4})b_{i-1,0} \quad , 0 < i \leq m \quad \dots (5.1)$$

$$b_{i,0} = (1 - P_{E4})^i b_{0,0} \quad , 0 \leq i \leq m \quad \dots (5.2)$$

Then we can write $b_{i,k}$ in terms of $b_{i,0}$

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad , 0 \leq i \leq m \text{ and } 0 \leq k \leq W_i - 1$$

$$b_{i,k} = \frac{W_i - k}{W_i} (1 - P_{E4})^i b_{0,0} \quad , 0 \leq i \leq m \text{ and } 0 \leq k \leq W_i - 1$$

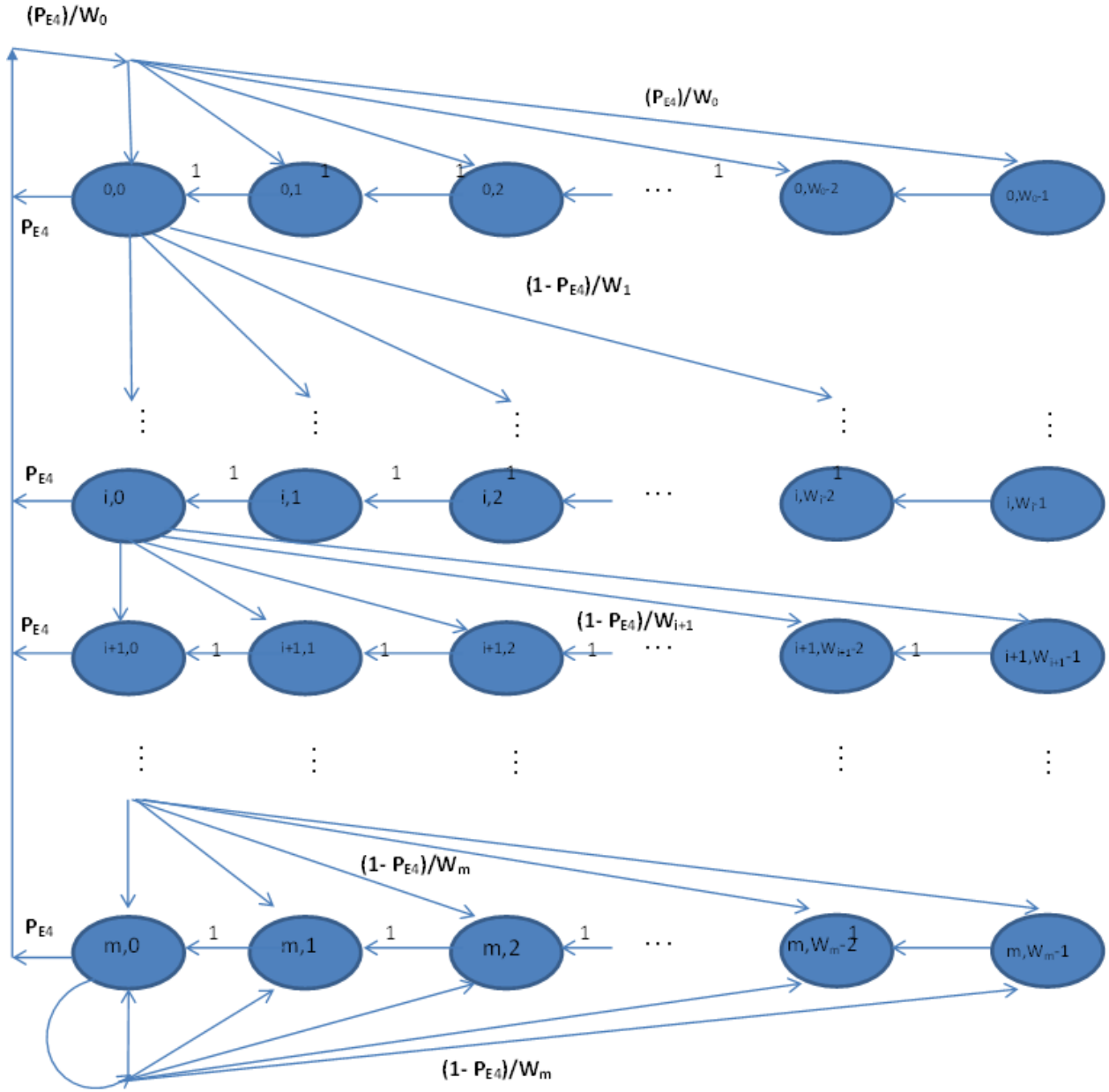


Fig. 5.5 Markov Chain Model for CRMAC protocol.

$$b_{i,k} = \frac{2^i W_0 - k}{2^i W_0} (1 - P_{E4})^i b_{0,0} \quad , 0 \leq i \leq m \text{ and } 0 \leq k \leq W_i - 1 \quad \dots (5.3)$$

by imposing the normalization condition we can have the following expression

$$1 = \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^m \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} (1 - P_{E4})^i \cdot b_{0,0} \quad , 0 < i \leq m \text{ and } 0 < k \leq W_i - 1$$

Using the property of power series $\sum_{k=1}^n k = \frac{1}{2}n(n+1)$, the above equation reduce to

$$1 = \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^m (1 - P_{E4})^i b_{0,0} \frac{W_i + 1}{2} \quad , 0 \leq i \leq m \text{ and } 0 \leq k \leq W_i - 1$$

$$1 = \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} = \frac{b_{0,0}}{2} \sum_{i=0}^m (1 - P_{E4})^i (W_i + 1) \quad , 0 \leq i \leq m \text{ and } 0 \leq k \leq W_i - 1$$

Replace W_i with $W_i = 2^i W$

$$\begin{aligned} 1 &= \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} = \frac{b_{0,0}}{2} \sum_{i=0}^m (1 - P_{E4})^i \cdot (2^i W_0 + 1) \\ &= \frac{b_{0,0}}{2} \left\{ W_0 \sum_{i=0}^m ((2(1 - P_{E4}))^i) + \sum_{i=0}^m (1 - P_{E4})^i \right\} \\ b_{0,0} &= \frac{2}{\sum_{i=0}^m (W_0 (2(1 - P_{E4}))^i + (1 - P_{E4})^i)} \quad \dots (5.4) \end{aligned}$$

Using the following property from the geometric series $\sum_{k=0}^n x^k = \frac{x^{n+1}-1}{x-1}$ the above expression can be rearranged to obtain an expression for $b_{0,0}$

$$b_{0,0} = \frac{2P_{E4}(2P_{E4} - 1)}{W_0(P_{E4}((1 - (2(1 - P_{E4}))^{m+1})) + (2P_{E4} - 1)(1 - (1 - P_{E4})^{m+1}))}, \quad \dots (5.5)$$

for $0 \leq i \leq m$ and $0 \leq k \leq W_i - 1$.

Now we can drive an expression for transmission probability τ of an arbitrary station at a random slot time. A station transmits only when the backoff counter timer becomes zero.

Therefore, a transmission probability of any transmitting station at any time slot is given by

$$\tau = \sum_{i=0}^m b_{i,0} = \sum_{i=0}^m (1 - P_{E4})^i b_{0,0}$$

$$\tau = \frac{2(1-(1-P_{E4})^{m+1})(2P_{E4}-1)}{W_0(P_{E4}((1-(2(1-P_{E4})^{m+1}))+2P_{E4}-1)(1-(1-P_{E4})^{m+1}))} \quad \dots (5.6)$$

for $0 \leq i \leq m$ and $0 \leq k \leq W_i - 1$

In terms of transmission failure, we can re-write eqn.5.6 as follows

$$\tau = \sum_{i=0}^m b_{i,0} = \sum_{i=0}^m (1 - P_{E4})^i b_{0,0}$$

$$\tau = \sum_{i=0}^m (1 - P_{E4})^i b_{0,0}$$

$$\tau = \frac{2(1-(P_{tf})^{m+1})(1-2P_{tf})}{W_0((1-P_{tf})((1-(2(P_{tf})^{m+1}))+1-2P_{tf})(1-(P_{tf})^{m+1}))} \quad \dots (5.7)$$

For $m=0$ the transmission probability expression becomes

$$\tau = \frac{2}{W_0+1} \quad \dots (5.8)$$

Based on the features of cognitive radio system, let's drive the throughput and delay of DCF MAC protocol for the three access mechanisms, namely Basic, RTS/CTS, and M-CTS access mechanisms. Generally, for the sack of our analysis and simulation, we label the MAC protocols for cognitive radio network based on the three access mechanism as CR-MAC protocol. In the derivation we have introduced the spectrum sensing phase which is mandatory for the cognitive radio network/system.

Let's define two events on the status of neighboring primary users (PUs) to a secondary user (SU). H_0 represents the hypothesis that the neighboring PUs of an arbitrary SU are not active, and H_1 represents the hypothesis that the neighboring PUs of an arbitrary SU are active. Let P_{H_0} denotes the occurrence probability of event H_0 , and P_{H_1} denotes the occurrence probability of event H_1 . Let's define additional variable V to denotes the probability a SU can access the channel, which can be expressed in terms of probability of false alarm (p_f), and probability of detection (p_d).

An arbitrary SU can access the channel under two conditions; the first one is when the channel is actually idle and sensed idle by the secondary user (SU), and the second one is when the channel is actually busy (it is being used by the primary user(s)) but sensed idle by the sensing arbitrary SU. Therefore, the probability an arbitrary secondary user can access the channel is given by

$$V_k = (1 - p_{f,k})P_{H_0,k} + (1 - p_{d,k})P_{H_1,k} \quad \dots (5.9)$$

Where $k=1, 2, 3, \dots, M$, and $(1-V_k)$ will be the probability an arbitrary SU cannot access the channel (sense the channel busy).

I. PU Detection at the Opportunistic Transmitter (E1)

When a secondary user has a packet to transmit, first it performs carrier sensing. In the carrier sensing phase if it doesn't detect any signal then it transmits prepare to sense (PTS) frame to the intended secondary receiver. Following the PTS frame transmission and reception both of the SUs perform spectrum sensing. During the spectrum sensing period the transmitting secondary user may detect PUs and discontinue the communication, this is called transmitter blocking. The probability of this event where U_1 is the transmitter is given by

$$P_{E1} = (1 - V_1) \quad \dots (5.10)$$

The period of transmission failure due to event 1 for the basic, RTS/CTS, and M-CTS access mechanisms are respectively given by

$$T_{E1}^{bas} = PTS + SS + DIFS \quad \dots (5.11)$$

$$T_{E1}^{rts} = PTS + SS + DIFS \quad \dots (5.12)$$

$$T_{E1}^{mcts} = PTS + SS + DIFS \quad \dots (5.13)$$

When transmitter blocking occurs, the transmitting secondary user will defer its transmission for additional predefined blocking time (TB) and it enters to the backoff mechanism.

II. Collision between SUs Transmission (E2)

Collision between SUs transmission occurs when U1's RTS frame collides with other secondary user RTS frame for the case of RTS/CTS access mechanism, or when more than one SUs transmit data frame at the same time after the spectrum sensing phase for the case of basic access mechanism, or when more than one PTS frame are send to the same SU at the same time for the case of M-CTS access mechanisms. Let's drive the probability of collision between SUs transmission as follows

$$P_{RTS,k} = \text{prob. \{RTS transmission by an arbitrary SU at any time slot\}}$$

$$= \text{prob. \{a SU can access the channel at any time slot\}} \times$$

$$\text{prob. \{packet transmission by a SU at any time slot\}}$$

$$P_{RTS,k} = V_k \tau_k$$

$$P'_{RTS,k} = \text{prob. \{a SU do not transmit RTS at any time slot\}}$$

$$P'_{RTS,k} = 1 - P_{RTS,k}$$

$$P'_{RTS,k} = 1 - V_k \tau_k$$

$$P = \text{prob. \{none of the SUs among(M - 1) transmit at any time slot\}}$$

$$P = \prod_{k=1}^{M-1} (1 - P_{RTS,k})$$

$$P = \prod_{k=1}^{M-1} (1 - V_k \tau_k)$$

\mathbf{P} = prob. { at least one SU among $(M - 1)$ transmit RTS at any time slot} = $1 - P$

$$\mathbf{P} = 1 - \prod_{k=1}^{M-1} (1 - V_k \tau_k)$$

The probability of U1's transmission collides with other secondary user frame (E2) is given by

$$P_{E2} = V_1 \mathbf{P} = V_1 \left\{ 1 - \prod_{k=2}^M (1 - V_k \tau_k) \right\} \quad \dots (5.14)$$

Where $K=2, 3, 4, \dots, M$.

Due to collision there is transmission failure, and the period of this transmission failure for basic, RTS/CTS and M-CTS access mechanisms are respectively given by

$$T_{E2}^{bas} = PTS + SS + DATA + SIFS + ACK + DIFS \quad \dots (5.15)$$

$$T_{E2}^{rts} = PTS + SS + RTS + SIFS + CTS + DIFS \quad \dots (5.16)$$

$$T_{E2}^{mcts} = PTS + SS + CTS + DIFS \quad \dots (5.17)$$

III. Collision of SU's Transmission with PU Transmission (due to miss detection by the transmitting SU) (E3)

During the spectrum sensing time after receiving PTS from U1, if the intended secondary receiver (U2) detects the presence of primary user(s), it will fail to respond to the RTS frame sent from the intended secondary transmitter (U1) which happens due to miss

detection by the transmitting SU. This is called receiver blocking. The occurrence probability of this event is given by

$$P_{E3} = V_1(1 - V_2) \prod_{k=3}^M (1 - V_k \tau_k) \quad \dots (5.18)$$

The period of transmission failure due to receiver blocking for basic, RTS/CTS, and M-CTS access mechanisms are respectively given by

$$T_{E3}^{\text{bas}} = \text{PTS} + \text{SS} + \text{DATA} + \text{SIFS} + \text{ACK} + \text{DIFS} \quad \dots (5.19)$$

$$T_{E3}^{\text{rts}} = \text{PTS} + \text{SS} + \text{RTS} + \text{SIFS} + \text{CTS} + \text{DIFS} \quad \dots (5.20)$$

$$T_{E3}^{\text{mcts}} = \text{PTS} + \text{SS} + \text{CTS} + \text{DIFS} \quad \dots (5.21)$$

IV. Successful Transmission (E_4)

Successful transmission between the intended secondary transmitter (U1) and the intended secondary receiver (U2) is accomplished when both of them do not detect PU(s) and the remaining SUs do not transmit. The probability of successful transmission is given by

$$P_{E4} = V_1 V_2 (1 - \tau_2) \prod_{k=3}^M (1 - V_k \tau_k) \quad \dots (5.22)$$

The period of successful transmission for basic, RTS/CTS, and M-CTS access mechanisms are respectively given by

$$T_{E4}^{\text{bas}} = \text{PTS} + \text{SS} + \text{DATA} + \text{SIFS} + \text{ACK} + \text{DIFS} \quad \dots (5.23)$$

$$T_{E4}^{\text{rts}} = \text{PTS} + \text{SS} + \text{RTS} + \text{SIFS} + \text{CTS} + \text{SIFS} + \text{DATA} + \text{SIFS} + \text{ACK} + \text{DIFS} \quad \dots (5.24)$$

$$T_{E4}^{\text{mcts}} = \text{PTS} + \text{SS} + \text{CTS} + \text{SIFS} + \text{DATA} + \text{SIFS} + \text{ACK} + \text{DIFS} \quad \dots (5.25)$$

Generally speaking, the following expression holds true for an arbitrary SU which is in transmission mode

$$P_{E1} + P_{E2} + P_{E3} + P_{E4} = 1$$

$$P_{E4} = 1 - P_{E1} + P_{E2} + P_{E3} \quad \dots (5.26)$$

The above expression shows that a transmitted frame from an arbitrary SU may experience transmitter blocking, or collision from another SU(s) transmission, or receiver blocking. In general we call it transmission failure. The probability of transmission failure P_{tf} is therefore given by

$$P_{tf} = P_{E1} + P_{E2} + P_{E3} \quad \dots (5.27)$$

Then, the probability a packet of an arbitrary SU is successfully transmitted can be expressed as

$$P_{E4} = 1 - P_{tf} \quad \dots (5.28)$$

In the next section the possible events a SU experience while it is in overhearing or in listening mode are modeled. We have considered two broad cases of channel detection outcome scenarios by an arbitrary SU i.e. when it is detected idle or busy.

V. Idle Channel Detection (E_5)

This event happens when the arbitrary secondary user U_1 listens to the channel and detects it idle at the current time slot and the previous DIFS. If it is in backoff state and the backoff timer is not zero, U_1 will decrement its backoff timer by 1 at the end of the current time slot, and if the backoff timer is zero, U_1 will start transmitting at the end of the current time slot. The probability of no PTS transmission among the $M-1$ SUs in the current transmission time and the previous DIFS is given by two different scenarios

- 1) The SU detects idle channel when all the SUs do not detect the PU(s) and do not want to transmit. This probability is given by

$$P_{ID1} = PH_o(1 - p_f) \prod_{k=1}^{M-1} (1 - V_k \tau_k) \quad \dots (5.29)$$

2) The SU detects idle channel when all the M-1 SUs detect the channel busy and defer their transmission (due to false alarm) at the same time. The probability is given by

$$P_{ID2} = PH_o(p_f) \quad \dots (5.30)$$

The probability of idle channel detection by an arbitrary SU is given by

$$P_{E5} = P_{ID1} + P_{ID2} = PH_o(1 - p_f) \prod_{k=1}^{M-1} (1 - V_k \tau_k) + PH_o(p_f) \quad \dots (5.31)$$

The period of idle channel detection for all the three access mechanisms is given by

$$T_{E5} = \text{current time slot } (\delta) + \text{DIFS} \quad \dots (5.32)$$

Busy Channel Detection (p_b)

Now let's derive the probability of busy channel detection by an arbitrary SU while in listening mode. The channel could be detected to be busy by an arbitrary SU when it detects PU(s) signals only, or when it detects SU(s) signal only or when it detects both SU and PU signals due to miss detection error.

VI. Only PU's Signal Detection (E₆)

This event occurs when an arbitrary SU overhear PU signal only. This case happens when all of the SUs miss detect PU presence but do not want to transmit, or when all of the M-1 SUs detect PU signal and defer their transmission at that time slot. The probability all the M-1 SUs miss detects PU presence but they do not transmit is given by

$$P_{pu1} = PH_1(1 - p_d) \prod_{k=1}^{M-1} (1 - V_k \tau_k) \quad \dots (5.33)$$

The probability all the M-1 SUs detects PU presence and defer their transmission is given by

$$P_{pu2} = PH_1(p_d) \quad \dots (5.34)$$

Then the probability of only PU signal detection is given by $P_{E6} = P_{pu1} + P_{pu2}$

$$P_{E6} = PH_1(1 - p_d) \prod_{k=1}^{M-1} (1 - V_k \tau_k) + PH_1(p_d) \quad \dots (5.35)$$

At this time the secondary user (U1) will freeze its back off timer and defers for a time length of T_{E1} for the three access mechanisms.

VII. Only SU(s) Signal Detection (E7)

This event occurs when an arbitrary SU detects SU(s) signal only at an arbitrary time slot. An arbitrary SU detects SU(s) signal only when all the SUs detect the channel idle and more than two SUs transmit simultaneously (SUs transmission collision), or when all the SUs detect the channel idle and only one SU transmit and the intended receiver do not transmit and it can access the channel at the same time slot (successful transmission).

The probability all the SUs detect the channel idle and more than two SUs transmit simultaneously is given by (this is a collision between SUs transmission)

$$P_{SSC} = PH_o(1 - p_f) \sum_{i=2}^{M-1} \binom{M-1}{i} \prod_{x=2}^i (V_x \tau_x) \prod_{y=i+1}^{M-1} (1 - V_y \tau_y) \quad \dots (5.36)$$

At this time the arbitrary SU who is listening to the channel (which is in backoff state) will defers its communication for a time of T_C since it knows that a collision has occurred, and T_C for RTS/CTS and basic access mechanisms can be given by

$$T_C^{bas} = PTS + SS + DATA + DIFS \quad \dots (5.37)$$

$$T_C^{rts} = PTS + SS + RTS + DIFS \quad \dots (5.38)$$

$$T_C^{mcts} = PTS + SS + DIFS \quad \dots (5.39)$$

The probability all the SUs detect the channel idle and only one SU transmit and the intended receiver do not transmit but it can access the channel at that time slot (this is a successful transmission) is given by

$$P_{ST} = PH_o(1 - p_f) \binom{M-1}{1} V_x \tau_x V_y (1 - \tau_y) \prod_{i=1}^{M-3} (1 - V_i \tau_i) \quad \dots (5.40)$$

At this time the listening SU will defer its transmission for a period of T_{ST} which is equivalent to T_{E4}^{bas} for basic access, T_{E4}^{rts} for RTS/CTS access, and T_{E4}^{mcts} for M-CTS access mechanism.

The probability all the $M-2$ SUs detect the channel idle, and only one SU transmit but the intended receiver cannot access the channel (Receiver Blocking) is given by

$$P_{RB} = PH_o(1 - p_f) \binom{M-1}{1} V_x \tau_x (1 - V_y) \prod_{i=1}^{M-3} (1 - V_i \tau_i) \quad \dots (5.41)$$

Therefore, the probability an arbitrary SU detects only SU(s) signals is given by

$$P_{E7} = P_{SSC} + P_{ST} + P_{RB}$$

$$P_{E7} = PH_o(1 - p_f) \left\{ \begin{array}{l} \binom{M-1}{1} V_x \tau_x V_y (1 - \tau_y) \prod_{i=1}^{M-3} (1 - V_i \tau_i) \} + \\ \binom{M-1}{1} V_x \tau_x (1 - V_y) * \prod_{i=1}^{M-3} (1 - V_i \tau_i) \} + \\ \sum_{i=2}^{M-1} \binom{M-1}{i} \left\{ \prod_{x=1}^i (V_x \tau_x) * \prod_{y=i+1}^{M-1} (1 - V_y \tau_y) \right\} \end{array} \right\} \quad \dots (5.42)$$

VIII. Detection of both PU and SU Signals (E8)

This event represents collision between PU(s) and SU(s) transmission. It occurs when an arbitrary SU detects the transmission of both the PU and SU. An arbitrary SU detects both transmissions when the transmitting SU miss detect the channel idle when it is actually

occupied by the PU(s). The probability an arbitrary SU detects the transmission of both PU and SU signal is given by the probability at least one SU transmit due to miss detection

$$P_{E8} = P_{PS} = PH_1(1 - p_d) \sum_{i=1}^{M-1} \binom{M-1}{i} \prod_{x=1}^i (V_x \tau_x) * \prod_{y=i+1}^{M-1} (1 - V_y \tau_y) \quad \dots (5.43)$$

For this scenario the secondary user which is in backoff state will defers its communication for a time of $T_{E8} = T_{E3}$.

Generally speaking, the following expression holds true for an arbitrary SU who is in listening mode.

$$P_{E5} + P_{E6} + P_{E7} + P_8 + P_{E9} = 1 \quad \dots (5.44)$$

Let's define the throughput S of a system. The throughput of a MAC protocol can be defined as a fraction of time the SU has the full privilege to access the licensed channel opportunistically and be able to successfully transmit its payload.

$$S = \frac{E[\text{Payload Information transmitted in a slot time}]}{E[\text{length of a slot time}]}$$

The average length of a slot time for basic, RTS/CTS and M-CTS access mechanisms are given by

$$E[\text{slot}]^{\text{bas}} = P_{E5} \delta + P_{E6} T_{E1}^{\text{bas}} + P_{SSC} T_C^{\text{bas}} + P_{RB} T_{E2}^{\text{bas}} + P_{ST} T_{E4}^{\text{bas}} + P_{E8} T_{E8}^{\text{bas}} + P_{E9} T_{E9}^{\text{bas}} \quad \dots (5.45)$$

$$E[\text{slot}]^{\text{rts}} = P_{E5} \delta + P_{E6} T_{E1}^{\text{rts}} + P_{SSC} T_C^{\text{rts}} + P_{RB} T_{E2}^{\text{rts}} + P_{ST} T_{E4}^{\text{rts}} + P_{E8} T_{E8}^{\text{rts}} + P_{E9} T_{E9}^{\text{rts}} \quad \dots (5.46)$$

$$E[\text{slot}]^{\text{mcts}} = P_{E5} \delta + P_{E6} T_{E1}^{\text{mcts}} + P_{SSC} T_C^{\text{mcts}} + P_{RB} T_{E2}^{\text{mcts}} + P_{ST} T_{E4}^{\text{mcts}} + P_{E8} T_{E8}^{\text{mcts}} + P_{E9} T_{E9}^{\text{mcts}} \quad \dots (5.47)$$

Then, the average throughput of the MAC protocols for the three access mechanisms can be expressed in terms of their corresponding average slot time as follows

$$S^{\text{bas}} = \frac{P_{ST} E[P]}{P_{E5} \delta + P_{E6} T_{E1}^{\text{bas}} + P_{SSC} T_C^{\text{bas}} + P_{RB} T_{E2}^{\text{bas}} + P_{ST} T_{E4}^{\text{bas}} + P_{E8} T_{E8}^{\text{bas}} + P_{E9} T_{E9}^{\text{bas}}} \quad \dots (5.48)$$

$$S^{rts} = \frac{P_{ST}E[P]}{P_{E5}\delta + P_{E6}T_{E1}^{rts} + P_{SSC}T_C^{rts} + P_{RB}T_{E2}^{rts} + P_{ST}T_{E4}^{rts} + P_{E8}T_{E8}^{rts} + P_{E9}T_{E9}^{rts}} \quad \dots (5.49)$$

$$S^{mcts} = \frac{P_{ST}E[P]}{P_{E5}\delta + P_{E6}T_{E1}^{mcts} + P_{SSC}T_C^{mcts} + P_{RB}T_{E2}^{mcts} + P_{ST}T_{E4}^{mcts} + P_{E8}T_{E8}^{mcts} + P_{E9}T_{E9}^{mcts}} \quad \dots (5.50)$$

5.3.2 Packet Delay Analysis for CR-MAC

Generally, the average packet delay, $E(D)$, for successfully transmitted packet can be defined as the amount of time it takes for a packet to reach the destination starting from the time it is being ready for transmission (at the top of the output queue of the MAC layer) till an acknowledgment is received.

Packet drop probability (P_{drop}) is the probability a packet is dropped when it reaches the retry limit or the probability a packet reaches the last stage and experiences more collision, where m is the number of stages (retry limit). The probability a packet is successfully transmitted at an arbitrary stage i is given by

$$P_{suc}(i) = (1 - P_{E4})^i(P_{E4}) \quad 0 \leq i \leq m \quad \dots (5.51)$$

The packet is dropped when the retry limit is reached, then the packet drop probability becomes

$$P_{drop} = 1 - \sum_{i=0}^m P_{suc}(i) = 1 - \sum_{i=0}^m P_{tf}^i(1 - P_{tf}) = 1 - \sum_{i=0}^m (1 - P_{E4})^i(P_{E4})$$

$$P_{drop} = 1 - (1 - P_{tf}) \sum_{i=0}^m P_{tf}^i = 1 - (1 - P_{tf}) \left(\frac{P_{tf}^{m+1} - 1}{P_{tf} - 1} \right) = P_{tf}^{m+1} = (1 - P_{E4})^{m+1} \quad \dots (5.52)$$

The probability a packet is not dropped, means a packet do not experience more than m collision (it is transmitted at arbitrary stage before experiencing more than m number of collision) is given by

$$P'_{drop} = 1 - P_{drop} = 1 - P_{tf}^{m+1} \quad \dots (5.53)$$

The probability a packet reaches in backoff stage i given that it is not dropped is given by the following conditional probability (unless the retry limit is not reached, at any stage it has the probability to experience collision or may succeed to transmit)

$$p(S_i \setminus P_{\text{notdropped}}) = \frac{p(S_i \cap P_{\text{notdropped}})}{p(P_{\text{notdropped}})} = \frac{p(S_i) + p(P_{\text{notdropped}}) - p(S_i \cup P_{\text{notdropped}})}{p(P_{\text{notdropped}})}$$

$$p(S_i \setminus P_{\text{notdropped}}) = \frac{P_{\text{tf}}^i + P'_{\text{drop}} - p(S_i \cup P_{\text{notdropped}})}{P'_{\text{drop}}}$$

$$p(S_i \setminus P_{\text{notdropped}}) = \frac{P_{\text{tf}}^i + 1 - P_{\text{tf}}^{m+1} - p(S_i \cup P_{\text{notdropped}})}{1 - P_{\text{tf}}^{m+1}}$$

Where $p(S_i \cup P_{\text{notdropped}}) = 1$, then the probability a packet reaches in backoff stage i given that it is not dropped is given by

$$p(S_i \setminus P_{\text{notdropped}}) = \frac{P_{\text{tf}}^i - P_{\text{tf}}^{m+1}}{1 - P_{\text{tf}}^{m+1}} \quad \dots (5.54)$$

Where $p(S_i)$ is the probability a packet reach in backoff stage i , and $p(P_{\text{notdropped}})$ is the probability a packet is not dropped.

The average delay of a packet at any arbitrary backoff stage i is given by

$$W_{\text{avg}}^i = \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} = \frac{W_i + 1}{2} \quad \dots (5.55)$$

Then the average number of slots required to successfully transmit a packet becomes

$$E(X) = \sum_{i=0}^m \frac{P_{\text{tf}}^i - P_{\text{tf}}^{m+1}}{1 - P_{\text{tf}}^{m+1}} W_{\text{avg}}^i = \sum_{i=0}^m \frac{(W_i + 1)(P_{\text{tf}}^i - P_{\text{tf}}^{m+1})}{2(1 - P_{\text{tf}}^{m+1})}$$

$$E(X) = \sum_{i=0}^m \frac{(2^i W + 1)(P_{\text{tf}}^i - P_{\text{tf}}^{m+1})}{2(1 - P_{\text{tf}}^{m+1})} \quad \dots (5.56)$$

The average packet delay a station experience is given by

$$E(D) = E(X).E(slot) \quad \dots (5.57)$$

For the three access mechanisms the average packet delay expressions become

$$\begin{aligned} E(D)^{bas} &= E(X).E(slot)^{bas} \\ &= \{P_{E5}\delta + P_{E6}T_{E1}^{bas} + P_{SSC}T_C^{bas} + P_{RB}T_{E2}^{bas} + P_{ST}T_{E4}^{bas} + P_{E8}T_{E8}^{bas} \\ &\quad + P_{E9}T_{E9}^{bas}\} \cdot \sum_{i=0}^m \frac{(2^iW + 1)(P_{tf}^i - P_{tf}^{m+1})}{2(1 - P_{tf}^{m+1})} \quad \dots (5.58) \end{aligned}$$

$$\begin{aligned} E(D)^{rts} &= E(X).E(slot)^{rts} \\ &= \{P_{E5}\delta + P_{E6}T_{E1}^{rts} + P_{SSC}T_C^{rts} + P_{RB}T_{E2}^{rts} + P_{ST}T_{E4}^{rts} \\ &\quad + P_{E8}T_{E8}^{rts} + P_{E9}T_{E9}^{rts}\} \cdot \sum_{i=0}^m \frac{(2^iW + 1)(P_{tf}^i - P_{tf}^{m+1})}{2(1 - P_{tf}^{m+1})} \quad \dots (5.59) \end{aligned}$$

$$\begin{aligned} E(D)^{mcts} &= E(X).E(slot)^{mcts} \\ &= \{P_{E5}\delta + P_{E6}T_{E1}^{mcts} + P_{SSC}T_C^{mcts} + P_{RB}T_{E2}^{mcts} + P_{ST}T_{E4}^{mcts} + P_{E8}T_{E8}^{mcts} \\ &\quad + P_{E9}T_{E9}^{mcts}\} \cdot \sum_{i=0}^m \frac{(2^iW + 1)(P_{tf}^i - P_{tf}^{m+1})}{2(1 - P_{tf}^{m+1})} \quad \dots (5.60) \end{aligned}$$

5.4 Simulation and Discussion

In this section simulation results for CR-MAC protocol are presented and discussed. The simulations are carried out to show the performance of CR-MAC protocol in terms of throughput and average packet delay as key MAC performance indicators.

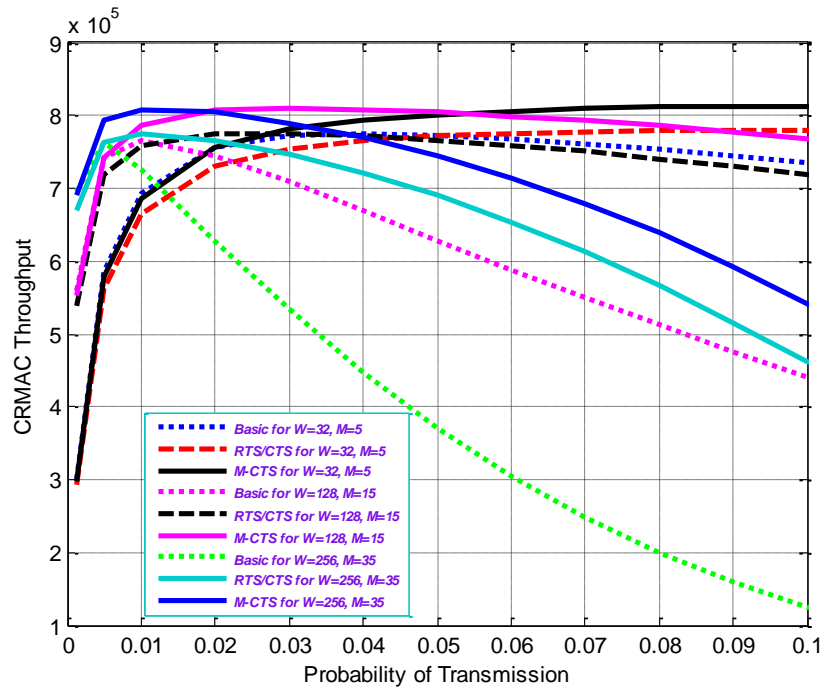
The simulator used is an event driven MATLAB simulator (MATLAB R2013b). We choose MATLAB because it is a powerful simulator to work with analytical and more of physical layer dominated tasks. To perform the simulations we have used the following parameters which are presented in a tabular form below.

Table 5.1 CR-MAC protocol simulation parameters [70]

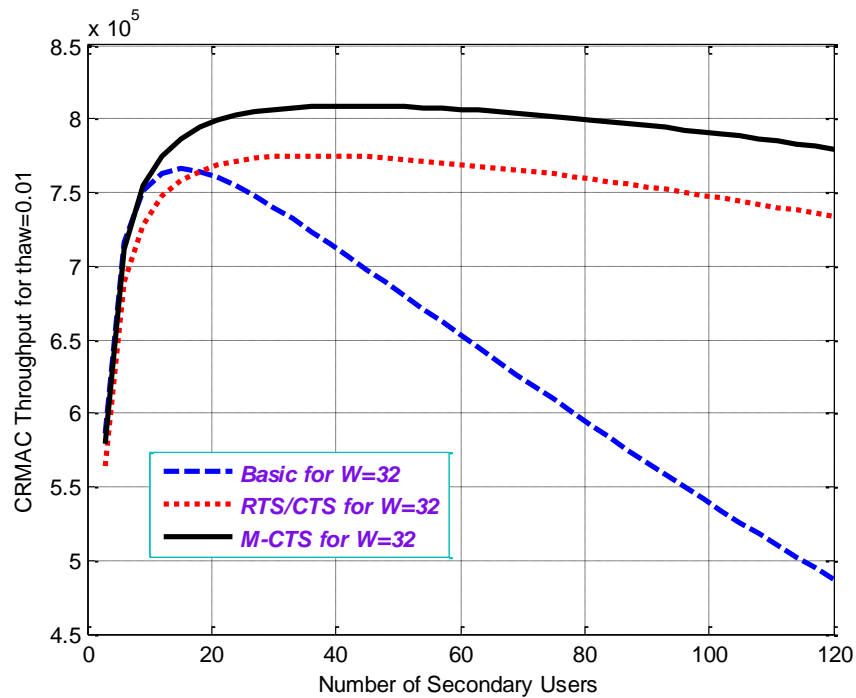
Simulation Parameters used	
<i>Channel Bit Rate</i>	<i>1 Mbit/sec</i>
<i>Slot Time</i>	<i>20μsec</i>
<i>Spectrum Sensing Time</i>	<i>0.5ms</i>
<i>SIFS</i>	<i>10μsec</i>
<i>DIFS</i>	<i>50μsec</i>
<i>Initial Contention Window Size (W)</i>	<i>32</i>
<i>Maximum Backoff Stage (m)</i>	<i>5</i>
<i>PHY Header</i>	<i>192 bits</i>
<i>MAC Header</i>	<i>272 bits</i>
<i>Packet Payload</i>	<i>8000 bits</i>
<i>PTS</i>	<i>112 bits + PHY Header</i>
<i>RTS</i>	<i>160 bits + PHY Header</i>
<i>CTS</i>	<i>112 bits + PHY Header</i>
<i>ACK</i>	<i>112 bits + PHY Header</i>

Moreover, the following parameters are used in the simulations, probability of false alarm ($P_f=0.01$), probability of detection ($P_d=0.9$), and probability of vacant channel availability ($P_{H_0}=0.9$) unless otherwise.

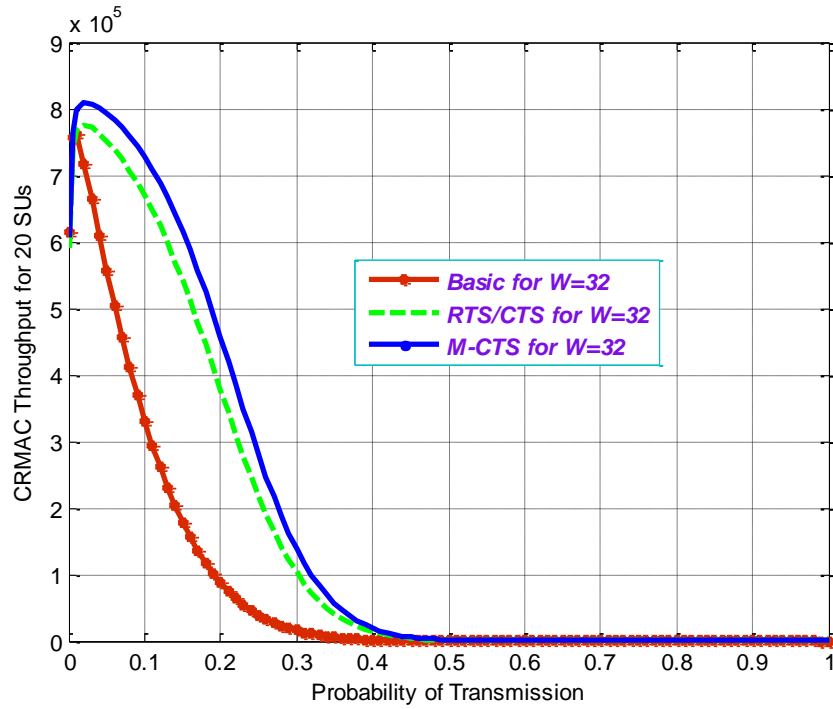
In most of the simulations, the performance comparisons are performed for the three medium access mechanisms, these are Basic Access Mechanism, RTS/CTS Access Mechanism, and M-CTS Access Mechanism. Fig. 5.6 shows the throughput performance of CR-MAC protocols by varying number of SUs, probability of transmission, contention window size, and probability of vacant channel detection measured in bit per second. Whereas, fig. 5.7 shows the effect of varying number of SUs, probability of transmission, and contention window size on the performance of the average packet delay of CR-MAC protocols based on the three access mechanisms which is measured in second.



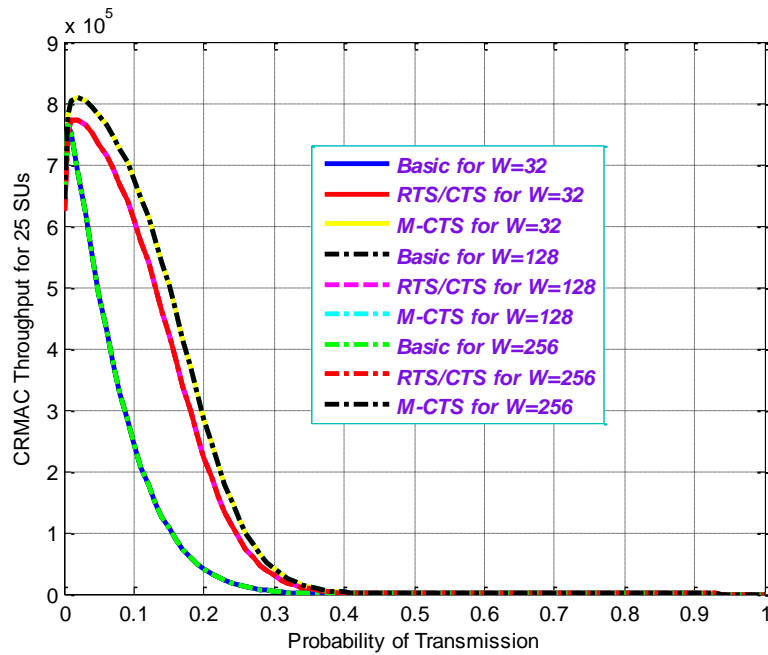
5.6a) Effect of varying probability of transmission on the throughput performance of CR-MAC protocol for Basic, RTS/CTS, and M-CTS protocol.



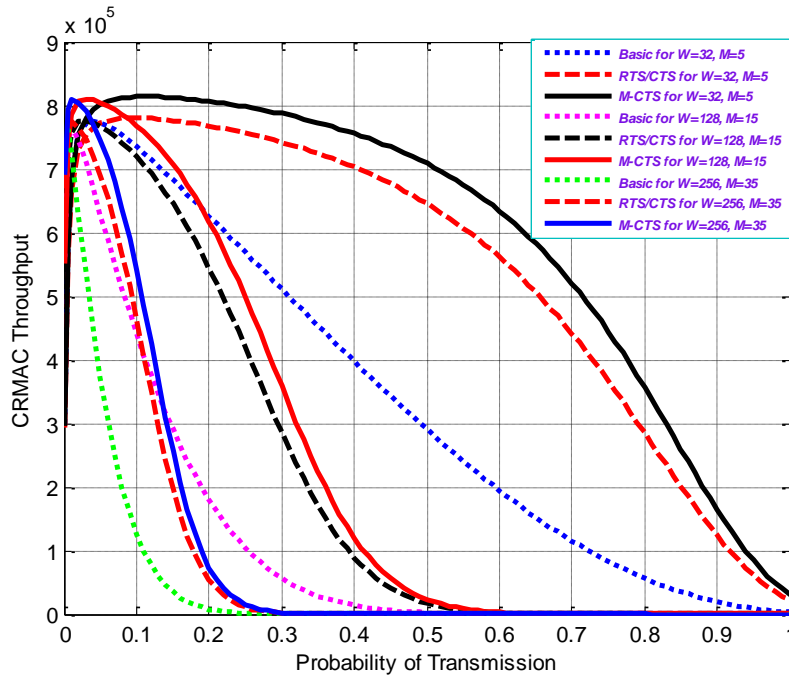
5.6b) Effect of varying number of SUs on the throughput performance of CR-MAC protocol for Basic, RTS/CTS, and M-CTS protocol for constant probability of transmission.



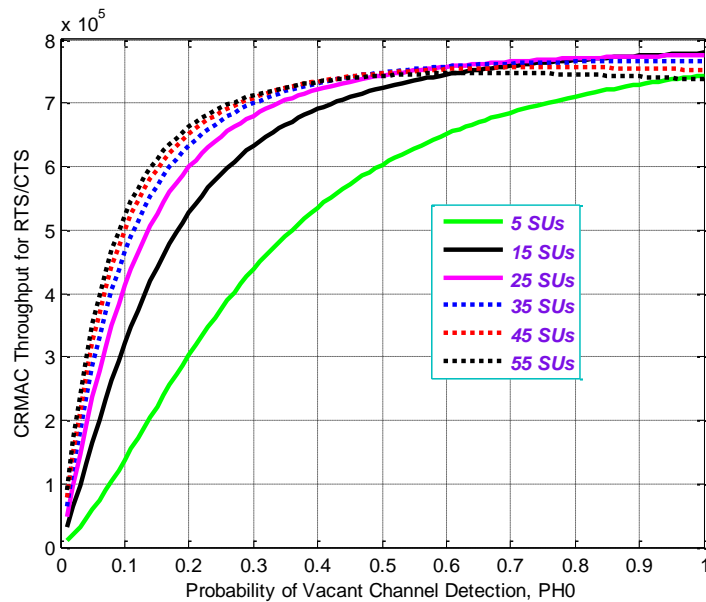
5.6c) Effect of varying probability of transmission on the throughput performance of CR-MAC protocol for Basic, RTS/CTS, and M-CTS protocol for fixed number of SUs (20 SUs).



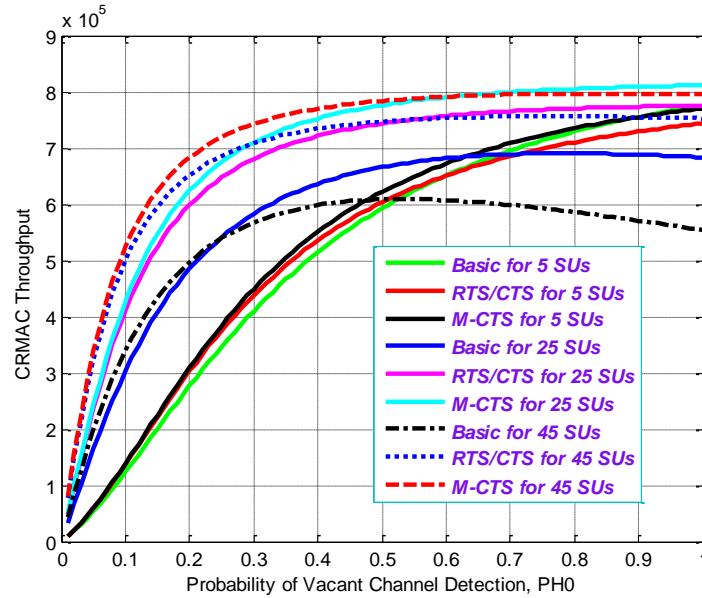
5.6d) Effect of varying probability of transmission on the throughput performance of CR-MAC protocol for Basic, RTS/CTS, and M-CTS protocol for different number contention window sizes ($W=32$, $W=128$, $W=256$) and constant number of SUs (25 SUs).



5.6e) Effect of varying probability of transmission on the throughput performance of CR-MAC protocol for Basic, RTS/CTS, and M-CTS protocol for different contention window sizes and number of SUs.



5.6f) Effect of varying probability of vacant channel detection (PH_0) on the throughput performance of CR-MAC protocol for RTS/CTS access mechanism for different number of SUs and constant probability of transmission (0.02).



5.6g) Effect of varying probability of vacant channel detection (P_{H0}) on the throughput performance of CR-MAC protocol for Basic, RTS/CTS, and M-CTS access mechanisms for different number of SUs and constant probability of transmission (0.02).

Fig. 5. 6 Throughput of CR-MAC Protocol for Basic, RTS/CTS, and M-CTS access mechanisms evaluated for different number of SUs, Probability of transmission, and Probability of vacant channel detection.

Simulation in fig. 5.6 (a) shows the throughput performance of CR-MAC protocol for Basic, RTS/CTS, and M-CTS access mechanisms. The simulation is operated by varying the probability of transmission for different number of SUs of 5, 15 and 35 and contention window size of $W=32$, $W=128$, and $W=256$. For all the scenarios, the proposed ECR-MAC protocol developed based on M-CTS access mechanism outperforms the remaining CR-MAC protocols developed based on the Basic and RTS/CTS access mechanisms. The simulation shows that the throughput of CR-MAC protocols (for all of the three access mechanisms) is high for lower probability of transmission, large number of SUs and contention window size. This is true because, as the probability of transmission increases, the probability of collision will increase as a result of which the amount of successful transmission will decrease and the throughput will continues to decline. Moreover, the simulation shows that having lower number of SUs results better throughput for all the probability of transmission, this is because of the chance of packet transmission by many nodes at the same time is low for small number of secondary users. The best throughput performance is

observed for ECR-MAC protocol developed based on the proposed M-CTS access mechanism in relative to the other CR-MAC protocols.

The simulation in fig. 5.6 (b) is carried out for constant contention window size ($W=32$) and constant probability of transmission (0.01) by varying number of SUs. The throughput of CR-MAC protocol for Basic, RTS/CTS, and M-CTS access mechanisms exhibit the maximum throughput value for small number of SUs. As the number of SUs increase the throughput performance for basic access starts declining faster than the RTS/CTS and M-CTS access mechanisms. As the number of SUs becomes larger and larger, the numbers of contending nodes will increase which increase the chance of collision and degrade the throughput of the CR-MAC protocols in general. The M-CTS access mechanism shows superior throughput performance for all number of SUs especially for larger number of SUs.

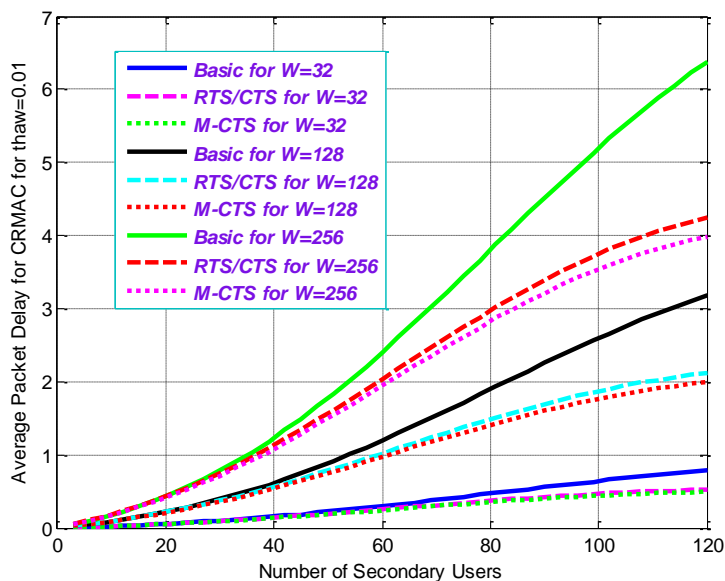
Simulation in fig. 5.6 (c) shows the effect of varying probability of transmission on the throughput performance of CR-MAC protocols for constant number of SUs (20) and constant contention window size ($W=32$). For low probability of transmission better throughput is observed. This is due to the fact that as the probability of transmission decreases, the probability of transmission failure decreases which decrease the probability the packet get dropped and increases the chance of successful packet transmission. From the three CR-MAC protocols, the ECR-MAC protocol shows better throughput performance for different value of probability of transmission and retry limit of five.

In fig. 5.6 (d), the effect of varying probability of transmission on the throughput performance of CR-MAC protocols developed based on the three access mechanism is simulated. The simulation is carried out to show the effect of varying contention window size on the throughput performance. It is operated for contention window sizes of $W=32$, $W=128$ and $W=256$, and for constant number of SUs which is twenty five SUs. The simulation result shows that contention window size has no impact on the throughput of CR-MAC protocols for all the three access mechanisms, which is true since the expression for the throughput of CR-MAC protocol is independent of the contention window size but it is dependent on the retry limit which is constant and assumed to be five.

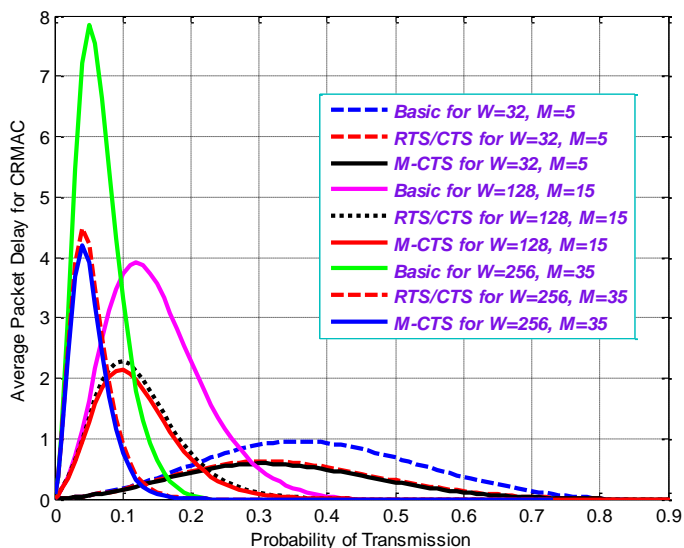
The simulation in fig. 5.6 (e) shows the effect of varying probability of transmission on the throughput performance of CR-MAC protocols designed based on Basic, RTS/CTS, and M-CTS access mechanisms for different contention window sizes and number of SUs. The simulation shows that as the probability of transmission becomes larger for example more than 0.5, the throughput of CR-MAC protocols except the one simulated for 5 numbers of SUs become zero. This is due to the fact that collision probability of an arbitrary cognitive user is dependent on two variables; these are number of SU and probability of transmission. Increasing the probability of transmission for constant number of SU will increase the collision probability. However, the collision probability relatively becomes small for small number of SU compare to very large number of SU for a given probability of transmission. Generally, the simulation shows that as the number of SUs increases the throughput performance decreases for all probability of transmission..

The simulations shown in fig. 5.6 (f), and (g) present the impact of varying spectrum availability rate (P_{H0}) on the throughput performance of CR-MAC protocols. This parameter is the most significant parameter for spectrum opportunistic network such as cognitive radio network. The simulation is carried out for Basic, RTS/CTS, and M-CTS access mechanisms with constant probability of transmission (0.02), and for different number of SUs. The simulations show the throughput performance improvement of CR-MAC protocols as the rate of spectrum availability increases. The simulations show that the CRN archives the maximum MAC throughput for the highest probability of vacant channel detection. This is true in the sense that cognitive radio networks are opportunistic network which opportunistically utilizes the unused spectrum. As the spectrum utilization rate of the primary network become low, the performance of the opportunistic network increases. For this assumption also the proposed M-CTS access based MAC protocol called ECR-MAC, shows better throughput performance over the other two types of CR-MAC protocols. The maximum performance is observed for number of SU of twenty five, especially for RTS/CTS and M-CTS access mechanisms. Moreover, the performance of ECR-MAC protocol shows superior performance for higher probability of vacant channel detection.

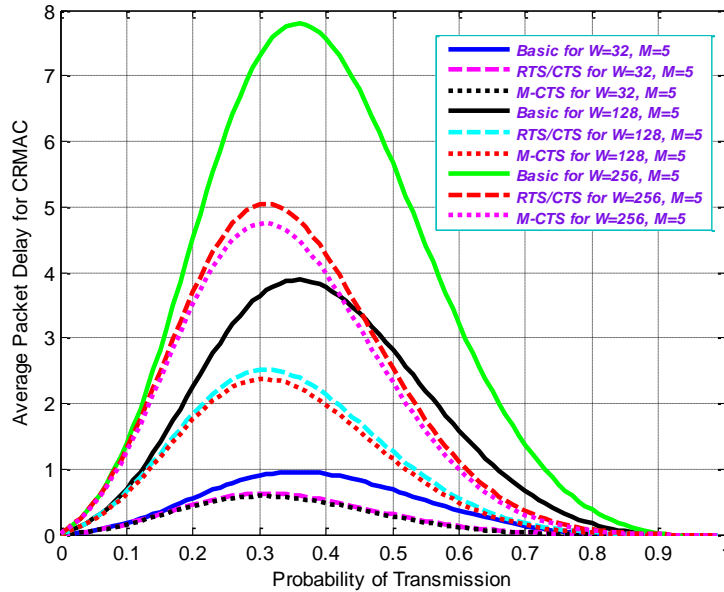
Moreover, due to lack of collision avoidance the basic access mechanism shows least performance for larger number of SUs, larger contention window size, and higher probability of transmission.



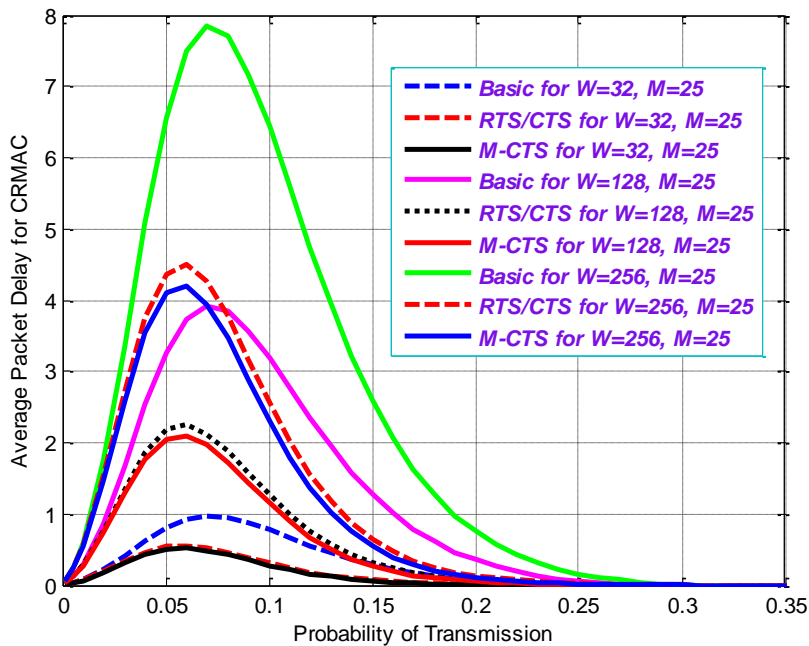
5.7a) Effect of varying number of SUs on the performance of average packet delay of CRMAC protocol for different contention window sizes maintaining probability of transmission constant for Basic, RTS/CTS, and M-CTS access mechanisms.



5.7b) Effect of varying probability of transmission on the performance of average packet delay of CRMAC protocol for different contention window sizes and number of SUs for Basic, RTS/CTS, and M-CTS access mechanisms.



5.7c) Effect of varying probability of transmission on the performance of average packet delay of CRMAC protocol for different contention window sizes while maintaining number of SUs constant (5 SUs) for Basic, RTS/CTS, and M-CTS access mechanisms.



5.7d) Effect of varying probability of transmission on the performance of average packet delay of CRMAC protocol for different contention window sizes while maintaining number of SUs constant (25 SUs) for Basic, RTS/CTS, and M-CTS access mechanisms.

Fig. 5. 7 Average Packet Delay of CRMAC Protocol for Basic, RTS/CTS, and M-CTS access mechanisms.

Simulations in fig. 5.7 show the behavior of average packet delay of CRMAC protocol for the three access mechanisms. The simulation in fig. 5.7 (a) shows the effect of varying number of SUs on the performance of average packet delay of CRMAC protocol for different contention window sizes and constant probability of transmission for Basic, RTS/CTS, and M-CTS access mechanisms. For all contention window sizes, the average packet delay increases as the number of secondary users' increases. Moreover, the average packet delay for larger contention window size is longer than those having relatively smaller contention window size, because contention window size has a direct impact on average packet delay. As the contention window size becomes larger, the amount of time a node wait in the backoff window will increase and becomes more longer when it experiences a collision since the contention window size get doubled for every collision. This is clearly observed in the simulation, see contention window size of 32 and 256 as an example. The delay due to larger number of SUs and larger contention window size can be examined from the simulation output, where the impact of large contention window size is very significant compared to the delay due to larger number of SUs. Similarly, as the number of SUs becomes larger the probability of collision will be higher which results longer packet delay, and the problem pronounced more even when the contention window becomes larger.

Table 5.2 M-CTS based CR-MAC (ECR-MAC) throughput comparison in kbps

Number of SUs	3	6	9	12	15	30	45	60	75	90	105	120
Throughput gain compared with RTS	14.69	27.01	32.71	36.06	38.34	44.31	47.73	50.50	53.00	55.37	57.65	59.85
Throughput gain compared with basic	-10.66	-15.27	-12.91	-8.11	-2.23	31.63	65.84	98.25	128.36	155.98	181.02	203.44

Generally, the saturated throughput performance of ECR-MAC protocol is presented quantitatively in table 5.2. The relative saturated throughput gain with respect to RTS/CTS and basic access mechanisms based CR-MAC protocols. The relative saturated throughput is presented in kbps for different number of SUs. The empirical result shows that the basic access mechanism based CR-MAC protocol exhibit superior performance in terms of saturated throughput. For example, the basic access based CR-MAC protocol show good performance for number of SUs less than or equal to fifteen; whereas, for SUs more than sixteen the M-CTS access based CR-MAC protocol (ECR-MAC) shows good performance. For

any number of SUs, M-CTS based CR-MAC protocol shows better performance compared with the RTS/CTS based CR-MAC protocol.

The simulations in fig. 5.7 (b), fig. 5.7 (c), and fig. 5.7 (d) show that as the probability of transmission increases, the number of SUs that attempt to transmit increases especially in saturated condition. For saturated condition, as the probability of transmission becomes larger and larger, the probability a transmission sees collision increase, and ultimately the throughput starts to decline which results no successful transmission. For limited number of retry limit, as the probability of transmission becomes higher, in almost all the time the channel is detected idle and the chance of collision becomes high, which results fast packet drop. Under all scenarios the proposed M-CTS access mechanism results lower average packet delay in relative to Basic and RTS/CTS access mechanisms.

In this chapter an enhanced random access MAC protocol for CRN (ECR-MAC) based on M-CTS access mechanism has been proposed. The performance of this proposed MAC protocol has been compared with the performance of two other variant of random access MAC protocols based on basic and RTS/CTS access mechanisms. Throughput and average packet delay have been used to evaluate the performance of the proposed protocol. Probability of transmission, contention window size, and number of SUs has been used as controlling parameters. For all scenarios the proposed MAC protocol, ECR-MAC show better performance in terms of throughput and average packet delay. In the next chapter, three new directional random access cognitive radio MAC (CR-MAC) protocols have been proposed.

Chapter-6

DIRECTIONAL RANDOM ACCESS MAC PROTOCOLS FOR COGNITIVE RADIO NETWORKS (DCR-MAC)

6.1 Introduction

In this chapter we are going to present the design and analysis of directional random access MAC protocol for CRWMN. We have proposed three directional random access MAC protocols for CRNs in general to the CRWMN in particular using the three access mechanisms. Simulations are carried out to compare the performance of the proposed MAC protocols in terms of average throughput and average packet delay by using the following parameters namely beamwidth, number of SUs, contention window size, probability of transmission and retry limit for the three access mechanisms. Moreover, the performances of the proposed DCR-MAC protocols are compared with omni-directional CR-MAC protocols and the proposed directional protocols show better performance in terms of average throughput and packet delay.

Directional antennas have many advantages over omni-directional antenna system in wireless networks such as improving network capacity, reducing interference, increasing coverage area, improving spectrum usage, improving energy efficiency, and the likes. In spite of the major benefits of directional antenna to the wireless domain, it has introduced new challenges to the MAC layer. The most popular MAC protocol in the wireless domain particularly in the wireless LAN and multi-hop wireless networks is the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The CSMA/CA MAC protocol cannot be used with directional antenna without modification, because of the newly emerged challenges such as deafness, New Hidden Terminal Problem (NHT), Head-of-Line Blocking,

Communication Range Under-Utilization, Neighbors Location Discovery, and MAC-Layer-Capture. These challenges are presented briefly in the next section [118]-[120].

6.2 Challenges of Directional Antenna in Random Access MAC Protocols

In this section we present the common challenges a random access MAC protocol may face while incorporating directional antenna to the system. These are deafness, new hidden terminal problem, head-of-line blocking, communication range under-utilization, neighbors' location discovery, and MAC-Layer-Capture.

6.2.1 Deafness

Deafness occurs when the intended receiver is beamformed to a direction which is away from the transmitter that want to initiate communication without knowing communication is in progress with other node. At this time the transmitter is deaf to all direction except in the direction of communication. As a result of deafness a node will be in unnecessary retransmission schedule that decrease network capacity at large, increase the contention window (short term unfairness because a node which has the shortest contention window will have the privilege to access the medium), and may create deadlock scenario (the transmitter which want to transmit might become deaf to another transmitters) [118], [120], [123], [124], [126].

6.2.2 New Hidden Terminal Problem (NHT)

The main problem associated with hidden terminal is packet collision. The conventional hidden terminal problem created by omnidirectional antenna is alleviated by the use of Request to Send (RTS) and Clear to Send (CTS) mechanism. However, the use of directional antennas introduced new hidden terminal problems which are hidden terminal problem due to unheard RT/CTS and hidden terminal problem due to asymmetry in antenna gain. The frequency of occurrence of the later problem is rare but the former would be very significant [118]-[127].

6.2.3 Head-of-Line Blocking

In the omnidirectional communication there is no head-of-line blocking because only there is one medium and one node can use it at a time (no concurrent transmission). However, due to the directional antenna the medium is spatially divided and it supports parallel transmission on one medium. Head-of-line blocking occurs when the packet at the top of the queue is destined to a busy node/direction but there exists a subsequence packets destined to non-busy node/direction, like in FIFO system [121].

6.2.4 Communication Range Under-Utilization

One advantage of directional antennas is range extension which has a direct impact on the network deployment cost by decreasing the number of nodes/hops required to cover a given area. However, most of the proposed MAC protocols using directional antennas require the system to switch between directional and omnidirectional communication. This phenomenon hinders the full exploitation of range extension while the system is operating in omnidirectional mode.

6.2.5 MAC-Layer-Capture

MAC-layer-capture in directional communication occurs when a node receives a packet not intended for it. In such situation, the node comes to know that the packet is not destined to it only when it reaches at the MAC layer. The time it wastes in decoding a packet not destined to it results spectrum underutilization and decreases the network performance. This phenomena is known as MAC-layer-capture [125].

6.2.6 Neighbors' Location Discovery

The information about the location of neighbors is vital in case of directional antennas to enhance the link quality. This information helps the transmitting nodes to beamform in the direction of the receiver so that the gain is maximized [121]. Exact location information reduces the effect of interference from other nodes to a large extent.

Devices such as GPS are used in nodes to determine the location of the neighbors. GPS is costly and doesn't work in indoor environments. These limitation refrain GPS from easy usability. Various schemes have been proposed to solve the issue of neighbor discovery. Actually, neighbor discovery must be supported with the direction of arrival information. So, for simplicity, many existing protocols assume that the positions of neighbors are known ahead.

6.3 Directional MAC protocol for CRWMNs

In this section we are going to present our works which is the design of directional random access MAC protocol for CRNs in general and to CRWMNs in particular. WMN has either a chain or grid types of networking topology. In the WMNs the nodes are connected in such a way that traffic is generated in to or away from the mesh gateways. The mesh routers located in the proximity of the mesh gateway are more congested than those which are located far away from the mesh routers.

We are proposing a CRWMN where the mesh routers and the mesh gateways are equipped with multiple antenna systems (MU-MIMO system). The mesh routers and the mesh gateways are empowered by cognitive radio capabilities. The mesh routers and the mesh gateways performs spectrum sensing using the multiple antenna systems so as to decrease the spectrum sensing time, and improves the primary users detection probability and decrease the probability of false alarm. By using beamforming techniques it is possible to improve the spectrum utilization efficiency of the opportunistically available spectrum, and the network capacity by allowing concurrent transmission.

More importantly, to manage the traffic congestion created due to the mesh networking topology, it could be possible to assume mesh routers which are more closer to the mesh gateway to be equipped with more number of antenna in relative to the mesh routers which are located far away from the possible nearby mesh gateways(s) to reduce the system complexity. It could also be possible to equip the mesh gateways with Massive MIMO systems so as to communicate concurrently with more than one mesh router at a time. However, if system complexity and cost are not considered as a pressing parameters,

it could be possible to assume a mesh routers and mesh gateways which are intelligent enough to decide how many number of its antenna elements should be activated to manage the current traffic.

6.3.1 System Model and Analysis

Consider $N \times N$ grid type network topology, assume that part of this network is shown below in fig 6.1 (a), it is assumed that there are $N=9$ cognitive mesh routers connected in grid type mesh topology (3×3) which are numbered from one up to nine. If all of these cognitive mesh routers operate in omni-directional communication only one cognitive mesh router get access to the opportunistically available channel and the other will defer their transmission (only one link exist), but due to directional communication there could be at most $(M-1)/2$ links for odd M and $M/2$ links for even M . Therefore, the use of directional antenna in grid type CRWMN improves the spectral efficiency and network capacity literary by $(M-1)/2$ times, see fig.6.1 (a).

In our system design we assumed two phases; the signaling phase and the data communication phase. Since the locations of the mesh routers or mesh gateways are known (due to less mobility, it is not difficult to know the location of the routers and gateways), it is possible to use MAC-MU-MIMO for the signaling phase to broadcast the signaling to all the remaining mesh nodes. In the signaling phase, the transmitting SU sends prepare to sense (PTS) frame to its entire neighbor SUs after detecting the channel idle using carries sensing. Those which receive the PTS will not initiate communication to this direction for a time not more than successful transmission time. However, it can initiate communication to other than the preoccupied direction. During the data communication phase, the SU uses its entire array element to transmit different data streams to the intended SU receiver so as to maximize the transmission capacity. The minimum number of antenna element used in the data transmission phase will be decided by the transmitting SU. The intended secondary transmitter and secondary receiver will exchange their respective number of antenna elements during the signaling phase. This operation will help to reduce the effect of new hidden terminal problem which is seen in directional communication.

Consider a CRMN which has uniformly distributed N number of SU nodes in a square area and each one of them are equipped with multiple antennas. Let U be an arbitrary secondary user, where the transmission and interference area of U with range d covers M number of SUs when it operates in omni-directional modes. Let ρ be the node density, therefore the number of nodes for a coverage range of d is given by

$$M = \pi d^2 \rho \quad \dots (6.1)$$

For a directional antenna with beam width of θ , the number of nodes which is going to be covered by the beam produced by any arbitrary node U is given by

$$M_b = \frac{\theta}{2\pi} \pi d^2 \rho = \frac{\theta}{2} d^2 \rho \quad \dots (6.2)$$

Then the maximum number of concurrent transmissions is given by

$$N_c = \frac{M}{M_b} = \frac{\pi d^2 \rho}{\frac{\theta}{2} d^2 \rho} = \frac{2\pi}{\theta} \quad \dots (6.3)$$

In reality, it is very difficult to enjoy this maximum concurrent transmission gain due to the demand of coordinating central node that decides which node should communicate with which one for the sack of maximizing spectrum utilization efficiency. However, it is analytically possible to drive the average number of links that could be established among the M secondary users which is presented below.

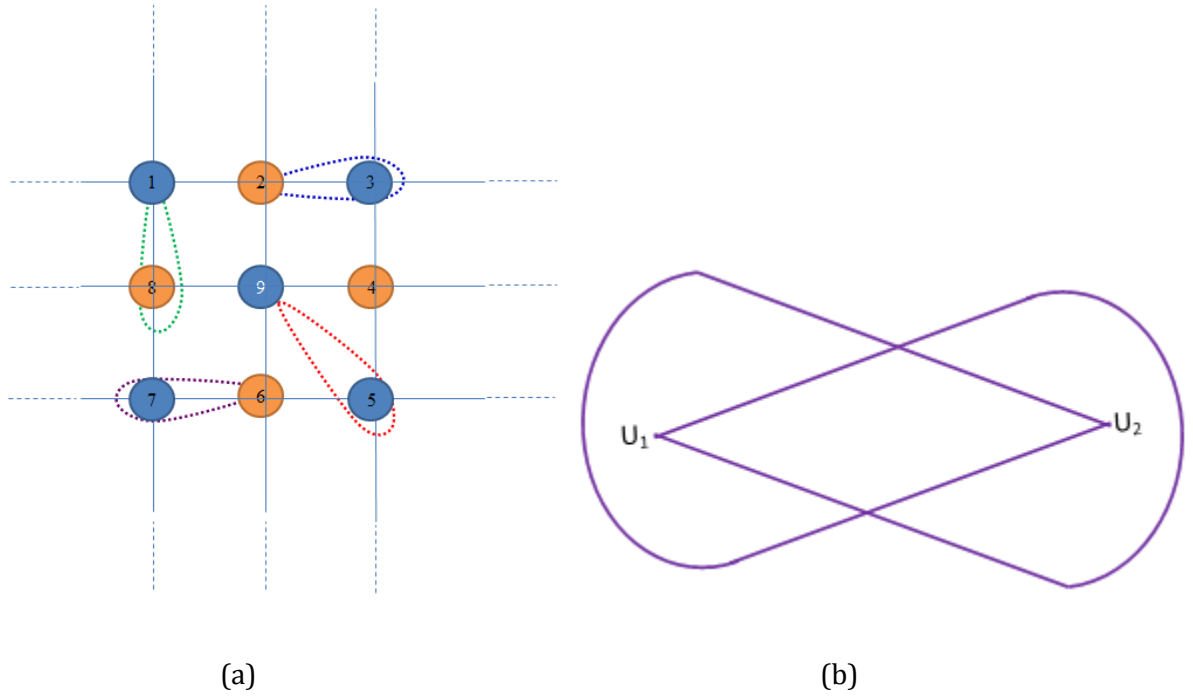


Fig. 6. 1 (a) directional grid type mesh networking, (b) Pictorial representation of directional link between any arbitrary secondary users

In fig. 6.1(b) a directional communication link is presented between two secondary users U_1 and U_2 . When U_1 establish link with U_2 , the area covered by the directional link is given by

$$A_{link} = \text{Area of the two Sectors} - \text{Area of the Intersection}$$

$$\text{Area of a Sector} = A_s = \frac{\theta r^2}{2} \quad \dots (6.4)$$

Ratio of area of a sector to the disc surface becomes

$$A_{ratio}^s = \left(\frac{\theta r^2}{2}\right) / (\pi r^2) = \frac{\theta}{2\pi} \quad \dots (6.5)$$

$$\text{Area of the Intersection} = A_I = \frac{r^2}{2} \tan\left(\frac{\theta}{2}\right) \quad \dots (6.6)$$

The ratio of the area of the intersection to the disc surface area becomes

$$A_{ratio}^I = \frac{1}{2\pi} \tan\left(\frac{\theta}{2}\right) \quad \dots (6.7)$$

Then area of the surface covered by the directional communication can be re-write as

$$A_{link} = 2A_s - A_I = \theta r^2 - \frac{r^2}{2} \tan\left(\frac{\theta}{2}\right) \quad \dots (6.8)$$

The ratio of area of the surface occupied by the directional communication to the disc surface area becomes

$$A_{ratio}^L = \frac{\theta r^2 - \frac{r^2}{2} \tan\left(\frac{\theta}{2}\right)}{\pi r^2} = \frac{\theta - \frac{1}{2} \tan\left(\frac{\theta}{2}\right)}{\pi} \quad \dots (6.9)$$

Then the maximum possible number of link that can be directionally established is given by

$$L_{max} = \frac{\pi}{\theta - \frac{1}{2} \tan\left(\frac{\theta}{2}\right)} \quad \dots (6.10)$$

Then, the average number of nodes covered with this directional communication given that a tagged node covers M nodes (uniformly distributed) in omnidirectional communication is given by

$$M' = M A_{ratio}^L = \frac{M\left(\theta - \frac{1}{2} \tan\left(\frac{\theta}{2}\right)\right)}{\pi} \quad \dots (6.11)$$

Having this link successful, the remaining number of nodes which are eligible for establishing another concurrent successful communication is given by

$$M_1 = M - M' = M\left(1 - \frac{\left(\theta - \frac{1}{2} \tan\left(\frac{\theta}{2}\right)\right)}{\pi}\right) \quad \dots (6.12)$$

Out of these M_1 nodes, the probability a node establishes a successful link without disturbing the initial communicating nodes is given by $\frac{M_1}{M}$. The remaining number of nodes which are eligible for establishing the next concurrent successful transmission is given by

$$M_2 = M_1 - M'$$

$$M_2 = M - 2M' \quad \dots (6.13)$$

Therefore, the minimum number of nodes which are eligible for establishing the last possible link is given by

$$M_{L_{max}} = M_{L_{max}-1} - M'$$

$$M_{L_{max}} = M - L_{max}M'$$

$$M_{L_{max}} = M \left(1 - L_{max} \left(\frac{M \left(\theta - \frac{1}{2} \tan \left(\frac{\theta}{2} \right) \right)}{\pi} \right) \right) \quad \dots (6.14)$$

The probability of establishing the first link among any arbitrary pair of nodes from the M nodes domain is given by $\frac{M_0}{M}$, where $M_0 = M - 1$, for large number of nodes we can approximate $M_0 \cong M$. The probability of establishing a link with the remaining number of nodes without creating interference to the nodes of previously established link, is given by $\frac{M_i}{M}$, where $1 \leq i \leq L_{max}$, and M_i is the remaining number of nodes.

The average number of concurrent directional link can be calculated as follows

$$L_{avg} = \sum_{i=0}^{L_{maz}} \frac{M_i}{M} \quad \dots (6.15)$$

Eqn.6.3 shows that the maximum number of concurrent transmission is not dependent on the number of nodes, rather it is dependent on the radiation pattern (beamwidth) of the multiple antenna which is dependent on number of antenna elements, distance of separation between antenna elements and the excitation phase (it is analyzed in chapter three).

Now let's analyze the proposed directional MAC protocols for cognitive radio system (DCR-MAC) which are contention based protocols developed based on the three access

mechanisms, namely basic, RTS/CTS, and M-CTS mechanisms. Every transmission is performed directionally and reception is performed omni-directionally between two secondary users (SUs).

The proposed DCR-MAC protocols operate as follows. DCR-MAC protocols operate in time slot bases. The time axis is divided in to time slots denoted by δ . SU with a packet to transmit must performs carrier sensing, if it detects a signal from PU or SU, it will defer its transmission and continue its carrier sensing operation at the beginning of every time slots. SU that detects no carrier will send a directional prepare to sense frame (DPTS) to the direction of the intended secondary receiver and the remaining neighbor since it is assumed that every SU user has location information of their neighbor SUs. Following the DPTS frame both of the users perform spectrum sensing to detect the presence of PU in their corresponding vicinity. The spectrum sensing outcomes might be either one of the following as presented in tabular form below.

Table 6.1 Spectrum Sensing Outcomes of an arbitrary SU operating in sensing mode

S.No.	Transmitter Spectrum Sensing (SS) Outcome	Receiver Spectrum Sensing (SS) Outcome	Result
1.	<i>PU Detection</i>	<i>PU Detection</i>	<i>No transmission following SS (Transmitter Blocking)</i>
2.	<i>PU Detection</i>	<i>No PU Detection</i>	<i>No transmission following SS (Transmitter Blocking)</i>
3.	<i>No PU detection</i>	<i>PU Detection</i>	<i>There shall be transmission but the receiver does not respond (SU and PU Collision)</i>
4.	<i>No PU detection</i>	<i>No PU detection</i>	<i>There shall be at least one transmission (successful transmission or collision between SUs transmissions)</i>

Following the spectrum sensing operation outcomes, three contentions based medium access mechanisms for the directional cognitive radio network MAC protocol are proposed which essentially use multiple antenna technology. These access mechanisms are directional basic access mechanism, directional RTS/CTS mechanisms, and directional M-CTS access mechanism. The basic operation principle of directional basic access and directional RTS/CTS access mechanisms is similar to the conventional IEEE 802.11 DCF protocols except its customization so as to suit the directional antenna and cognitive radio network behaviors.

All the signaling operations performed till a SU starts transmitting its data packet are considered to take place in the signaling phase whereas the data packet and the acknowledgment frame will be part of the data communication phase.

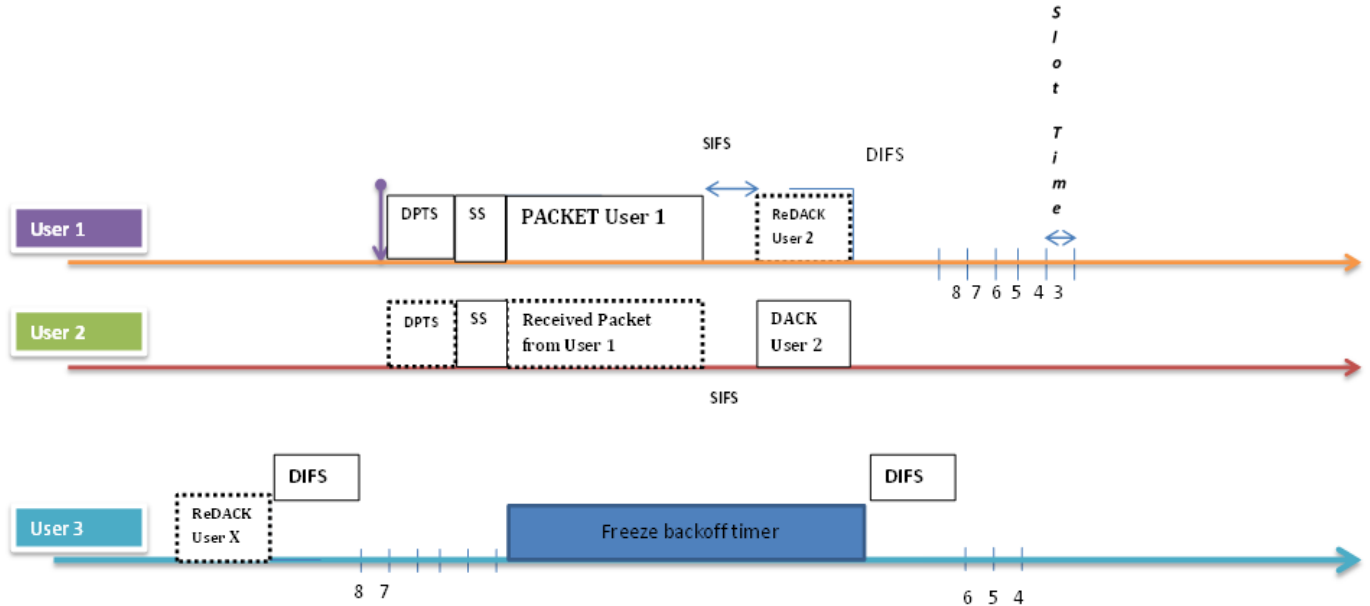


Fig. 6. 2 Directional Basic Access Mechanism for cognitive radio network

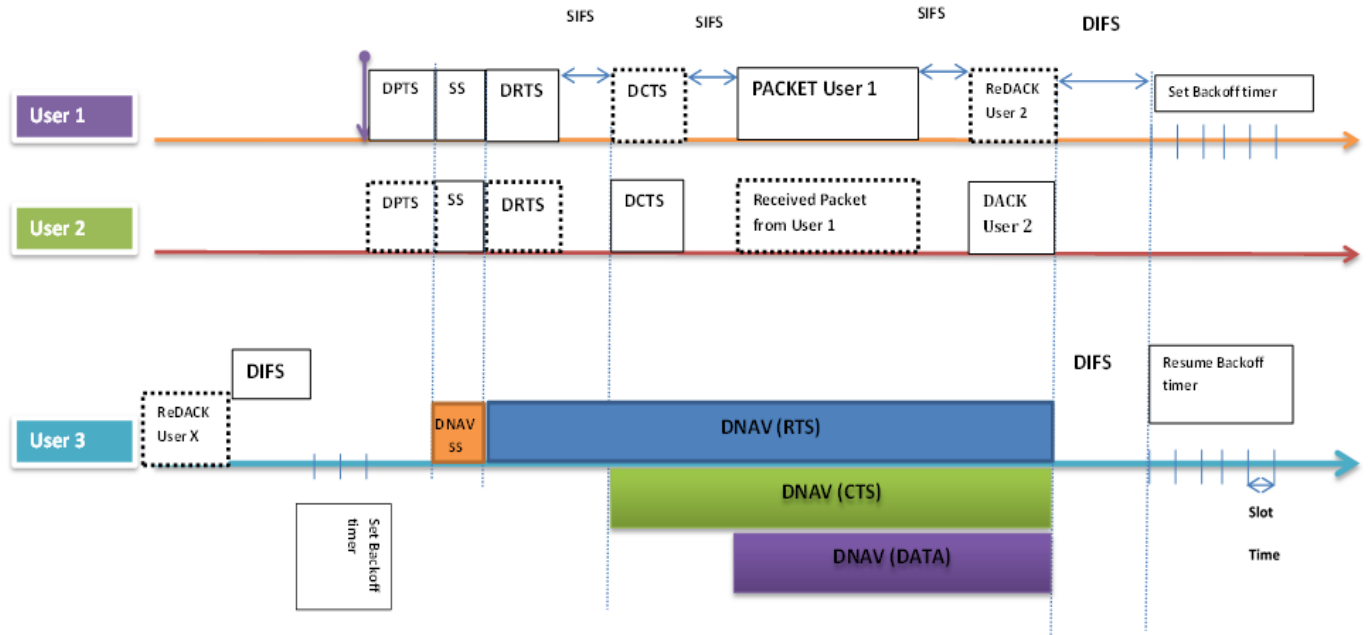


Fig. 6. 3 Directional RTS/CTS Access Mechanism for cognitive radio network

DPTS and SS frames will be exchanged in the signaling phase of the basic access mechanism, whereas, DPTS, SS, DRTS and DCTS frames will be exchanged in the signaling phase of the directional RTS/CTS access mechanisms, and then the data communication phase will follow for data packet and acknowledgment frame exchange.

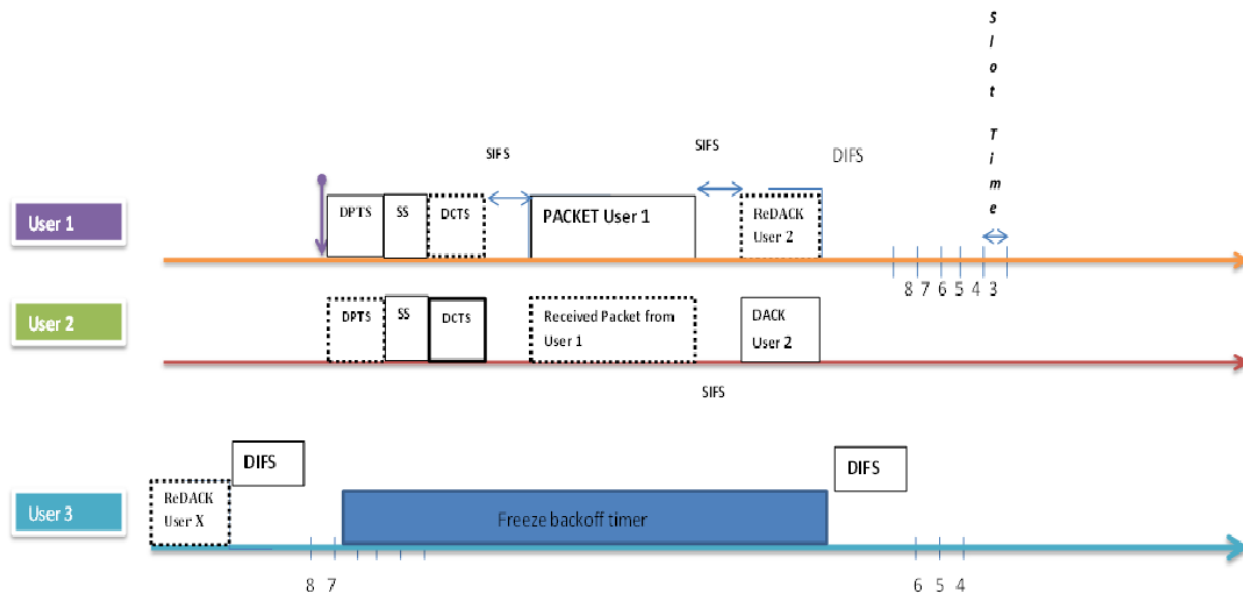


Fig. 6. 4 Directional M-CTS Access Mechanism for cognitive radio network

In the directional M-CTS access mechanism, a SU that wants to transmit make carrier sensing and if it does not detect any signal it sends DPTS frame to the intended SU so as to reserve the coming slot for spectrum sensing and both of them perform spectrum sensing to detect the PU. The intended SU respond with DRTS frame to the transmitting SU, following the DRTS frame the transmitting SU transmit the data packet and if it is successfully received by the intended SU, the receiving SU will send an acknowledgment frame.

The directional M-CTS access mechanism reduces one DCTS frame and one SIFS compared to the directional RTS/CTS access mechanism, and compared to the directional basic access mechanism it introduces one DRTS frame and one SIFS during a successful transmission process. When collision is detected on the channel, the amount of time an overhearing SU freezes its backoff timer will be smaller for the directional M-CTS access mechanism than

the other two types. With respect to directional basic access, the hybrid access mechanism freezing time during collision is less than by the amount of time used to transmit a DATA packet, whereas with respect to directional RTS/CTS access mechanism the freezing time during collision is less than by the amount of time used to transmit a DRTS frame.

6.4 Design and Performance Analysis of Directional MAC Protocols for CRN (DCR-MAC)

In this section the design and analysis of directional CSMA/CA MAC protocol for CRNs is presented. The following assumptions are considered in the design and analysis of DCR-MAC. There is no secondary users' mobility; every SU knows the location of its neighbors; transmission and reception are done directionally and omni-directionally respectively; the SUs always have packet to transmit (Saturated Condition); and there are M number of SUs under the omni-directional coverage of any arbitrary SU among themselves.

The performance of DCR-MAC protocols for the three access mechanisms, including the one proposed and analyzed in the previous chapter is presented. The proposed DCR-MAC protocols developed based on the M-CTS access mechanism shows good performance among the other directional MAC protocols proposed for the CRWMN.

The packet transmission at each SU can be modeled as a single server queue system. Based on DCR-MAC, there exist five possible events occurring in directional packet transmission attempt of arbitrary SUs. These are, Transmitter Blocking (E1), Collision between SUs' directional transmission to the direction of the same SU (E2), Collision between SU and PU transmission (E3), Receiver in Communication (E4), and Successful Directional Transmission (E5).

Now let's compute the probability and respective transmission period for each one of these events. First let's define two hypotheses on the status of neighboring PUs to an arbitrary SU. H_0 represents the hypothesis that the neighboring PUs of an arbitrary SU is not active, and H_1 represents the hypothesis that the neighboring PUs of a secondary user is active. Let P_{H_0} denotes the occurrence probability of event H_0 , and P_{H_1} denotes the occurrence

probability of event H_1 . Let's define additional variable V to denote the probability a SU can access the channel, which can be expressed in terms of probability of false alarm (p_f), and probability of detection (p_d).

An arbitrary SU can access the channel under two conditions; the first one is when the channel is idle and sensed idle by an arbitrary SU, and the second one is when the channel is busy (it is being used by the primary user(s)) but sensed idle by the arbitrary SU. Therefore, the probability an arbitrary SU can access the channel is given by

$$V_k = (1 - p_{f,k})P_{H0,k} + (1 - p_{d,k})P_{H1,k} \quad \dots (6.16)$$

Where $k=1, 2, 3, \dots, M$

6.4.1 Transmitter Blocking (E1)

When an arbitrary SU has a packet to transmit, first it performs carrier sensing. In the carrier sensing time if it doesn't detect any signal then it transmits prepare to sense (PTS) frame directionally to the intended secondary receiver. During the spectrum sensing period the transmitting secondary user may detect PUs and discontinue the communication, this is called transmitter blocking. The probability of this event considering an arbitrary SU U_1 as a transmitter is given by

$$P_{E1}^D = (1 - V_1) \quad \dots (6.17)$$

The period of transmission failure due to event 1 for the three access mechanisms is given by

$$T_{E1}^{Dbas} = DPTS + SS + DIFS \quad \dots (6.18a)$$

$$T_{E1}^{Drts} = DPTS + SS + DIFS \quad \dots (6.18b)$$

$$T_{E1}^{Dmcts} = DPTS + SS + DIFS \quad \dots (6.18c)$$

When transmitter blocking occurs, the transmitting SU will defer its transmission for additional predefined blocking time (TB) but those SUs covered by the transmitting beam may attempt transmission after an additional time of DIFS if the channel is sensed idle at the beginning of the time slot.

6.4.2 Directional Transmission Collision between SUs (E2)

DRTS failure occurs when more than one DRTS are sent to the direction of the intended receiver at the same time slot. At this time, the intended receiver fails to respond to the DRTS due to collision. Let us consider an arbitrary secondary user U2 as a receiver and U1 as a transmitter, and drive an expression for the probability of directional collision.

$$\begin{aligned}
 P_{DRTS} &= \text{prob.}\{RTS \text{ transmission to } U_2\text{'s direction at any time slot}\} \\
 &= \text{prob.}\{a \text{ SU can access the channel at any time slot}\}x \\
 &\quad \text{prob.}\{ \text{packet transmission by a SU at any time slot}\}x \\
 &\quad \text{prob.}\{ \text{packet transmission to the direction of } U_2\}
 \end{aligned}$$

$$P_{DRTS,k} = V_k \tau_k \frac{\beta}{2\pi} c(\beta)$$

$$P'_{DRTS,k} = \text{prob.}\{ a \text{ SU do not transmit DRTS in the direction of } U_2 \text{ at any time slot}\}$$

$$P'_{DRTS,k} = 1 - P_{DRTS,k}$$

$$P'_{DRTS,k} = 1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta)$$

$$\begin{aligned}
 \mathbf{P} &= \text{prob.}\{ \text{none of the SUs among } (M \\
 &\quad - 2) \text{ transmit DRTS in the direction of } U_2 \text{ at any time slot}\}
 \end{aligned}$$

$$\mathbf{P} = \prod_{k=1}^{M-2} (1 - P_{DRTS,k})$$

$$P = \prod_{k=1}^{M-2} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta)\right)$$

$P = \text{prob.} \{ \text{at least one SU among } (M - 2) \text{ transmit DRTS in the direction of } U_2 \text{ at any time slot} \} = 1 - P$

$$P = 1 - \prod_{k=1}^{M-2} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta)\right)$$

The probability of DRTS failure is given by

$$P_{E2}^D = V_1 P = V_1 \left\{ 1 - \prod_{k=2}^M \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) \right\} \quad \dots (6.19)$$

Where $K = 3, 4, \dots, M$.

Due to collision there is transmission failure, and the period of this transmission failure for the three access mechanism is given by

$$T_{E2}^{\text{Dbas}} = \text{DPTS} + \text{SS} + \text{DDATA} + \text{SIFS} + \text{DACK} + \text{DIFS} \quad \dots (6.20a)$$

$$T_{E2}^{\text{Drts}} = \text{DPTS} + \text{SS} + \text{DRTS} + \text{SIFS} + \text{DCTS} + \text{DIFS} \quad \dots (6.20b)$$

$$T_{E2}^{\text{Dmcts}} = \text{DPTS} + \text{SS} + \text{DCTS} + \text{DIFS} \quad \dots (6.20c)$$

6.4.3 Collision of SU's directional RTS with PU transmission (Receiver Blocking)- (E3)

During the spectrum sensing time if the intended secondary receiver (U2) detects the presence of primary user(s), it will fail to respond to the DRTS frame sent from the intended secondary transmitter (U1). This is called receiver blocking only when there is

only one secondary user (U1) transmitting to the direction of the intended secondary receiver.

$$P_{E3}^D = V_1(1 - V_2) \prod_{k=3}^M \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) \quad \dots (6.21)$$

The period of transmission failure due to receiver blocking is given by

$$T_{E3}^{\text{Dbas}} = \text{DPTS} + \text{SS} + \text{DDATA} + \text{SIFS} + \text{DACK} + \text{DIFS} \quad \dots (6.22a)$$

$$T_{E3}^{\text{Drts}} = \text{DPTS} + \text{SS} + \text{DRTS} + \text{SIFS} + \text{DCTS} + \text{DIFS} \quad \dots (6.22b)$$

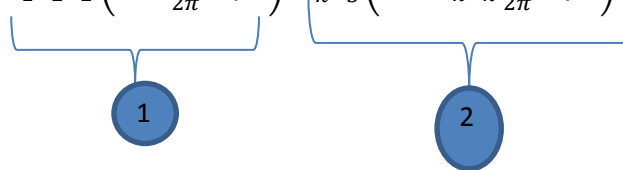
$$T_{E3}^{\text{Dmcts}} = \text{DPTS} + \text{SS} + \text{DCTS} + \text{DIFS} \quad \dots (6.22c)$$

6.4.4 Receiver Already in Communication (E4)

This is event happens when the intended secondary user (U2) is already in communication with another secondary user which is not in the direction of the intended secondary transmitter (U1). The case when the U2 is acting as transmitter and receiver are different. At this time the intended secondary transmitter cannot respond to the DPTS/DRTS sent by the intended Secondary receiver (U2), which is the unique case that we experience due to beamforming. When it is acting as a receiver collision will occur and it is considered in case 2. Our interest is when U2 is acting as a transmitter in the direction other than U1, the probability is given by

$$P_{E4}^D = \text{prob.} \{U_2 \text{ transmit to another SU not in the direction of } U_1$$

at the time slot when U_1 is sending DRTS to the direction of U_2 \}

$$P_{E4}^D = \underbrace{V_1 V_2 \tau_2 \left(1 - \frac{\beta}{2\pi} c(\beta) \right)}_1 \underbrace{\prod_{k=3}^M \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right)}_2 \quad \dots (6.23)$$


Where 1 and 2 represent probability of U2 transmission other than U1 direction and the probability the remaining (M-2) SUs do not transmit in the direction of U2 .

The period of transmission failure due to this event for the three access mechanism is given by

$$T_{E4}^{Dbas} = DPTS + SS + DDATA + SIFS + DACK + DIFS \quad \dots (6.24a)$$

$$T_{E4}^{Drts} = DPTS + SS + DRTS + SIFS + DCTS + DIFS \quad \dots (6.24b)$$

$$T_{E4}^{Dmcts} = DPTS + SS + DCTS + DIFS \quad \dots (6.24c)$$

6.4.5 Successful Directional Transmission (E5)

Successful directional transmission between the intended secondary transmitter (U₁) and the intended secondary receiver (U₂) is accomplished when both of them detects no PU, and U₂ is not communicating with another SU (U₂ is not transmitting) and U₁ is the only transmitter in the direction of U₂ at that time slot. The probability of successful directional transmission is given by

$$P_{E5}^D = V_1 V_2 (1 - \tau_2) \prod_{k=3}^M \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) \quad \dots (6.25)$$

The period of successful transmission for the three access mechanisms is given by

$$T_{E5}^{Dbas} = DPTS + SS + DDATA + SIFS + DACK + DIFS \quad \dots (6.26a)$$

$$T_{E5}^{Drts} = DPTS + SS + DRTS + SIFS + DCTS + SIFS + DDATA + SIFS + DACK + DIFS \quad \dots (6.26b)$$

$$T_{E5}^{Dmcts} = DPTS + SS + DCTS + SIFS + DDATA + SIFS + DACK + DIFS \quad \dots (6.26c)$$

Then, for an arbitrary SU which is in transmission mode the sum of the probabilities of the following expression holds true

$$P_{E5}^D = 1 - (P_{E1}^D + P_{E2}^D + P_{E3}^D + P_{E4}^D)$$

$$P_{E5}^D = 1 - P_{Dtf} \quad \dots (6.27)$$

Where $P_{Dtf} = P_{E1}^D + P_{E2}^D + P_{E3}^D + P_{E4}^D$

Possible Events when an arbitrary SU, U1 is in Backoff State (Listening mode)

The following possible events could be detected when an arbitrary Secondary User (U_1) is in listening mode (backoff state). An arbitrary SU who is in listening mode could detect the channel idle (no PU and SU transmission), or it detects PU signal only, or it may detects both SU and PU signals (PU-SU collision detection). Generally, we can classify the detection output as idle channel or busy channel detection. Now let's derive expression for the occurrence probability of these events and the corresponding time length that U_1 will defer. By the time when the backoff timer become zero and finds the channel idle, the node will start transmitting.

6.4.6 Idle Channel Detection (E6)

This event occurs when the arbitrary SU which is in listening state detects no transmission from both the PUs and SUs at the time slot. The arbitrary SU may detect the channel idle for either one of the following scenarios: when all the SUs detects the channel idle but there is no transmission to the direction of the detecting SU, or when all the $M-1$ SUs detects the channel busy due to false alarm and defer their transmission, or when some of the SUs detects the channel idle but do not transmit to the direction of the detecting SU and the remaining SUs detect the channel busy due to false alarm and defer their transmission, or when all the $M-1$ SUs detect the channel idle but they do not transmit (in back off state). The probability of idle channel detection expression for an arbitrary SU can be derived as follows.

The probability all of the SUs detects the channel idle but there is no directional transmission to the direction of the detecting SU is given by

$$P_{ID1}^D = PH_0(1 - p_f) \prod_{k=1}^{M-1} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right)$$

The probability all of the M-1 SUs detects the channel busy due to false alarm and defer their transmission is given by

$$P_{ID2}^D = PH_0(p_f)$$

Therefore, the probability of idle channel detection by an arbitrary SU is given by

$$P_{E6}^D = (P_{ID1}^D + P_{ID2}^D)$$

$$P_{E6}^D = PH_0(1 - p_f) \prod_{k=1}^{M-1} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) + PH_0(p_f) \dots (6.28)$$

At this time U1 will decrement its back off timer by 1 at the end of the current time slot.

Now let's analyze the probability of busy channel detection by an arbitrary SU in terms of PU signal detection only, SU signal detection only, and in terms of both PU and SU signal detection.

6.4.7 Only PU's Signal Detection (E7)

An arbitrary SU may detect PU signal only when one of the following events occurs; when all of the SUs detect the channel busy and defer their transmission, or when all of the M-1 SUs detect the channel idle but do not want to transmit to the direction of the detecting SU, or when some of the SUs detect the channel idle and transmit to the direction other than the detecting SU and the remaining SUs may detect the channel busy and defer transmission or the remaining SUs may detect the channel idle but do not want to transmit (may be in back off state). The probability expression of only PU signal detection by an arbitrary SU is given by the sum of the following probabilities.

The probability all of the SUs detect the channel busy and defer their transmission is given by

$$P_{PU1}^D = PH_1 p_d$$

The probability all of the $M-1$ SUs detect the channel idle but do not transmit to the direction of the detecting SU is given by

$$P_{PU2}^D = PH_1(1 - p_d) \prod_{k=1}^{M-1} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right)$$

Therefore, the probability of PU signal detection by an arbitrary SU is given by

$$P_{PU}^D = P_{PU1}^D + P_{PU2}^D$$

$$P_{E7}^D = PH_1(1 - p_d) \prod_{k=1}^{M-1} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) + PH_1 p_d \quad \dots (6.29)$$

At this time the detecting SU will freeze its backoff timer for some time duration depending on the access mechanisms (for our case it freezes for a time length of T_{E1}^D).

6.4.8 Only SU's Signal Detection (E8)

An arbitrary SU detects only SU(s) signal when one of the following conditions are satisfied. When all the SUs detect the channel idle and only one SU transmit to the direction of the detecting SU and the receiving SU can communicate with the transmitting SU (at this time the SU detects a successful transmission), or when all the SUs detect the channel idle and more than two SUs transmit in the direction of the detecting SU (at this time the SU detects collision), or all the SUs detects the channel idle and only one SU transmit in the direction of the detecting SU but the intended receiver might already been in communication with other SU not in the direction of the detecting SU, or when some of the SUs detect the channel busy due to false alarm and defer transmission but when the remaining SUs transmit to the direction of the detecting SU (at this time collision of SUs transmission is detected by the detecting SU). The expression for the probability of detecting PU signal only is derived below.

The probability all of the SUs detect the channel idle and only one SU transmit to the direction of the detecting SU and the receiving SU can communicate with the transmitting SU (at this time the SU detects a successful transmission) is given by

$$P_{ST}^D = PH_0(1 - p_f) \binom{M-1}{1} (V_x \tau_x \frac{\beta}{2\pi} c(\beta)) V_y (1 - \tau_y) \prod_{k=1}^{M-2} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right)$$

The detecting SU shall defer its transmission for a period of T_{E5}^D which is given by eqn.7.26.

The probability all of the SUs detect the channel idle and more than two SUs transmit in the direction of the detecting SU (at this time the SU detects collision) is given by

$$P_{SSC}^D = PH_0(1 - p_f) \sum_{k=1}^{M-1} \binom{M-1}{k} \left\{ \prod_{y=1}^k (V_y \tau_y \frac{\beta}{2\pi} c(\beta)) \prod_{x=k+1}^{M-1} \left(1 - V_x \tau_x \frac{\beta}{2\pi} c(\beta) \right) \right\}$$

At this stage, the listening node defer its transmission for a period of T_C^D which is given by

$$T_C^{D\text{bas}} = \text{PTS} + \text{SS} + \text{DATA} + \text{DIFS} \quad \dots (6.30a)$$

$$T_C^{D\text{rts}} = \text{PTS} + \text{SS} + \text{RTS} + \text{DIFS} \quad \dots (6.30b)$$

$$T_C^{D\text{mcts}} = \text{PTS} + \text{SS} + \text{DIFS} \quad \dots (6.30c)$$

The probability all the SUs detects the channel idle and only one SU transmit in the direction of the detecting SU but the intended receiver might initiate communication with other SU which is not in the direction of the detecting SU at the same time slot is given by

$$P_{SDC}^D = PH_0(1 - p_f) \binom{M-1}{1} \left(V_x \tau_x \frac{\beta}{2\pi} c(\beta) \right) V_y \tau_y \left(1 - \frac{\beta}{2\pi} c(\beta) \right) \prod_{k=3}^{M-1} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right)$$

At this time the detecting node defer its transmission for a period of T_{E4}^D .

The probability all of the (M-2) SUs detects the channel idle and only one SU transmission is detected but this communication might be interrupted due to the invisible directional

communication to the detector. The invisible directional communications may happen in one of the following conditions. The first condition is when the intended SU receiver receives more than one request in different direction at the same time slot (for example more than one RTS frames or DATA packet), at this time the intended receiver fail to respond to any of the SUs, as a result of which communication failure could be detected by the detecting SU (we may call this event as collision at the intended SU receiver). The second condition is observed when there is at least one transmission to the direction of the intended transmitter and the intended transmitter may receive more than one acknowledgments (for example more than one CTS or ACK frames) at the same time slot which results in communication failure detection at the detecting SU (we may call this event as collision at the intended SU transmitter).

The probability of detecting communication failure by an arbitrary detecting SU due to a collision observed at the intended SU receiver is given by

$$P_{TFRC}^D = PH_0(1 - p_f) \binom{M-1}{1} (V_x \tau_x \frac{\beta}{2\pi} c(\beta)) V_y (1 - \tau_y) \sum_{k=1}^{M-3} \binom{M-3}{k} \left\{ \prod_{z=1}^k (V_z \tau_z \frac{\beta}{2\pi} c(\beta)) \prod_{x=k+1}^{M-3} \left((1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta)) \right) \right\}$$

Since every user start transmission at the beginning of a time frame, the time period the detecting SU defer its transmission for this event is given by T_{E4}^D .

The probability of detecting communication failure by an arbitrary detecting SU due to a collision observed at the intended SU transmitter is given by

$$P_{FTC}^D = PH_0(1 - p_f) \binom{M-1}{1} (V_x \tau_x \frac{\beta}{2\pi} c(\beta)) V_y (1 - \tau_y) \sum_{k=1}^{M-3} \binom{M-3}{k} \left\{ \prod_{z=1}^k (V_z \tau_z \frac{\beta}{2\pi} c(\beta)) \prod_{x=k+1}^{M-3} \left((1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta)) \right) \right\}$$

The time period the detecting SU defer its transmission for this event is given by T_{E4}^D .

Therefore, the probability of only SU signal detection is given by

$$P_{E8}^D = P_{ST}^D + P_{SSC}^D + P_{SDC}^D + P_{TFRC}^D + P_{TFTC}^D \quad \dots (6.31)$$

$$\begin{aligned} P_{E8}^D = & PH_0(1 - p_f) \left\{ \binom{M-1}{1} \left(V_x \tau_x \frac{\beta}{2\pi} c(\beta) \right) V_y (1 - \tau_y) \prod_{k=1}^{M-3} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) \right. \\ & + \sum_{k=1}^{M-1} \binom{M-1}{k} \left\{ \prod_{y=1}^k (V_y \tau_y \frac{\beta}{2\pi} c(\beta)) \prod_{x=k+1}^{M-1} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) \right\} \\ & + \binom{M-1}{1} \left(V_x \tau_x \frac{\beta}{2\pi} c(\beta) \right) V_y \tau_y \left(1 - \frac{\beta}{2\pi} c(\beta) \right) \prod_{k=1}^{M-3} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) \\ & + 2 \binom{M-1}{1} (V_x \tau_x \frac{\beta}{2\pi} c(\beta)) V_y (1 \\ & - \tau_y) \sum_{k=1}^{M-3} \binom{M-3}{k} \left\{ \prod_{z=1}^k (V_z \tau_z \frac{\beta}{2\pi} c(\beta)) \prod_{x=k+1}^{M-3} \left(1 - V_k \tau_k \frac{\beta}{2\pi} c(\beta) \right) \right\} \left. \right\} \end{aligned}$$

6.4.9 Detection of both PU and SU signal (E9)

An arbitrary SU detects both the PU and SU signal when one of the following conditions occurs. An arbitrary SU detects both the SU and PU signals when the PU is present and all the M-1 SUs miss detect the presence of PU and at least one among these SUs transmit in the direction of the detecting SU, or when the PU is present and some of the SUs detect the presence of PU and defer transmission and the remaining SUs miss detect the PU presence and start transmitting to the direction of the detecting SU. The expression for probability of detecting both PU and Su signal simultaneously is derived below.

The probability all the M-1 SUs miss detect the presence of PU and at least one among these SUs transmit in the direction of the detecting SU is given by

$$P_{PS}^D = PH_1(1 - p_d) \sum_{k=1}^{M-1} \binom{M-1}{k} \left\{ \prod_{y=1}^k (V_y \tau_y \frac{\beta}{2\pi} c(\beta)) \prod_{x=k+1}^{M-1} \left(1 - V_x \tau_x \frac{\beta}{2\pi} c(\beta) \right) \right\}$$

Therefore, the probability of detecting both SU and PU signal is given by

$$P_{E9}^D = P_{PS}^D$$

$$P_{E9}^D = PH_1(1 - p_d) \sum_{k=1}^{M-1} \binom{M-1}{k} \left\{ \prod_{y=1}^k (V_y \tau_y \frac{\beta}{2\pi} c(\beta)) \prod_{x=k+1}^{M-1} \left(1 - V_x \tau_x \frac{\beta}{2\pi} c(\beta) \right) \right\} \quad \dots (6.32)$$

For this event the detecting node defer its transmission for a period of T_{E3}^D .

6.5 Throughput for DCR-MAC protocols

Therefore, the total average throughput of directionally cognitive radio MAC protocol can be expressed by

$$U^D = \frac{E[\text{Payload Information transmitted in a slot time}]}{E[\text{length of a slot time}]} \quad \dots (6.33)$$

$$E[\text{slot}]^{\text{Dbas}} = P_{E6}^D \delta + P_{E7}^D T_{E1}^{\text{Dbas}} + P_{ST}^D T_{E5}^{\text{Dbas}} + P_{SSC}^D T_C^{\text{Dbas}} + P_{SDC}^D T_{E4}^{\text{Dbas}} + P_{TFRC}^D T_{E4}^{\text{Dbas}} + P_{TFTC}^D T_{E4}^{\text{Dbas}} + P_{E9}^D T_{E3}^{\text{Dbas}} \quad \dots (6.34a)$$

$$E[\text{slot}]^{\text{Drts}} = P_{E6}^D \delta + P_{E7}^D T_{E1}^{\text{Drts}} + P_{ST}^D T_{E5}^{\text{Drts}} + P_{SSC}^D T_C^{\text{Drts}} + P_{SDC}^D T_{E4}^{\text{Drts}} + P_{TFRC}^D T_{E4}^{\text{Drts}} + P_{TFTC}^D T_{E4}^{\text{Drts}} + P_{E9}^D T_{E3}^{\text{Drts}} \quad \dots (6.34b)$$

$$E[\text{slot}]^{\text{Dmcts}} = P_{E6}^D \delta + P_{E7}^D T_{E1}^{\text{Dmcts}} + P_{ST}^D T_{E5}^{\text{Dmcts}} + P_{SSC}^D T_C^{\text{Dmcts}} + P_{SDC}^D T_{E4}^{\text{Dmcts}} + P_{TFRC}^D T_{E4}^{\text{Dmcts}} + P_{TFTC}^D T_{E4}^{\text{Dmcts}} + P_{E9}^D T_{E3}^{\text{Dmcts}} \quad \dots (6.34c)$$

$$U^D = L_{avg} \frac{P_{ST} E[L]}{E[\text{slot}]^D} \quad \dots (6.35)$$

$$U_{bas}^D = L_{avg} \frac{P_{ST} E[L]}{P_{E6}^D \delta + P_{E7}^D T_{E1}^{\text{Dbas}} + P_{ST}^D T_{E5}^{\text{Dbas}} + P_{SSC}^D T_C^{\text{Dbas}} + P_{SDC}^D T_{E4}^{\text{Dbas}} + P_{TFRC}^D T_{E4}^{\text{Dbas}} + P_{TFTC}^D T_{E4}^{\text{Dbas}} + P_{E9}^D T_{E3}^{\text{Dbas}}} \quad \dots (6.36a)$$

$$U_{rts}^D = L_{avg} \frac{P_{ST} E[L]}{P_{E6}^D \delta + P_{E7}^D T_{E1}^{\text{Drts}} + P_{ST}^D T_{E5}^{\text{Drts}} + P_{SSC}^D T_C^{\text{Drts}} + P_{SDC}^D T_{E4}^{\text{Drts}} + P_{TFRC}^D T_{E4}^{\text{Drts}} + P_{TFTC}^D T_{E4}^{\text{Drts}} + P_{E9}^D T_{E3}^{\text{Drts}}} \quad (6.36b)$$

$$U_{mcts}^D = L_{avg} \frac{P_{ST} E[L]}{P_{E6}^D \delta + P_{E7}^D T_{E1}^{\text{Dmcts}} + P_{ST}^D T_{E5}^{\text{Dmcts}} + P_{SSC}^D T_C^{\text{Dmcts}} + P_{SDC}^D T_{E4}^{\text{Dmcts}} + P_{TFRC}^D T_{E4}^{\text{Dmcts}} + P_{TFTC}^D T_{E4}^{\text{Dmcts}} + P_{E9}^D T_{E3}^{\text{Dmcts}}} \quad \dots (6.36c)$$

The maximum throughput of a directional MAC protocol is given by

$$U_{max}^D = L_{max} \frac{P_{ST} E[L]}{E[\text{slot}]^D} \quad \dots (6.37)$$

6.6 Average Packet Delay of DCR-MAC protocols

The same definition is used to drive the average packet delay $E(D)^D$ expression for DCR-MAC protocol. For successfully transmitted packet, it can be defined as the amount of time it takes for a packet to reach the destination using directional transmission starting from the time it is being ready for transmission until an acknowledgment is received.

The average number of slot required to successfully transmit a packet in DCR-MAC protocol is given by

$$E(X)^D = \sum_{i=0}^m \frac{P_{Dtf}^i - P_{Dtf}^{m+1}}{1 - P_{Dtf}^{m+1}} W_{avg}^i = \sum_{i=0}^m \frac{(2^i W + 1)(P_{Dtf}^i - P_{Dtf}^{m+1})}{2(1 - P_{Dtf}^{m+1})} \quad \dots (6.38)$$

Where $P_{Dtf} = P_{E1}^D + P_{E2}^D + P_{E3}^D + P_{E4}^D$

Then, the average packet delay a station experience in DCR-MAC protocol becomes

$$E(D)^D = E(X)^D \cdot E(slot)^D \quad \dots (6.39)$$

For the three access mechanisms the average packet delay expressions for DCR-MAC protocols become

$$\begin{aligned} E(D)_{bas}^D &= E(X)^D \cdot E(slot)^{Dbas} \\ &= \{P_{E6}^D \delta + P_{E7}^D T_{E1}^{Dbas} + P_{ST}^D T_{E5}^{Dbas} + P_{SSC}^D T_C^{Dbas} + P_{SDC}^D T_{E4}^{Dbas} + P_{TFRC}^D T_{E4}^{Dbas} + P_{TFTC}^D T_{E4}^{Dbas} \\ &+ P_{E9}^D T_{E3}^{Dbas}\} \cdot \sum_{i=0}^m \frac{(2^i W + 1)(P_{Dtf}^i - P_{Dtf}^{m+1})}{2(1 - P_{Dtf}^{m+1})} \quad \dots (6.40a) \end{aligned}$$

$$\begin{aligned} E(D)_{rts}^D &= E(X)^D \cdot E(slot)^{Drts} \\ &= \{P_{E6}^D \delta + P_{E7}^D T_{E1}^{Drts} + P_{ST}^D T_{E5}^{Drts} + P_{SSC}^D T_C^{Drts} + P_{SDC}^D T_{E4}^{Drts} + P_{TFRC}^D T_{E4}^{Drts} + P_{TFTC}^D T_{E4}^{Drts} \\ &+ P_{E9}^D T_{E3}^{Drts}\} \cdot \sum_{i=0}^m \frac{(2^i W + 1)(P_{Dtf}^i - P_{Dtf}^{m+1})}{2(1 - P_{Dtf}^{m+1})} \quad \dots (6.40b) \end{aligned}$$

$$\begin{aligned}
E(D)_{mcts}^D &= E(X)^D \cdot E(slot)^{Dmcts} \\
&= \{P_{E6}^D \delta + P_{E7}^D T_{E1}^{Dmcts} + P_{ST}^D T_{E5}^{Dmcts} + P_{SSC}^D T_C^{Dmcts} + P_{SDC}^D T_{E4}^{Dmcts} + P_{TFRC}^D T_{E4}^{Dmcts} \\
&\quad + P_{FTC}^D T_{E4}^{Dmcts} + P_{E9}^D T_{E3}^{Dmcts}\} \cdot \sum_{i=0}^m \frac{(2^i W + 1)(P_{Dtf}^i - P_{Dtf}^{m+1})}{2(1 - P_{Dtf}^{m+1})} \quad \dots (6.40c)
\end{aligned}$$

6.7 Simulation and Discussion

In this section different simulation works are presented to evaluate the performance of the proposed directional cognitive radio MAC protocol (DCR-MAC) in terms of average throughput and average packet delay which are measured in bit per second (bps) and second respectively. From our analytical derivation of average throughput and average packet delay we have seen that number of SU, contention window size, probability of transmission, retry limit, and beamwidth affects the behavior of the proposed directional random access MAC protocols. Therefore, these parameters are used to evaluate the proposed protocols by using simulation.

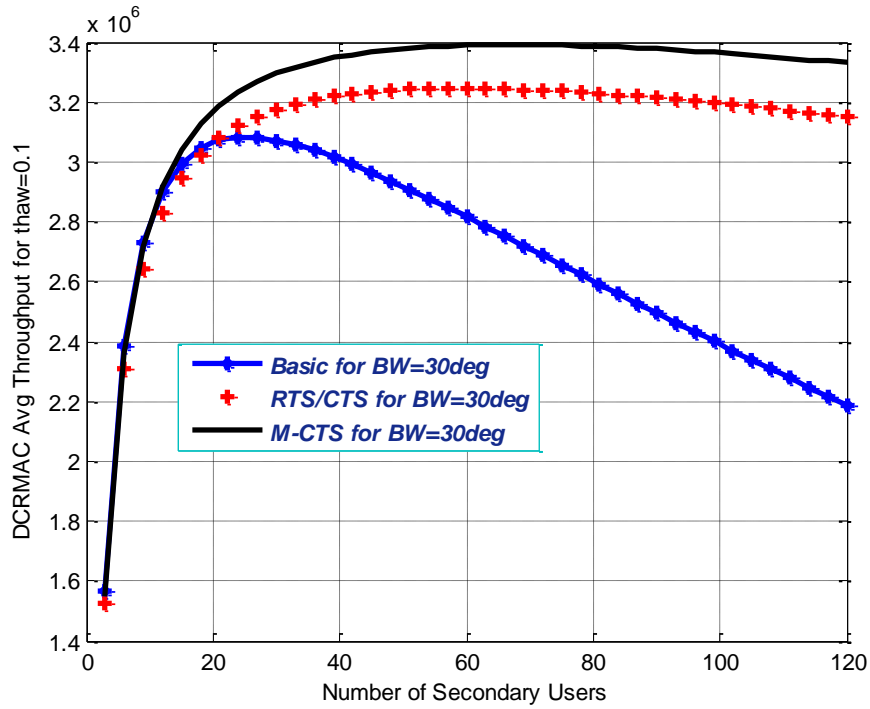
The simulator used is an event driven MATLAB simulator (MATLAB R2013b). We choose MATLAB because it is a powerful simulator to work with analytical and more of physical layer dominated tasks. We have examined OMNET++ and Network Simulator (NS-3) but none of these network simulators integrate the physical layer with the other network layer in a sufficient manner. This is to mean that they lack physical layer aspect of directional antenna and cognitive radio capabilities at the network interface module.

To perform the simulation using MATLAB simulator we have used the following parameters which are presented in a tabular form below. In general, the impact of the above mentioned parameters on the performance of the proposed random access MAC protocols for the CRWMN are observed and properly analyzed based on the simulation outputs.

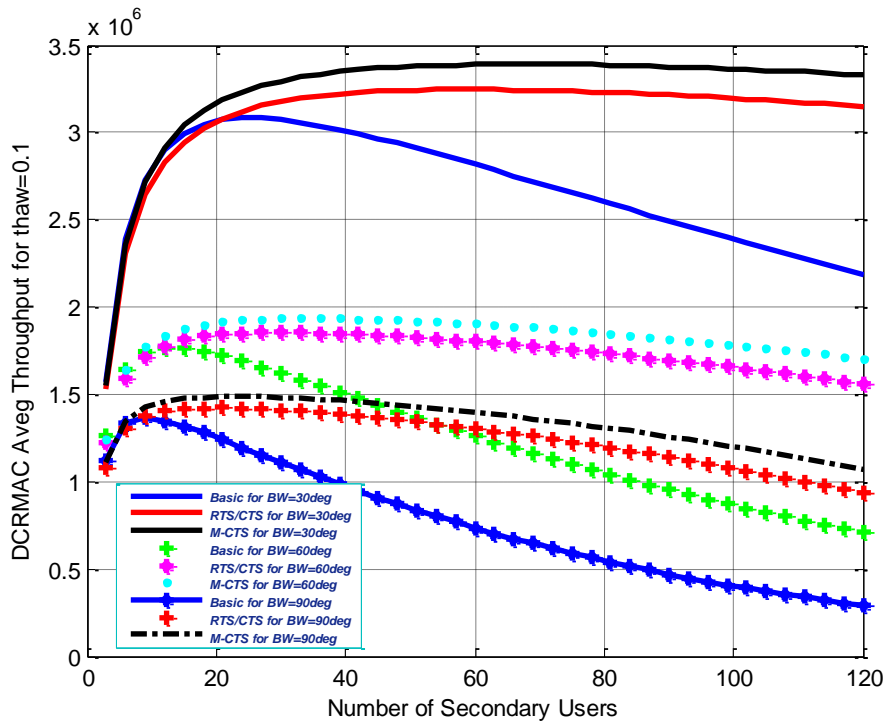
Table 6.2 DCR-MAC protocol simulation parameters

Simulation Parameters used	
<i>Channel Bit Rate</i>	<i>1 Mbit/sec</i>
<i>Slot Time</i>	<i>20μsec</i>
<i>Spectrum Sensing Time</i>	<i>0.5ms</i>
<i>SIFS</i>	<i>10μsec</i>
<i>DIFS</i>	<i>50μsec</i>
<i>Initial Contention Window Size (W)</i>	<i>32</i>
<i>Maximum Backoff Stage (m)</i>	<i>5</i>
<i>PHY Header</i>	<i>192 bits</i>
<i>MAC Header</i>	<i>272 bits</i>
<i>Packet Payload</i>	<i>8000 bits</i>
<i>DPTS</i>	<i>112 bits +PHY Header</i>
<i>DRTS</i>	<i>160 bits + PHY Header</i>
<i>DCTS</i>	<i>112 bits + PHY Header</i>
<i>DACK</i>	<i>112 bits + PHY Header</i>

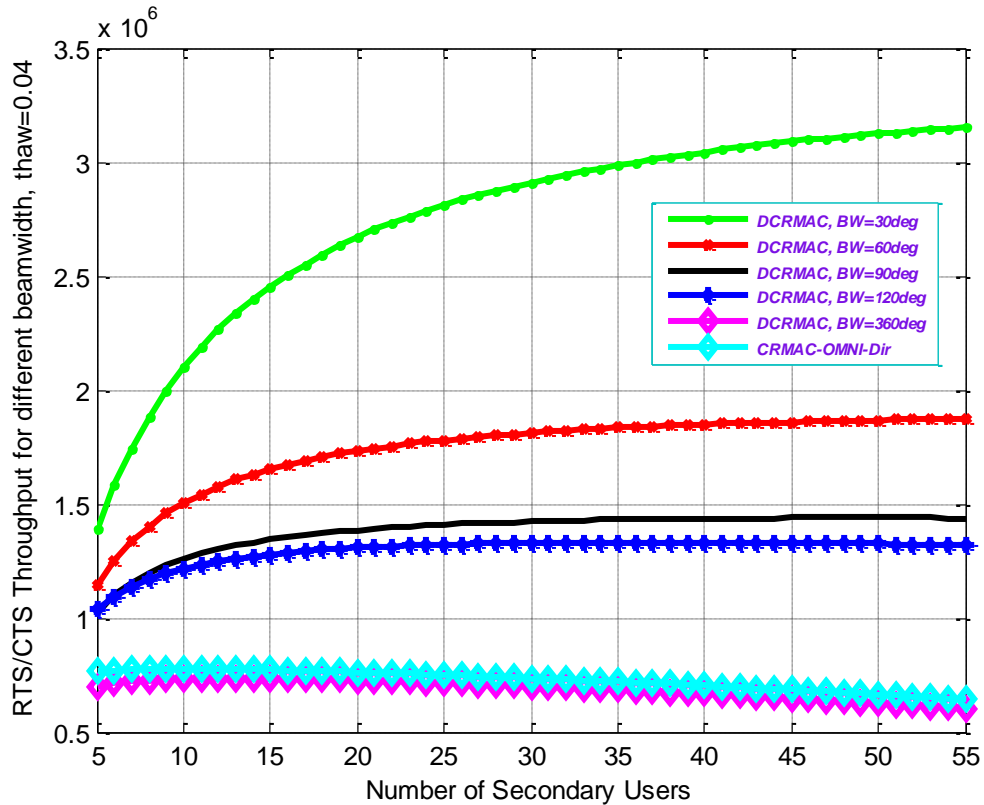
The throughput performance of DCR-MAC protocol for the three accessing mechanisms namely Basic, RTS/CTS, and M-CTS are presented in fig. 6.5 and fig. 6.6. For our simulations the throughput is measured in bit per second. The simulations are carried out based on the simulation parameters given in table 6.2. Besides, the following parameters are used in the simulations, probability of false alarm ($P_f=0.01$), probability of detection ($P_d=0.9$), and probability of vacant channel availability ($P_{H0}=0.9$) unless otherwise. These parameters are assumed because it is observed that the system shows the optimum performance near these values.



6.5a) DCR-MAC protocol Average throughput Vs number of secondary users for Basic, RTS/CTS, and M-CTS access Mechanisms



6.5b) DCR-MAC protocol Average throughput comparison for Basic, RTS/CTS, and M-CTS access Mechanisms for different Beamwidth Vs number of secondary users



6.5c) DCR-MAC protocol average throughput comparison for different beamwidth Vs CRMAC protocol throughput (CRMAC-OMNI-Dir) based on RTS/CTS access mechanism

Fig. 6.5 Impact of number of secondary users on the performance DCR-MAC throughput

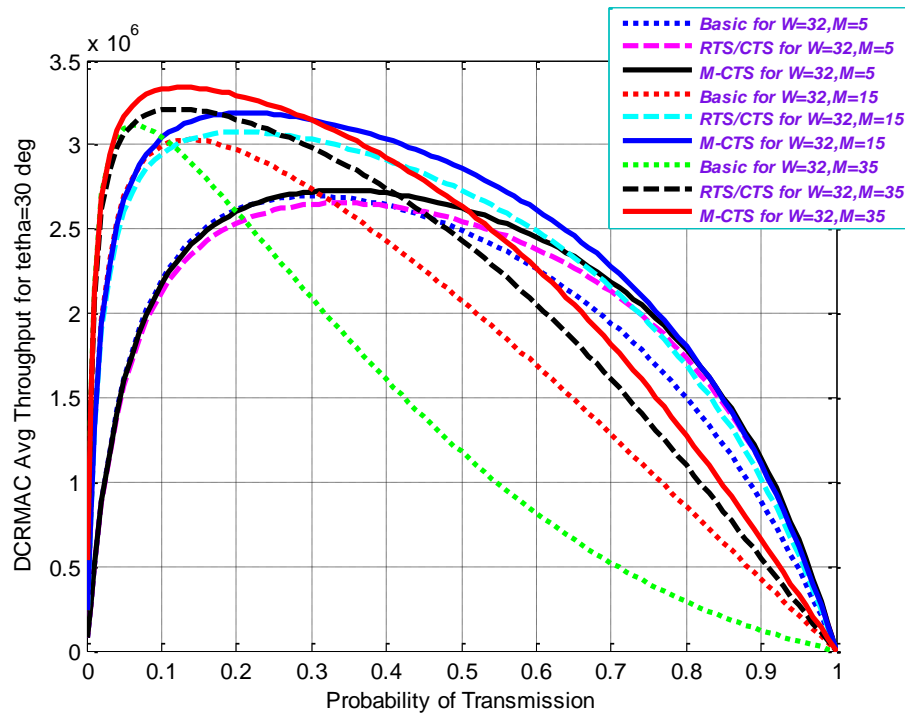
Simulation in fig. 6.5(a) shows the throughput performance of the three access mechanisms. The simulation is carried out for transmission probability of 0.1, and beamwidth of 30° . We used a multiple antenna to produce the required beamwidth (radiation pattern). The simulation result shows that the M-CTS access mechanism outperforms the remaining two access methods. As the number of SUs increases the average throughput of the three access mechanisms increases linearly and equally for almost number of users less than fifteen which was true for the conventional wireless communication system, but as the number of SUs keeps increasing the performance of the three access mechanisms becomes different. The performance of the Basic access mechanism keeps increasing with the increase of number of SUs only up to twenty SUs then the performance starts to decline. For the remaining two access mechanisms the performance increases with the increasing number of SUs but with the slow rate. The

performance of RTS/CTS mechanism becomes almost constant after forty number of SUs and starts to decline after nearly sixty number of SUs. The performance of M-CTS access mechanism keeps increasing up to sixty number of SUs and becomes constant and start to decrease its performance after eighty five SUs. As compared to the omni-directional CR-MAC protocol proposed in the previous chapter, all the three proposed directional CR-MAC protocols outperform the throughput performance by nearly four folds, this is due to the concurrent transmission capability of directional communication. The performance gain of the newly proposed access mechanism, M-CTS, brings an additional throughput gain of nearly 0.18Mbits/sec.

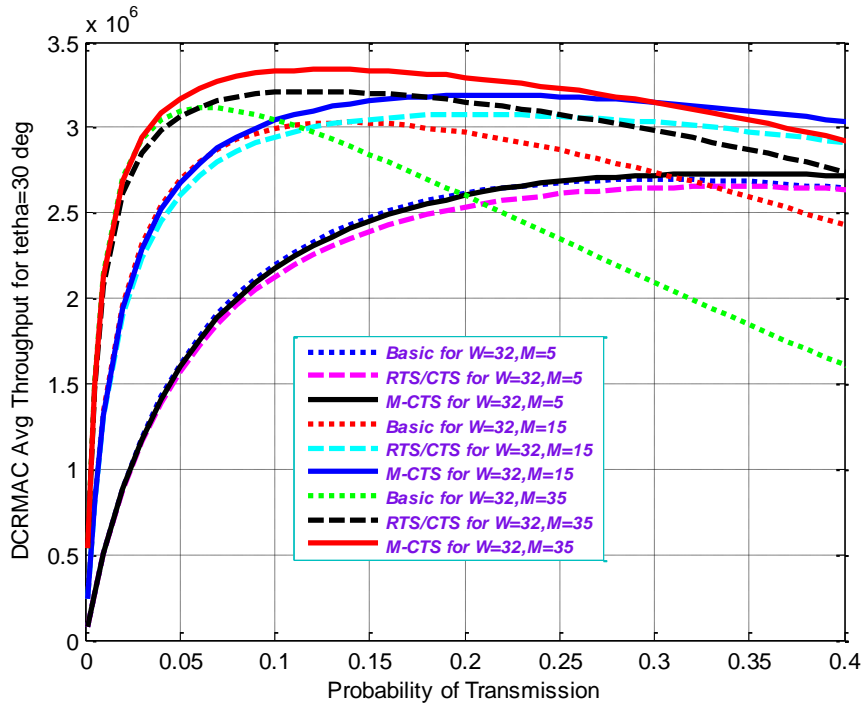
Simulation in fig. 6.5 (b) shows as the size of the antenna beam becomes wider and wider, the average throughput performance of the DCR-MAC protocol continuous decreasing. This is because as the antenna beamwidth increase the average number of concurrent transmissions decreases, in a single link much of the area will be covered which means much of the SUs will defer their transmission, and as a result it reduces the spectrum utilization efficiency and reduce the average throughput of the protocol. The beamwidth of multiple antenna system is also dependent on the number of array elements and distance of separation between the array elements. Therefore, narrower beamforming antenna is very fundamental and it is obtained either by increasing the number of antenna elements or by increasing the distance of separation. Moreover, from the simulation it is observed that the throughput performance does not show improvement after a certain number of SUs, for example for a beamwidth of 30° increasing number of SUs above 85 results more or less a constant throughput. This is due to the collision avoidance techniques used in RTS/CTS and M-CTS access mechanisms. However, the performance may show slow decrement after reaching the optimum point, this is due to the fact that once the optimum throughput is obtained with the optimum number of SUs, further increases of number of SUs increases the probability of collision which decreases the throughput performance.

Simulation in fig. 6.5 (c) shows a simulation carried out for directional RTS/CTS access mechanism for DCR-MAC and CRMAC (OMNI-Directional) for constant probability of transmission and different antenna beamwidth. In the simulation it is shown that the average throughput performance of DCR-MAC protocol with a radiation beamwidth of 360°

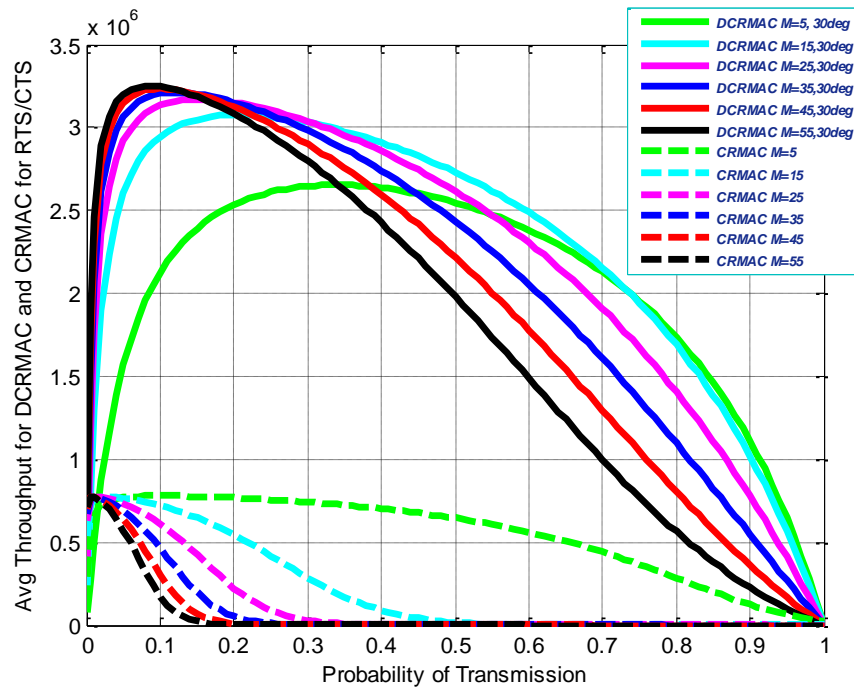
becomes almost the same as to the throughput performance of CRMAC which operates in omni directional mode. Generally, increasing the number of SUs improves the performance of average throughput of DCR-MAC protocol in a much meaning full way than the CRMAC protocol. This simulation also verifies the accuracy level of our system modeling.



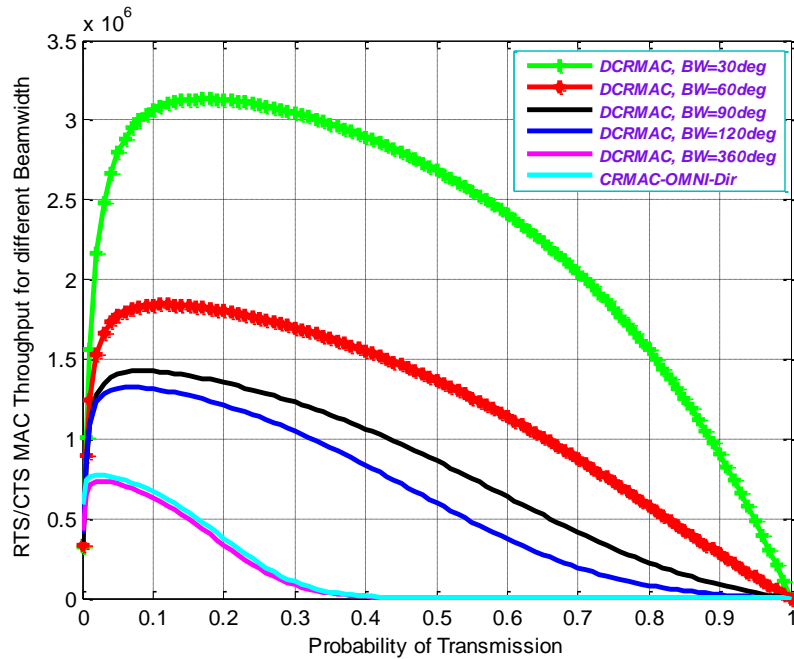
6.6a) Throughput performance comparison of DCR-MAC protocol for different number of secondary users Vs probability of transmission



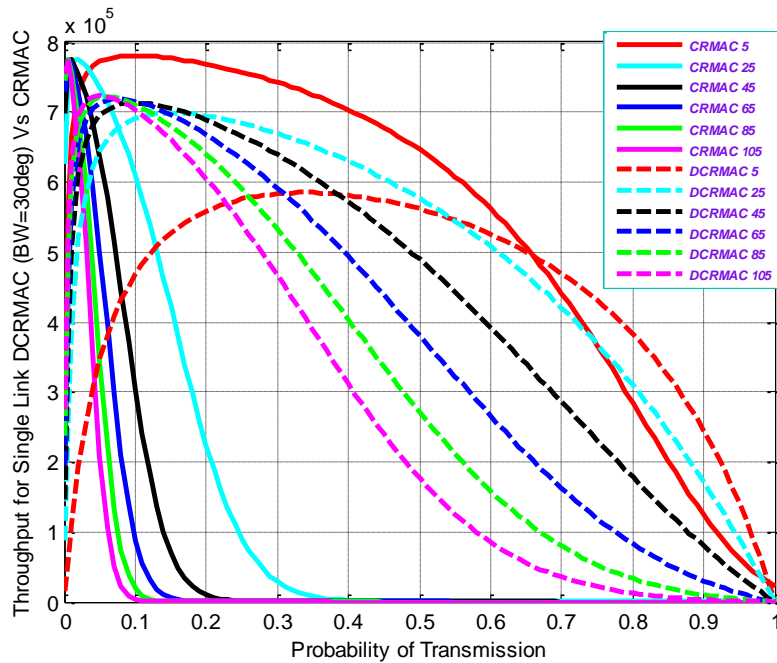
6.6b) Throughput performance comparison of DCR-MAC protocol for different number of secondary users Vs probability of transmission to clearly observe the optimum average throughput for beamwidth of 30° .



6.6c) Throughput performance comparison of DCR-MAC and CRMAC protocols for different number of secondary users Vs probability of transmission for beamwidth of 30° .



6.6d) Throughput performance comparison of DCR-MAC and CRMAC protocols for different beamwidth Vs probability of transmission for the RTS/CTS access mechanism.



6.6e) Single link throughput performance comparison of DCR-MAC and CRMALC protocols for different number of secondary users Vs probability of transmission for the RTS/CTS access mechanism.

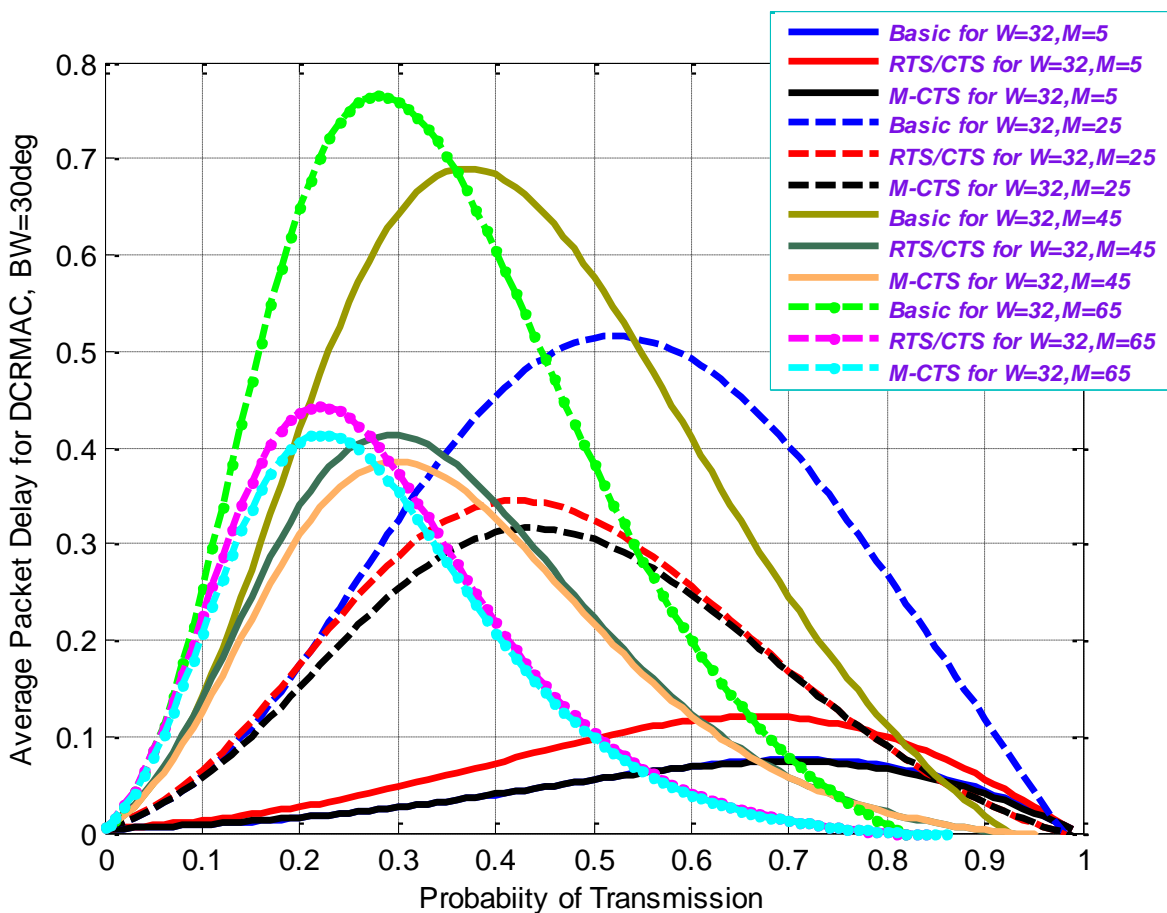
Fig. 6. 6 Impact of probability of transmission on the throughput of DCR-MAC protocol.

The simulation in fig. 6.6 presents the impact of probability of transmission on the performance of average throughput of DCR-MAC protocol. In fig. 6.6(a) the simulation shows that DCR-MAC protocol results better average throughput for lower probability of transmission particularly as the number of SUs becomes larger and larger. As the number of SUs and the probability of packet transmission becomes larger, greater number of the SUs attempt transmission and there will be a higher probability of collision which degrades the average throughput of the DCR-MAC protocol. Whereas, as the number of SUs becomes smaller and smaller and the average throughput decline very faster as the probability of transmission increases because due to high probability of transmission the probability of collision increases which results lower spectrum utilization efficiency. Fig. 6.6(b) shows that the average throughput of DCR-MAC protocol for a beamwidth of 30° become maximum around 0.1 probability of transmission for the three access mechanisms especially as the number of SUs becomes large. The graph shows the chopped section of the simulation.

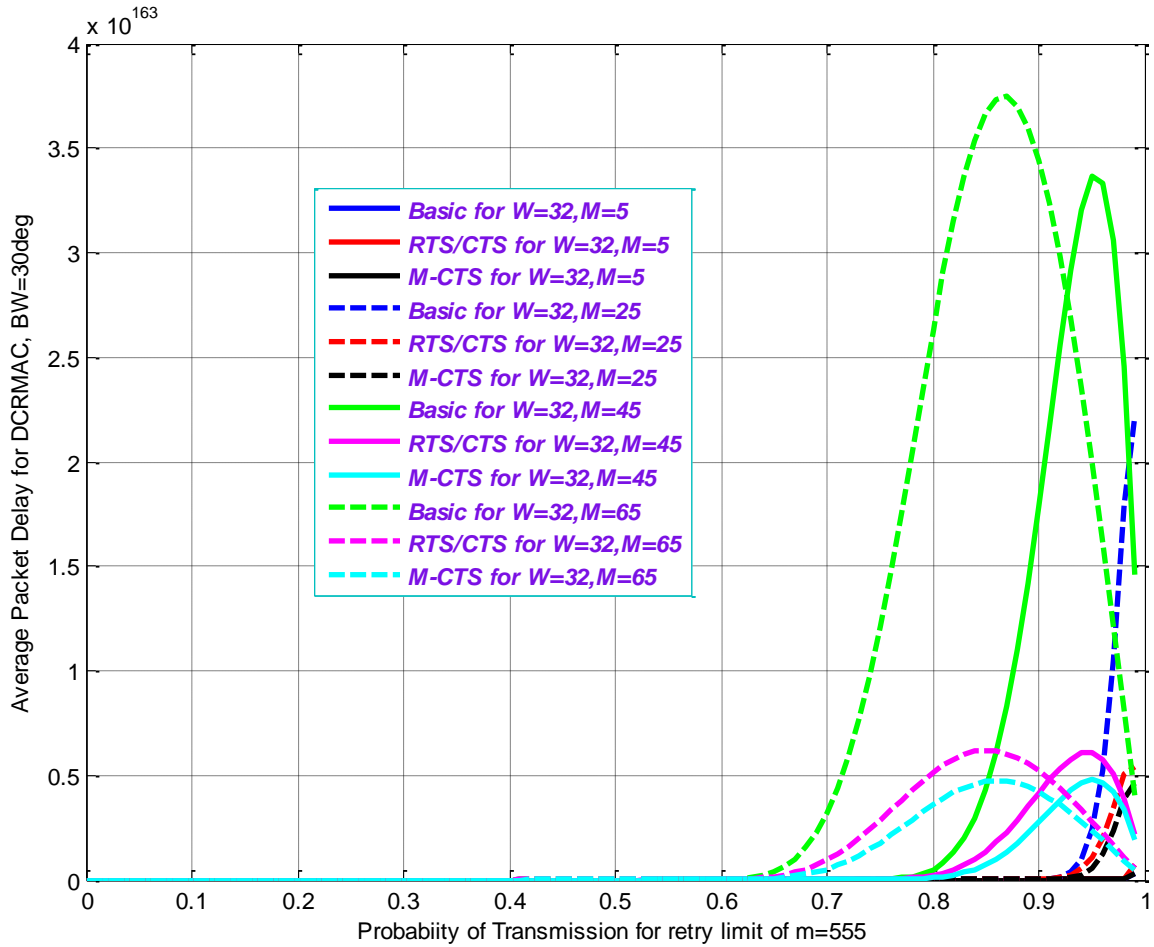
Simulation in fig. 6.6 (c) shows the throughput performance comparison between DCR-MAC and CRMAC protocols for RTS/CTS access mechanisms which holds true for both basic and M-CTS access mechanisms. The maximum average throughput of DCR-MAC protocol for a beamwidth of 30° is at least three times higher than the maximum throughput of CRMAC protocol. As the number of SUs becomes smaller the CRMAC protocol shows better performance gain (in terms of throughput) in relative to the DCR-MAC protocol this is due to poor spectrum utilization efficiency.

Similarly, fig. 6.6 (d) presents the effect of beamwidth variation on the average throughput of DCR-MAC protocol with respect to changes of probability of transmission for RTS/CTS access mechanism which holds true for the other two variants. The simulation shows that in all scenarios the maximum average throughput is observed for narrower beamwidth for all probability of transmission. For beamwidth of 360° where the DCR-MAC protocol operates like CRMAC protocol, the average throughput of DCR-MAC protocol for 360° becomes almost the same as the throughput of CRMAC protocol.

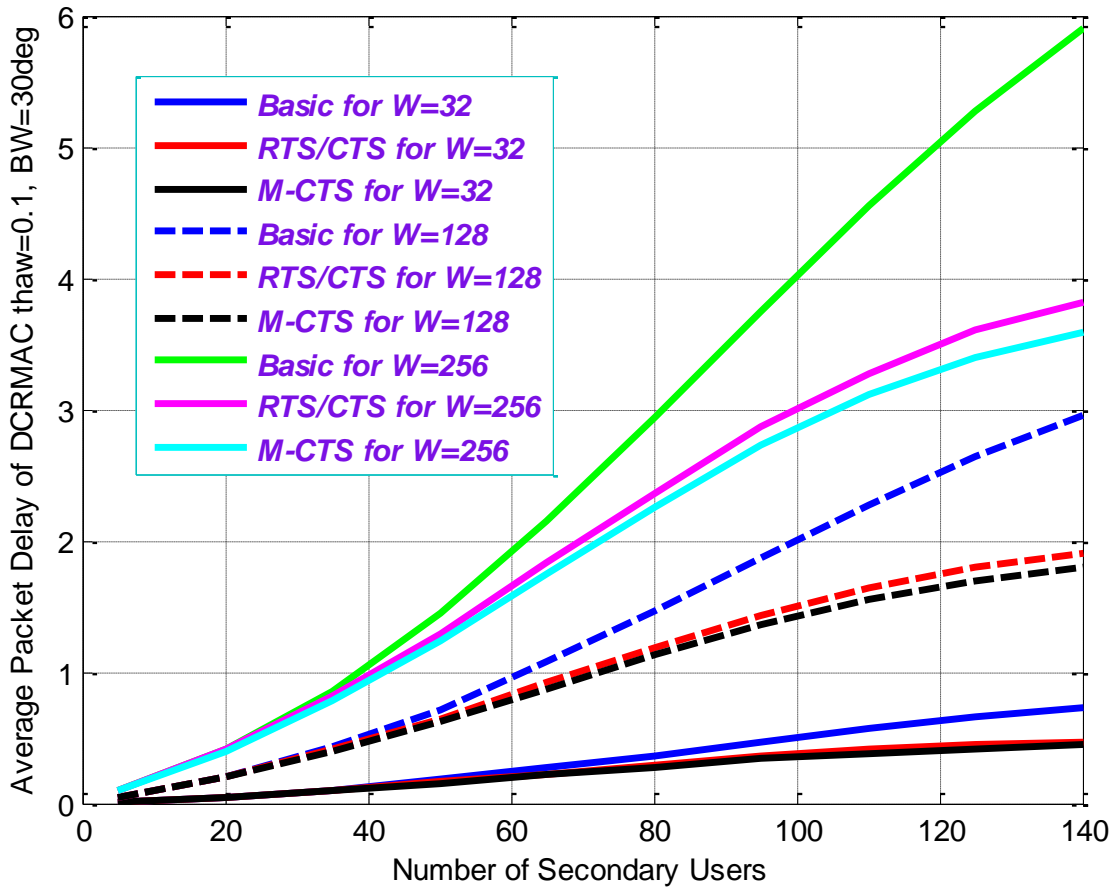
Simulation in fig. 6.6 (e) compare the throughput of a single link DCR-MAC protocol and the throughput of CRMAC protocols for different number of SUs and different values of probability of transmission. Until now the performance of DCR-MAC and CRMAC has been compared in terms of average throughput but the simulation in fig. 6.6(e) shows the throughput performance difference a node communicating using directional antenna and a node that communicates with omni-directional antenna would gain. As can be observed from the simulation, a node may enjoy the maximum throughput in CRMAC protocol than in DCR-MAC protocol. This is because the link in directional communication could fail due to hidden communication to the transmitter or receiver which decreases the maximum throughput but DCR-MAC shows remarkable performance for all probability of transmission in relative to CRMAC.



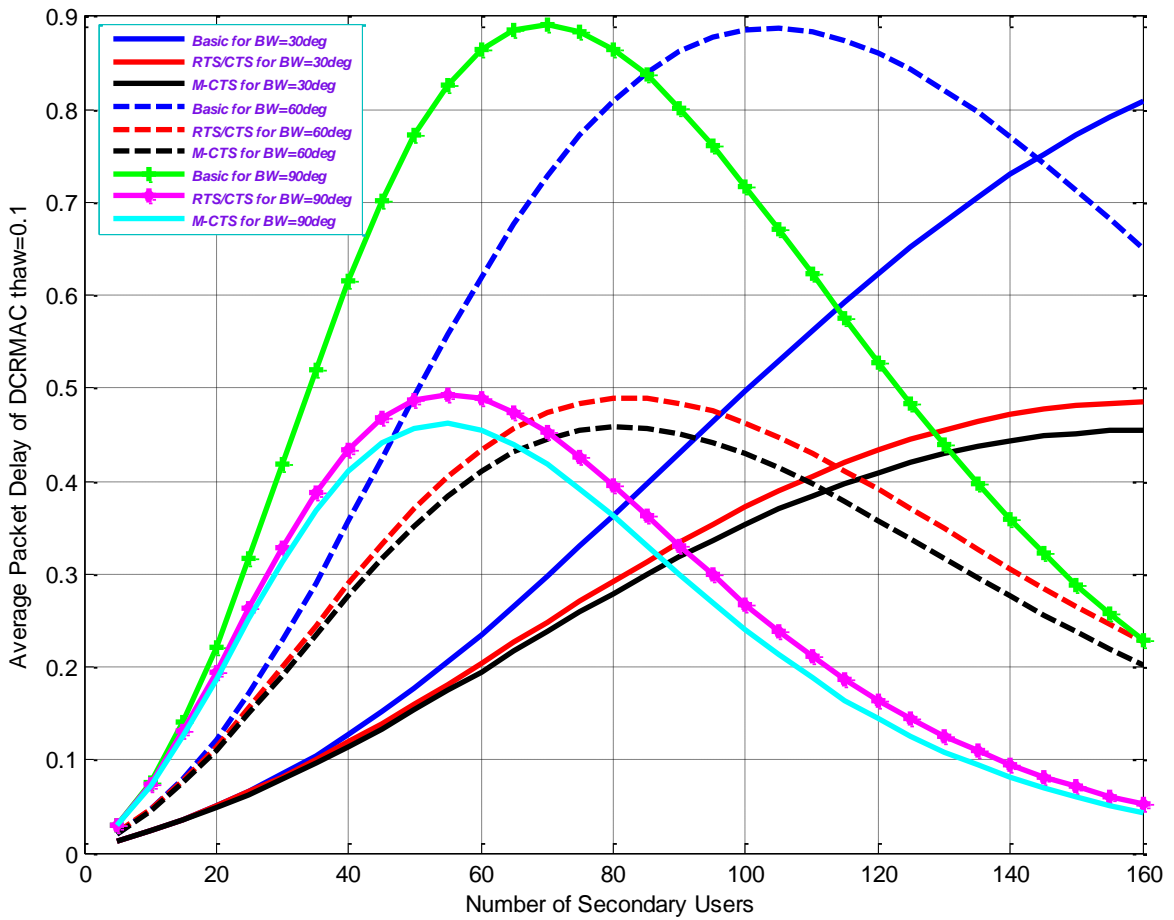
6.7a) Average Packet Delay performance comparison of DCR-MAC protocol for Basic, RTS/CTS, and M-CTS access mechanism for different number of secondary users, constant contention window size and beamwidth Vs probability of transmission.



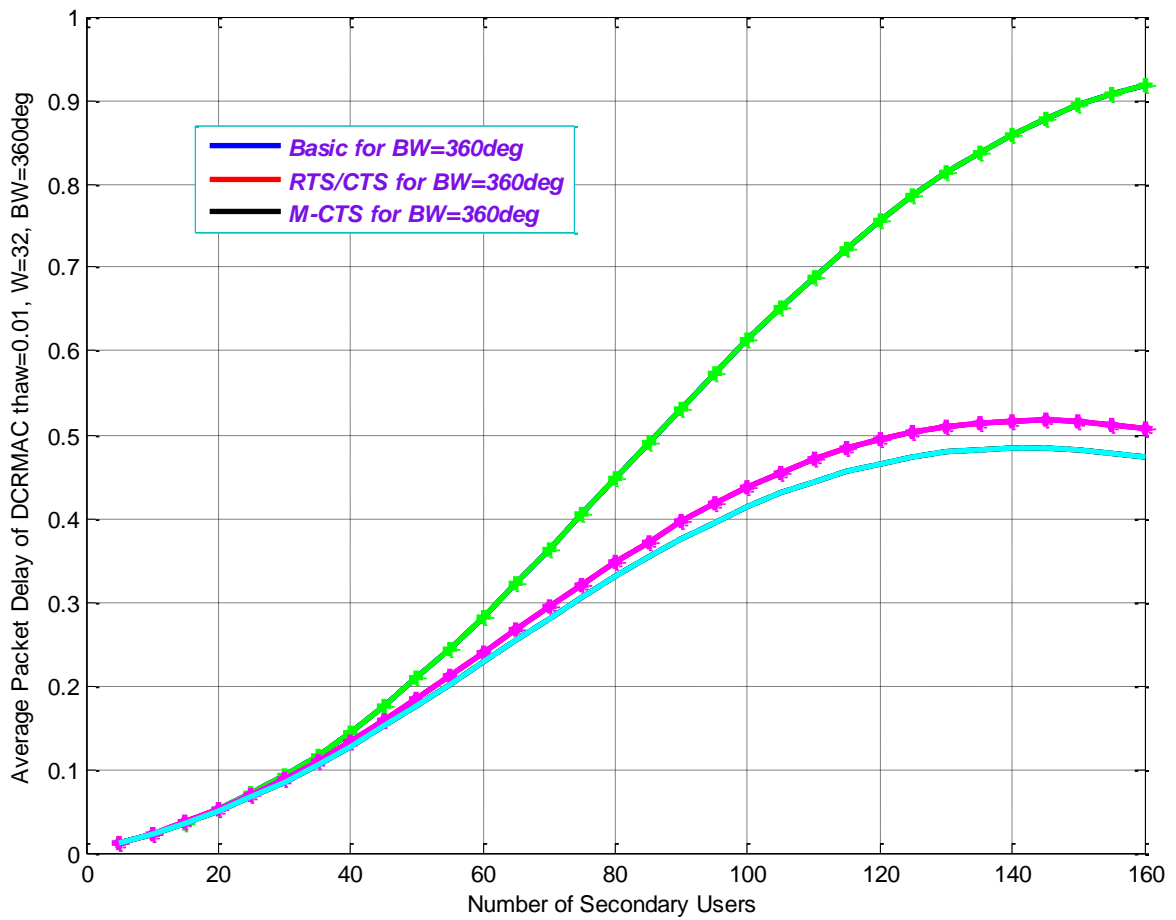
6.7b) Average Packet Delay performance comparison of DCR-MAC protocol for large number of retry limit ($m=555$) simulated for Basic, RTS/CTS, and M-CTS access mechanism for different number of secondary users, constant contention window size and beamwidth Vs probability of transmission.



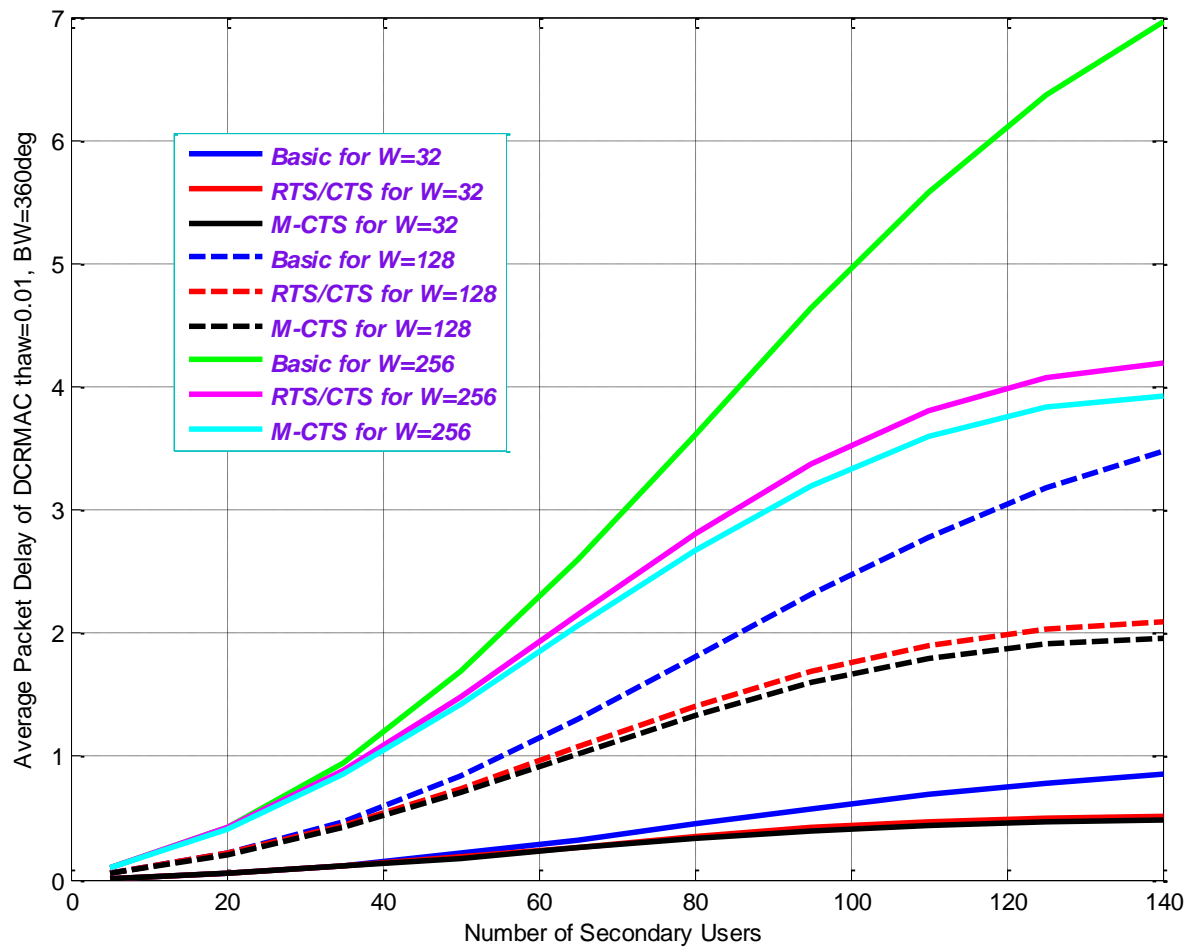
6.7c) Average Packet Delay performance comparison of DCR-MAC protocol for Basic, RTS/CTS, and M-CTS access mechanism for different contention window size, and constant beamwidth and probability of transmission Vs number of secondary users.



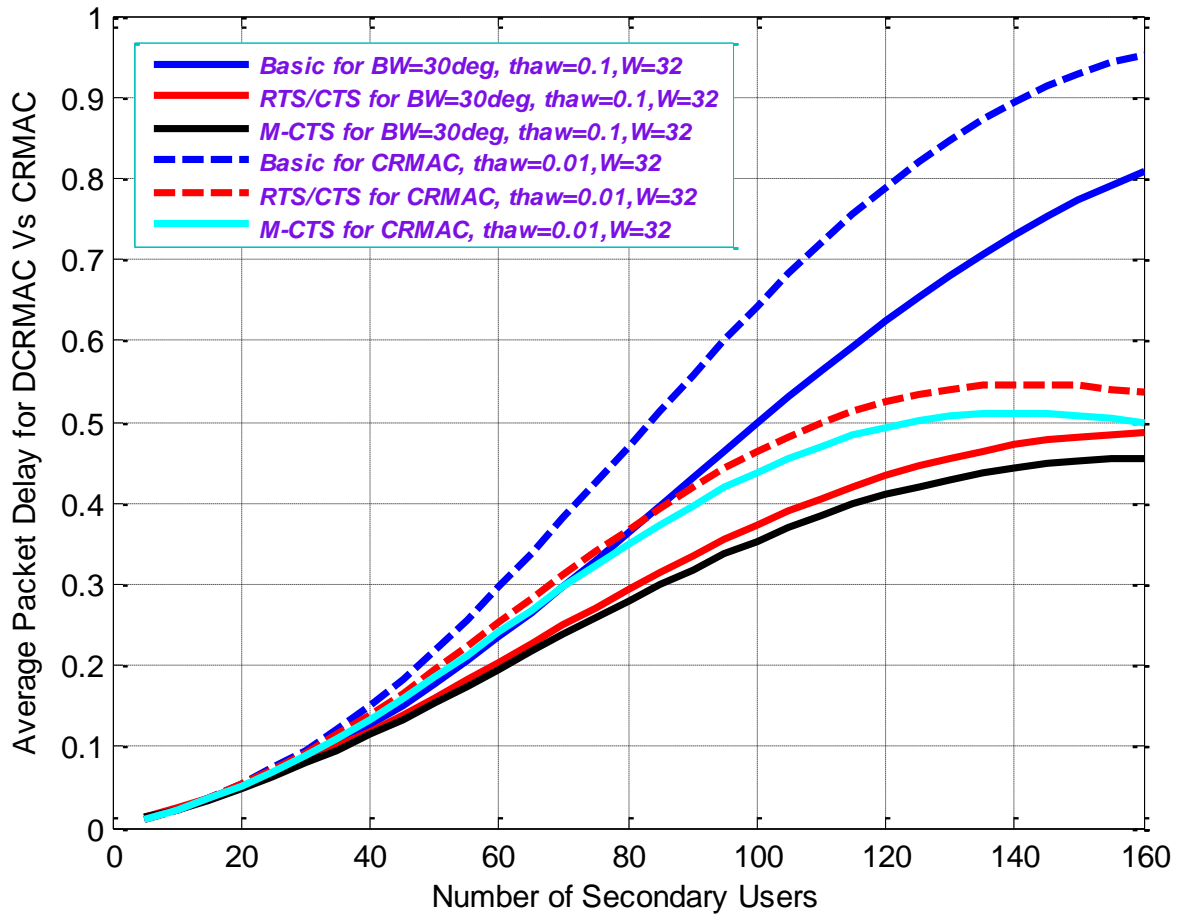
6.7d) Average Packet Delay performance comparison of DCR-MAC protocol for Basic, RTS/CTS, and M-CTS access mechanism for different beamwidth, and constant contention window size ($W=32$) and probability of transmission Vs number of secondary users.



6.7e) Average Packet Delay performance comparison of DCR-MAC protocol for Basic, RTS/CTS, and M-CTS access mechanism for constant beamwidth ($BW=360deg$), contention window size ($W=32$) and probability of transmission Vs number of secondary users.



6.7f) Average Packet Delay performance comparison of DCR-MAC protocol for Basic, RTS/CTS, and M-CTS access mechanism for different contention window size, and constant beamwidth ($W=360\text{deg}$) and probability of transmission (0.01) Vs number of secondary users.



6.7g) Average Packet Delay performance comparison of DCR-MAC and CRMAC protocols for Basic, RTS/CTS, and M-CTS access mechanisms for beamwidth ($BW=30$), contention window size ($W=32$), and probability of transmission ($0.1, 0.01$ respectively).

Fig. 6. 7 Impact of probability of transmission, number of secondary users, and beamwidth on the performance of average packet delay of DCR-MAC protocol.

Simulations in fig. 6.7 are carried out to show the average packet delay of DCR-MAC protocol for Basic, RTS/CTS and M-CTS access mechanisms. In our simulations the average packet delay is measured in second. The performance of the average packet delay of DCR-MAC protocol in terms of number of SUs, probability of transmission, contention window size, and beamwidth are presented. All the simulations are operated for stage $m=5$ which is also the same for retry limit. Fig. 6.7 (a) shows the average packet delay of DCR-MAC protocol simulated for different number of SUs by varying the probability of transmission by setting beamwidth ($BW=30$) constant. For all scenarios, the average packet delay of M-

CTS based DCR-MAC protocol results lower delay in relative to RTS/CTS and basic access mechanisms. The simulation shows that as the number of SUs increases, the maximum average packet delay a packet wait in the transmission queue increases for specific probability of transmission since at different probability of transmission a packet experiences different average packet delay. Moreover, as the probability of transmission becomes larger and larger which increases the probability a transmission sees collision (see Eqn. 4.8), the average packet delay start to decline due to the limited number of retry. If the number of retry limit becomes larger, the average packet delay becomes large. In other words, for infinity number of retry limit, the average packet delay becomes infinity, see fig. 6.7 (b) a simulation for large number of retry limit ($m=555$), for constant $BW=30^\circ$, and for different number of SUs and probability of transmission.

The simulation in fig. 6.7 (c) shows the impact of contention window size on the average packet delay of DCR-MAC protocol. The simulation is carried out for different contention window sizes ($W=32$, $W=128$, $W=256$), and constant probability of transmission and beamwidth ($BW=30^\circ$) by varying the number of SUs. The simulation shows that as the number of SUs increases the average packet delay of DCR-MAC protocol for all contention window size increases, however the average packet delay is higher for longer contention window size than shorter contention window size for the three access mechanisms. Due to the exponential backoff mechanism, when node's transmission encounters collision it will double its contention window size, therefore, as the contention window size increases the average length of time a packet waits in the queue before it gets transmitted or get dropped increases.

Simulation in fig. 6.7 (d) shows the effect beamwidth on the average packet delay of DCR-MAC protocol. In this simulation contention window size ($W=32$) and probability of transmission (0.1) is considered. The simulation is carried out for the three access mechanisms by varying the number of SUs. For all beamwidths ($BW=30^\circ$, $BW=60^\circ$, and $BW=90^\circ$) varying number of SUs results lower average packet delay for M-CTS access mechanism in relative to the other two access mechanisms. The simulation shows that larger beamwidth resulted longer average packet delay than narrow beamwidth. This is because, as the beamwidth becomes narrow, the number of concurrent transmission

becomes larger which decreases the number of SUs that will be forced to get in to backoff mechanisms. As the number of SUs increase, the residue SUs in backoff window increase, as a result of which the average packets delay they experience increases due to the nature of exponential backoff mechanism. If the beamwidth is assumed to be 360° and the probability of transmission is assumed to be 0.01 for constant contention window size ($W=32$), the average packet delay shown in fig. 6.7 (e) and (f) of the DCR-MAC protocol look like exactly the average packet delay result of CR-MAC protocols shown in fig. 5.7 (a) for contention window size of $W=32$, which is consistent. Moreover, from the simulation we can observe that as the number of SUs increases, the average packet delay increase somehow in a linear fashion, however, for larger beamwidth the average packet delay starts to decline this is due to collision. As the beamwidth becomes larger and larger the number of successful concurrent transmission decreases due to transmission failure because of collision, receiver blocking, transmitter blocking, and other factors. Therefore, as the beamwidth increases in a single link large number off SUs will be blocked from establishing concurrent transmission, however, those which are out of the directional communication of the ongoing transmission can initiate concurrent transmission but due to the large beamwidth the probability of transmission failure will be higher and due to the limited number of retry limit the packet will be dropped quickly.

The simulation in fig. 6.7(e) shows the average packet delay for the DCR-MAC and CRMAC protocols. The simulation is operated for constant window size ($W=32$), beamwidth ($BW=30^{\circ}$), and probability of transmission (0.1, 0.01 respectively) by varying the number of SUs. The simulation is carried out for the three access mechanisms. The simulation result shows that DCR-MAC protocol exhibit lowest average packet delay time than CRMAC protocol for all of the three access mechanisms. From the three access mechanisms M-CTS mechanism show the lowest average packet delay.

Table 6.3 M-CTS based directional CR-MAC throughput comparison in kbps for 30 Degree

Number of SUs	3	6	9	12	15	30	45	60	75	90	105	120
Throughput Gain with respect to RTS (kbps)	23.67	55.37	73.99	86.09	94.74	118.52	132.15	143.03	152.91	162.37	171.68	180.96
throughput Gain with respect to Basic (kbps)	-18.5	-25.6	-10.40	15.10	458.00	222.40	402.10	573.1	733.00	881.1	1017.4	1142.00

Table 6.4 M-CTS based directional and Omni-Directional CR-MAC

Number of SUs	3	6	9	12	15	30	45	60	75	90	105	120
Throughput of Directional (kbps)	1548.7	2362.6	2717.8	2915.4	3040.2	3294.8	3367.3	3389.3	3389.2	3376.8	3356.5	3330.2
Throughput of Omni-Directional (kbps)	407.17	552.22	605.35	632.35	648.3	675.92	679.12	675.58	668.89	660.27	650.23	639.00
Directional advantage in Percentage	380.36	427.84	448.96	461.04	468.95	487.45	495.83	501.69	506.69	511.43	516.20	521.16

To summarize our findings, we use table 6.3 and table 6.4. Compared to the three directional random access MAC protocols, the basic access based directional random access MAC protocol shows better performance for smaller number of SUs, particularly for number of SU of less than ten users. However, for greater than ten number of SU, the M-CTS based directional random access MAC protocol shows good performance. In all scenarios, M-CTS based directional random access MAC protocol shows good performance compared with RTS/CTS based directional random access MAC protocol.

Table 6.4 shows the comparative throughput advantage of M-CTS based directional random access MAC protocol in relative to omni-directional M-CTS based random access MAC protocol (ECR-MAC). The use of directional antenna with CRWMN improves the performance of the proposed directional random access MAC protocol based on M-CTS access mechanism, at least by 380 percent.

In this chapter, three directional random access MAC protocols for CRWMN have been proposed, and their performances in terms of average throughput and average packet delay have been examined. Due to directional communication which enables concurrent transmissions, the performance of M-CTS based DCR-MAC protocol shows a minimum of 380% improvement for network size of three numbers of SUs to 521% improvement for network size of one hundred twenty numbers of SUs with respect to M-CTS based omni-directional CR-MAC protocol. This conclusion also holds true for the other types of DCR-MAC protocols when compared with their respective omni-directional CR-MAC protocols.

Chapter-7

CONCLUSION & FUTURE WORK

CRN maximizes the spectrum utilization efficiency by using dynamic spectrum management strategy. In this research work, CRWMN is considered, specifically, the backbone mesh network is assumed. In this type of network, the mesh routers and the mesh gateways exhibit low mobility which is an important feature to overcome the physical size and power supply constraints that are commonly observed in wireless nodes. More importantly, this feature is suitable to integrate multiple antenna system to mesh routers and mesh gateways.

In different literature we have explored that equipping cognitive users with multiple antenna system improves the system performance by improving the channel capacity, reducing interference, reducing the spectrum sensing time, decreasing probability of false alarm, increasing probability of detection, power wastage reduction, range extension, and others.

In this dissertation, we have designed MAC protocols for CRN in general and to CRWMN in particular using multiple antenna systems. To evaluate the performance of the proposed random access MAC protocol we have used throughput and average packet delay as performance indicators. For the case of omni-directional antenna system number of SUs, probability of transmission, and contention window size have been used to evaluate the performance of the proposed Enhanced Cognitive Radio MAC protocol (ECR-MAC), whereas, beamwidth size is used as an additional parameter in evaluating the performance of the proposed directional random access MAC protocol.

We have proposed two novel random access MAC protocols these are enhanced random access MAC protocol called ECR-MAC protocol, and directional random access MAC protocol called DCR-MAC protocol.

ECR-MAC protocol is proposed by considering the unique nature of cognitive radio system and by modifying the RTS/CTS access mechanism. To evaluate the performance of ECR-MAC protocol we have modeled a system where all the SUs operate in saturated condition. In our system model, an arbitrary SU may experience any one of the four events when it is in transmitting mode or it may also experience another four events when it is in listening mode. All these events are modeled mathematically through stochastic process. The throughput and average packet delay expressions of the proposed MAC protocol are derived based on these events, and have been used to evaluate the proposed ECR-MAC protocol.

We carried out simulations to validate our mathematical model using MATLAB since our proposed protocol integrates the physical layer with the MAC layer. Using simulations it shown that the performance of the proposed MAC protocol namely ECR-MAC shows superior performance in terms of throughput and average packet delay.

The throughput performance of the proposed ECR-MAC protocol shows better performance compared with basic access and RTS/CTS access based CR-MAC protocols. It is shown that increasing number of SUs and contention window size decreases the throughput of the three MAC protocols which is consistence with the theoretical analysis. However, increasing probability of transmission for constant contention window size and SUs and retry limit of five (5) does not increase the throughput linearly, rather it increase for lower probability of transmission and start decreasing as the probability of transmission increase. This is due to the fact that for lower retry limit, as the probability of transmission keeps increasing, the probability of collision increases. As the probability of transmission and probability of collision increases, the SUs reach the retry limit so quickly and the packet gets dropped so fast. Moreover, the basic access CR-MAC protocol shows better performance in relative to RTS/CTS access based CR-MAC protocol for small number

of users, however, our proposed ECR-MAC protocol shows better performance for any number of users in relative to the basic and RTS/CTS access based CR-MAC protocol.

The performance of the proposed ECR-MCA protocol in terms of average packet delay shows relatively shorter delay when compared with the other two CR-MAC protocols. Number of SUs, contention window size, and probability of transmission are used to evaluate the performance of ECR-MAC protocol. As the number of SUs and contention window size increase, the average packet delay increases. Increasing the probability of transmission first increasing the average packet delay and then it starts decreasing for constant contention window size, number of SUs, and smaller retry limit of five (5). As the retry limit becomes larger and larger the average packet delay increases with increasing probability of transmission for constant contention window size and number of SUs.

Generally, the proposed ECR-MAC protocol shows superior performance compared with CR-MAC protocols developed based on basic access and RTS/CTS access mechanisms. For all scenarios ECR-MAC shows good performance and its performance shows relatively more improvement for network having small number of SUs, smaller contention window size, and smaller probability of transmission. However, the optimum performance is observed for network size between 30 and 60 numbers of SUs, then its performance show relatively small decrement. For the basic access based CR-MAC protocol, the performance is observed to be optimum for network size of 10 and 20 number of SUs, then its performance linearly decrease with the increase number of SUs since it has no collision avoidance technique. Moreover, ECR-MAC shows an average performance improvement of 5% in relative to RTS/CTS access based CR-MAC protocols which comes due to the elimination of the RTS frame and one SIFS slot during a successful transmission process and the amount of time an overhearing SU freezes its backoff timer will be small for the M-CTS access mechanism than the other two types because, the M-CTS access mechanism freezing time during collision is less than by the amount of time used to transmit a DATA packet minus the time it takes to transmit CTS frame, whereas with respect to RTS/CTS access mechanism the freezing time during collision is less than by the amount of time used to transmit an RTS frame and SIFS duration.

The second novel MAC protocols proposed in this dissertation are DCR-MAC protocols. In the design of DCR-MAC protocols, directional communication is the corner stone of our finding. All radiating elements exhibit some directivity, however the most directional antenna, array antenna (multiple antenna) is assumed in the design. The directivity of an array antenna is affected by the number of array element, distance of separation of the array element, element pattern, and the excitation phase. Therefore, the beamwidth of multiple antenna is affected by these parameters.

To evaluate the performance of DCR-MAC protocols we have modeled the system using stochastic process. In our system model, an arbitrary SU which is in directional transmission attempt may experience any one of the five events; or if it is in listening mode it may experience any one of the four events. We have modeled all these events mathematically using a stochastic process. Using the mathematical model of these events, we have developed a closed form expressions for the average throughput and average packet delay of the proposed three directional cognitive radio MAC protocols.

We have developed three directional random access MAC protocols for CRWMN based on the basic, RTS/CTS, and M-CTS access mechanisms. These protocols are developed by taking the directional communication in to account, and their performance is evaluated based on average throughput and average packet delay by varying the beamwidth of the radiation pattern, the number of SUs, probability of transmission, and contention window size. The performance evaluations of the DCR-MAC protocols show that larger number of SUs, longer contention window size, and broaden beamwidth reduce the performance of all the three directional MAC protocols. All the three directional random access MAC protocols show good performance improvement compared with non-directional random access CR-MAC protocols.

In general, from the three directional random access MAC protocols proposed for CRWMN, the M-CTS based MAC protocol outperforms the basic and RTS/CTS based MAC protocols in terms of average throughput and average packet delay. The single link performance of the three directional MAC protocols is relatively lower than the non-directional random access MAC protocol. This is due to the fact that directional communication enables concurrent

transmissions which decrease the single link performance and improves the network performance in a significant way.

The basic access based DCR-MAC protocol shows good performance for smaller number of SU (less than ten) compared with the RTS/CTS based but not in relative to M-CTS based DCR-MAC protocols hence the probability of collision for small number of SU is very small. However, for higher number of SU, the M-CTS based DCR-MAC protocol shows superior performance compared to both basic and RTS/CTS based DCR-MAC protocols. The performance gain of M-CTS based DCR_MAC protocol (for 30° beamwidth) compared with ECR-MAC protocol brings at least three hundred eighty percent (380%) throughput performance improvement which is a huge performance improvement. This improvement comes due to the use of directional antenna which enables concurrent transmission, elimination of RTS frame and SIFS time slot.

As future works, we recommend the following:-

Generally, the use of multiple antennas for spectrum sensing in cognitive radio network brings many advantages such as shorter sensing time, robustness to noise uncertainty, and better detection performance (better probability of detection, reduced probability of false alarm) in relative to single antenna detection techniques but it is at the expenses of system complexity. Therefore, designing less computational complex spectrum sensing system using multiple antennas could be one research direction.

Lack of comparative study on multiple antennas based spectrum detections in terms of sensing time, robustness to noise uncertainty, increased number of antennas and samples, impact of antenna correlation, computational complexity, noise variance mismatch, and other important parameters is mandatory to help the researchers decide easily which types of multiple antenna based spectrum sensing for which CR applications. Moreover, no study has been conducted to investigate suitable spectrum sensing technique which better ensemble the unique nature of CRWMNs. Therefore, investigation of suitable multiple antenna based spectrum sensing is mandatory.

The study on the different spectrum sharing revealed that hybrid spectrum sharing has superior performance over the other spectrum sharing techniques (interweave, underlay, and overlay) mainly in terms of capacity gain, bit error rate, and spectrum efficiency. However, a comprehensive performance comparison among these spectrum sharing is not available, for example comparing overlay with underlay, interweave with overlay, a hybrid (which combine interweave with underlay, and overlay with underlay) with others, and beamforming with the others.

The benefits of beamforming, particularly transceiver adaptive beamforming is huge since it eliminates the need for spectrum sensing. However, the system complexity of adaptive array antennas, and the overall network performance gain because of adaptive beamforming should be compared with the performance gain and system complexity due to the use of multiple antennas for both spectrum sensing and spectrum sharing.

The performance of M-CTS access mechanism is investigated for saturated condition; however, studying the performance of M-CTS access mechanism in unsaturated condition for both enhanced and directional cognitive radio MAC protocol could be an important research direction.

We have proposed multiple antenna based MAC protocols for cognitive radio wireless mesh network. We have assumed backbone network with distributed spectrum sensing techniques, however, evaluating the performance of M-CTS access mechanism for central spectrum sensing techniques could be one research direction for both single channel and multiple channels scenarios.

Evaluating the performance of the proposed MAC protocols for different spectrum sensing and sharing techniques could be another research direction. The capacity analysis for multiple antenna based CRWMN has not been explored.

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