DEVELOPMENT OF A CSMA MAC PROTOCOL AND THROUGHPUT ANALYSIS FOR MU-MIMO WLAN

by

Manobendu Sarker
Student ID. 0411062240

MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

Department of Electrical and Electronic Engineering
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
January 2017

The thesis entitled "**DEVELOPMENT OF A CSMA MAC PROTOCOL AND THROUGHPUT ANALYSIS FOR MU-MIMO WLAN**" submitted by Manobendu Sarker, Student ID. 0411062240F, Session: April, 2011 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING on January 28, 2017.

BOARD OF EXAMINERS

1. Fuddin 28/1/2017 ______________________ **Chairman** (Supervisor)
(Dr. Md. Forkan Uddin)
Associate Professor
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205

2. 28/1/17 ______________________ **Member** (Ex-officio)
(Dr. Quazi Deen Mohd Khosru)
Professor and Head
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205

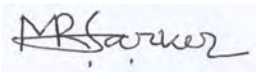
3. Lutfa Akter 28/1/2017 ______________________ **Member**
(Dr. Lutfa Akter)
Associate Professor
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka-1205

4. 28/01/2017 ______________________ **Member** (External)
(Dr. Rajesh Palit)
Associate Professor
Department of Electrical and Computer Engineering
North South University
Bashundhara, Dhaka 1229

CANDIDATE'S DECLARATION

I, do, hereby declare that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Signature of the candidate



Manobendu Sarker

Dedication

To my parents.

Acknowledgments

First and foremost, I would like to express my utmost gratitude to my supervisor, Dr. Md. Forkan Uddin, for his invaluable assistance, support and guidance throughout the course of this work. I am much indebted for his patience and encouragement over the years. Without his support and guidance, this thesis would not be possible.

I would like to thank Dr. Lutfa Akter and Dr. Rajesh Palit, for the time and effort in evaluating my work and providing valuable feedback and suggestions.

I am also thankful to my best friends Shekhor, Dipu, Rokon, Shubir and Partho for providing support and encouragement. Their suggestions helped me in countless ways.

Special thanks to my parents and my brother, Rothy for believing in me and encouraging me throughout my life. I am indebted to my family for their endless love, care and support.

And finally, I would like to thank the Almighty, the Lord of all creations, for blessing me with so many respected personalities around me and this auspicious achievement, in particular.

Abstract

With the proliferation of wireless devices as well as high bandwidth consuming applications, wireless local area networks (WLANs) has not only turned into the most popular form of wireless communication but also increased the emphasis on throughput in a significant manner. Multi-user multiple-input and multiple-output (MU-MIMO), an advance form of MIMO, has caught the eyes of the researchers due to its enormous capacity in enhancing the performance of wireless networks. IEEE 802.11 provides the physical layer (PHY) and medium access control (MAC) specifications for WLANs. Carrier sense multiple access with collision avoidance (CSMA/CA) is mainly utilized as the access mechanism in IEEE 802.11 based WLANs. However, the traditional CSMA/CA MAC protocol cannot use the full benefits from MU-MIMO technique in WLANs. The random access nature of the users to the shared medium is responsible for this. Therefore, MU-MIMO WLANs under the traditional CSMA/CA MAC protocol cannot employ all the resources simultaneously which results in the ineffective utilization of the resources.

In this thesis, we propose a carrier sensing based MAC protocol for MU-MIMO based WLANs system which can extract the full benefits of MU-MIMO technique. In the proposed protocol, multi-contention based users selection in uplink and concurrent multi-packet transmission in downlink are incorporated by introducing an additional control packet and using the existing control packets with some modifications into the frame structure. By utilizing these control packets, our protocol not only ensures the proper utilization of all the available resources but also efficiently encounters the joint uplink-downlink access based problems raised in MU-MIMO based WLAN environment.

We consider a single rate and single channel WLAN. The transmission power of each antenna is assumed to be equal. We model the WLAN system under the proposed MAC protocol as a discrete time Markov chain (DTMC). Based on the Markov chain, an analytical model is developed to compute the total throughput of a WLAN under saturation. The wireless characteristics, i.e., path loss, Rayleigh fading and log-normal shadowing under the physical interference model are taken

into account while modeling the throughput. These considerations make our analysis more practical.

The analytical model developed for throughput computation under the proposed MAC protocol is validated via simulation. We develop a MATLAB based simulator to find out the simulation results. For finding out different insights of the proposed protocol, the performances of this protocol are compared with CSMA/CA MAC and Uni-MUMAC [38] protocols. The simulators for CSMA/CA MAC and Uni-MUMAC protocols are also developed in MATLAB to find out their throughput performances. Using the simulation and analytical results, we demonstrate that the proposed MAC protocol significantly improves the throughput performance compared to the traditional CSMA/CA MAC protocol in WLANs. We also observe that our proposed MAC protocol provides better throughput than the Uni-MUMAC protocol.

Throughput performance of the proposed MAC protocol is analyzed by varying medium access rate of the users, data transmission rate, variance in shadowing and the number of users. The uplink throughput decreases with increasing the medium access rate of the AP. The throughput of downlink transmissions shows opposite nature compared to the uplink throughput under this condition. However, we obtain the opposite results when the AP accesses the channel with a fixed rate and the medium access rate of the users is increased. The throughput gains for both uplink and downlink transmissions decrease with increasing of data transmission rate. Interestingly we find that the impact of shadowing is insignificant on both uplink and downlink throughputs. Furthermore, with increasing the number of users, the uplink throughput increases and the downlink throughput decreases.

Contents

Dedication **iv**

Acknowledgments **v**

Abstract **vi**

1 Introduction **1**

1.1 Wireless Local Area Networks 1

1.1.1 WLAN Types 1

1.1.1.1 Ad Hoc Mode 2

1.1.1.2 Infrastructure Mode 2

1.1.2 WLAN Architecture 3

1.1.3 Advantages and Disadvantages of WLAN 3

1.2 Medium Access Control in Local Area Network 4

1.2.1 CSMA and Its Types 5

1.2.2 Carrier sensing multiple access with collision avoidance (CS-MA/CA) 6

1.2.2.1 Basic CSMA/CA 6

1.2.2.2 RTS/CTS CSMA/CA 7

1.3 MIMO 7

1.3.1 SU-MIMO 8

1.3.2 MU-MIMO 8

1.4 MIMO Decoding and Pre-coding 9

1.4.1 Decoding Schemes for Simultaneous Reception 9

1.4.2 Pre-coding Schemes for Simultaneous Transmission 11

1.5 Channel State Information 12

1.6 Wireless Propagation 13

1.6.1 Path Loss 13

1.6.2 Fading 14

1.6.3 Shadowing 14

1.7 Interference Model 15

1.7.1 Protocol Interference Model 15

1.7.2 Physical Interference Model 16
1.8 Motivation 16
1.9 Contributions 18
1.10 Thesis Organization 19

2 Background and Related Work **20**
2.1 MU-MIMO MAC Protocols 20
2.1.1 Uplink Protocols 20
2.1.2 Downlink Protocols 21
2.1.3 Integrated Uplink and Downlink Protocols 21
2.2 Throughput Modeling in WLANs 22
2.3 MU-MIMO Decoding and Pre-coding Model 23
2.3.1 ZF Decoding Scheme 23
2.3.2 ZF Pre-coding Scheme 25
2.3.3 Interference Model for MIMO Decoding/Pre-coding 25
2.4 Summary 26

3 Proposed MAC Protocol **27**
3.1 Overview of the Proposed MAC Protocol 27
3.2 Frame Structure 28
3.2.1 *PHY* Frame Structure 28
3.2.2 *MAC* Frame Structure 29
3.3 Medium Access Strategy 30
3.3.1 Uplink Transmission Process 31
3.3.2 Downlink Transmission Process 31
3.3.3 Illustration of the Protocol 32
3.3.3.1 Successful Uplink Transmissions 32
3.3.3.2 Successful Downlink Transmissions 34
3.3.3.3 Collision between the AP and Users 34
3.4 Advantages and Disadvantages of the Proposed Protocol 35
3.5 Summary 35

4 System Model and Throughput Modeling **36**
4.1 Description of System Model 36
4.1.1 Network Configuration 36
4.1.2 Wireless Propagation Model 37
4.2 Interference Model 38
4.2.1 Transmission of RTS Packet by the Users 38
4.2.2 Transmission of D-RTS Packet by the AP 38

4.2.3 Transmission of RC, U-CTS, DATA and U-ACK Packets by the AP . . . 39
4.2.4 Transmission of CTS, DATA and ACK Packets by the Users . 39
4.3 Model of the WLAN System using Discrete Time Markov Chain . . 39
4.4 Analysis of the Markov Chain . . . 44
4.4.1 Markov Chain Analysis for Uplink Transmission . . . 44
4.4.2 Markov Chain Analysis for Downlink Transmission . . . 47
4.4.3 Throughput Model . . . 48
4.5 Computation of K_N . . . 50
4.6 Summary . . . 51

5 Verification of Developed Analytical Model **54**
5.1 Model Verification . . . 54
5.1.1 Network Setup and Assumptions . . . 54
5.1.2 Simulator Set up . . . 55
5.1.3 Determination of Total Throughput . . . 56
5.1.4 Validation of Model . . . 57
5.1.5 Effect of Transmission Probability . . . 57
5.2 Summary . . . 59

6 Performance Analysis of Proposed MAC Protocol **61**
6.1 Description of the Baseline MAC and Uni-MUMAC Protocol . . . 61
6.1.1 Baseline MAC Protocol . . . 61
6.1.2 Uni-MUMAC Protocol . . . 62
6.2 Advantages of the Proposed Protocol . . . 62
6.2.1 Effect of Access probability . . . 65
6.2.2 Effect of Shadowing . . . 66
6.2.3 Effect of Transmission Rate . . . 68
6.2.4 Effect of Number of Users . . . 68
6.3 Summary . . . 69

7 Conclusion and Future Work **71**
7.1 Conclusion . . . 71
7.2 Future Work . . . 72

Bibiliography **74**

Appendix A Computation of $\psi(S_0)$ **79**

Appendix B Computation of P_1^{cp}, P_2^{cp}, P_1^s, P_2^s and P_3^s **82**

List of Tables

4.1 Transition probability p_{s_1,s_2} from a state s_1 to a state s_2 for uplink . . 42
4.2 Transition probability p_{s_1,s_2} from a state s_1 to a state s_2 for downlink 43

5.1 Values of β for different R 55
5.2 Simulation parameters 56

List of Figures

1.1 A typical WLAN in Ad hoc mode. 2
1.2 A typical WLAN in Infrastructure mode. 2
1.3 Basic CSMA/CA protocol [9]. 6
1.4 CSMA/CA protocol with RTS/CTS packet exchange [10]. 7
1.5 A SU-MIMO scheme. 8
1.6 A MU-MIMO scheme. 9
1.7 Uplink multi-user transmissions. 10
1.8 Downlink multi-user receptions. 11
1.9 Implicit CSI feedback procedures [15]. 12
1.10 Explicit CSI feedback procedures [15]. 13
1.11 Effect of path loss [17]. 14
1.12 Example of fading effect [18]. 14
1.13 Illustration of shadowing effect [19]. 15
1.14 Limitation of conventional CSMA/CA in uplink. 17
1.15 Collision created by the AP and users. 18

3.1 PHY frame format of IEEE 802.11ac [38]. 28
3.2 Frame structure of standard RTS packet [38]. 30
3.3 Frame structure of standard CTS packet [38]. 30
3.4 Illustration of proposed MAC protocol for $M = 3$. 33
3.5 Illustration of collision of the AP and users' RTS packet transmission. 34

4.1 The considered WLAN scenario consists of an AP with M antennas and single-antenna users. 37
4.2 Illustration of the Markov chain model for uplink MAC protocol for $M = 3$. 52
4.3 Illustration of the Markov chain model for downlink MAC protocol for $M = 3$. 53

5.1 (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 6.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$. 57

5.2 (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 9.4dB$ and $\sigma = 0dB$ for $M = 4$ and $M = 8$. 58
5.3 (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$. 58
5.4 (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 9.4dB$ and $\sigma = 10dB$ for $M = 4$ and $M = 8$. 59
5.5 (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 12.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$. 59

6.1 (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocols with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$, when $p_a = Np$. 64
6.2 (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocols with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 8$, when $p_a = Np$. 64
6.3 Percentage gains comparison for (a) uplink and (b) downlink with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$, when $p_a = Np$. . . . 65
6.4 Percentage gains comparison for total throughput with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$, when $p_a = Np$. 65
6.5 Effect of access probability on (a) uplink and (b) downlink throughput under the proposed protocol for $\beta = 9.4dB$ and $\sigma = 6.4dB$ when $M = 4$. 66
6.6 (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocol for $\beta = 9.4dB$ and $\sigma = 6.4dB$ when $M = 4$ and $p_a = 0.2$. 67
6.7 (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocols with $\beta = 9.4dB$ and varying σ for $M = 4$, when $p_a = Np$. 67
6.8 Percentage gains comparison for (a) uplink and (b) downlink with $\sigma = 6dB$ and varying β for $M = 4$, when $p_a = Np$. 68
6.9 (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocols with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$, when $p = 0.01$ and $p_a = 0.2$. 69

Abbreviations

WLAN	Wireless Local Area Network
PHY	Physical Layer
MAC	Medium Access Control
BSA	Basic Service Area
BSI	Basic Service Set
AP	Access Point
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
DCF	Distributed Coordination Function
PCF	Point Coordination Function
CSMA/CA	Carrier Sensing Multiple Access with Collision Avoidance
DIFS	DCF Interframe space
SIFS	Short Interframe space
ACK	Acknowledgment
RTS	Request to Send
CTS	Clear to Send
MIMO	Multiple-Input Multiple-Output
SU-MIMO	Single User MIMO
MU-MIMO	Multi-User MIMO
MUD	Multi-user Detection
ZF	Zero Forcing
MMSE	Minimum Mean Square Error
SIC	Successive Interference Cancellation
ML	Maximum Likelihood
SD	Sphere Decoding
MUIC	Multi-user Interference Cancellation
BD	Block diagonalization
DPC	Dirty Paper Coding
CSI	Channel State Information
SNR	Signal-to-Noise Ratio

SINR	Signal to Interference plus Noise Ratio
MPR	Multi-Packets Reception
A-MPDU	Aggregated- MAC Protocol Data unit
VHT	Very High Throughput
VHT-SIG-A	VHT Signal Field-A
PLCP	Physical Layer Convergence Protocol
PPDU	PLCP Protocol Data Unit
MPDU	MAC Protocol Data Unit
Group-ID	Group Identifier
L-STF	Legacy Short Training Field
L-LTF	Legacy Long Training Field
L-SIG	Legacy Signal
VHT-LTF	VHT Long Training Field
U-CTS	Uplink CTS
U-ACK	Uplink ACK
RC	Reception confirmation
D-RTS	Downlink RTS
PDF	Probability Density Function
DTMC	Discrete Time Markov Chain

List of Symbols

p	Transmission Probability of a User
p_a	Transmission Probability of AP
M	Number of Antennas in AP
N	Number of Users
P_{tr}	Transmit Power
P_r	Receive Power
N_o	Noise Power
η	Path Loss Exponent
r	Distance between Transmitter and Receiver
r_o	Far Field Cross-over Distance
σ	Shadowing Power
$\boldsymbol{H}$	Channel Matrix
β	SINR Threshold
R	Data Rate
$\mathcal{N}$	Set of Users
$\mathcal{P}'()$	Power Set
L_{RTS}	Transmission Time of a RTS Packet including one SIFS Time in Mini-slots
L_{D-RTS}	Transmission Time of a D-RTS Packet including one SIFS Time in Mini-slots
L_{CTS}	Transmission Time of a CTS Packet including one SIFS Time in Mini-slots
L_{RC}	Transmission Time of a RC Packet including one SIFS Time in Mini-slots
L_{DT}	Transmission Time of U-CTS, DATA and U-ACK Packets including three SIFS Time in Mini-slots
$L_{DT'}$	Transmission Time of DATA and U-ACK Packets including two SIFS Time in Mini-slots
$\psi()$	Stationary Probability of a State
S_0	Idle State for all Nodes
Ω	Total Throughput
P_m^c	Successful RTS Transmission Probability for a User of Set m
ρ_{up}	Efficiency of a successful Data Packet Transmission in Uplink
ρ_{dn}	Efficiency of a successful Data Packet Transmission in Downlink

Chapter 1

Introduction

1.1 Wireless Local Area Networks

Wireless local area networks (WLANs) are the most popular, simple and cheap way to connect laptops, tablet PCs, smart phones, digital cameras, TVs and set-top boxes etc. to the Internet. Wireless communications provide users and organizations many benefits like increased portability and flexibility. This versatility along with the cheap hardware and the use of license-free radio spectrum has led to an ever increasing demand for bandwidth in wireless networks. For instance, WLANs allow users to move their devices from place to place within an area without the need for wires and without losing network connectivity. This results in an increasing number of government agencies, businesses, and home users using, or anticipating the use of wireless technologies in their environments. Industry and academia have managed to satisfy this demand and tremendously increased the speed of WLANs over the last 20 years. IEEE 802.11 provides the physical layer (PHY) and medium access control (MAC) specifications for the widespread and popular WLANs which facilitates high-speed Internet access to the users. The major portion (approximately 48%) of overall Internet traffic is supported by current IEEE 802.11 WLANs [1]. From the first release of the IEEE 802.11 standard in 1997 to the IEEE 802.11ay [2] standard (an improvement on 802.11ad [3]), which is expected to release in 2017, the transmission speed is almost increased more than ten thousand times. This means that on average the maximum transmission rate of the IEEE 802.11 standard has nearly doubled two times in every five years. For more than two decades, WLAN is one of the most popular forms of communication in our day to day life.

1.1.1 WLAN Types

WLANs can be roughly divided into two types [4] according to its operation modes: ad hoc mode and infrastructure mode. They are described below.

1.1.1.1 Ad Hoc Mode

WLANs in ad hoc mode consist of peer-to-peer direct connections between clients with no intermediate hardware components involved which is shown in Fig. 1.1. Ad hoc local networks can be useful to make temporary connections in some situations, but they don't scale to support more than a few devices and also can pose security risks.

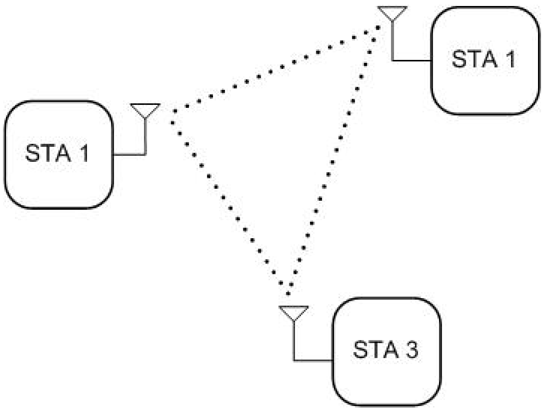


Figure 1.1: A typical WLAN in Ad hoc mode.

1.1.1.2 Infrastructure Mode

Fig. 1.2 shows an infrastructure-based WLAN. This type of WLAN allows users to move in a building while they are connected to the network. In an infrastructure network, a cell is also known as a basic service area (BSA). It contains a number of wireless stations. The size of a BSA depends on the power of the transmitter and receiver units, it also depends on the environment. A number of BSAs are connected to each other and to a distribution system by Access Points (APs). A group of stations belonging to an AP is called a basic service set (BSS). In this thesis, infrastructure mode WLANs are considered.

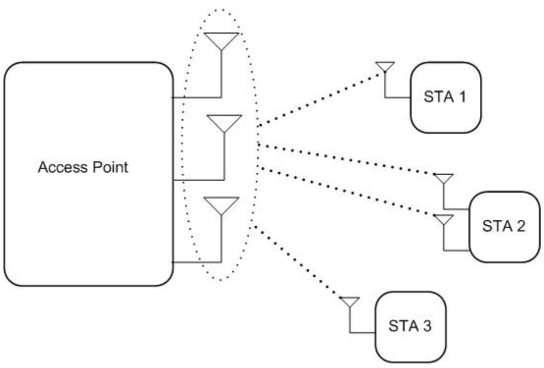


Figure 1.2: A typical WLAN in Infrastructure mode.

1.1.2 WLAN Architecture

WLAN architecture is composed of different components which help in establishing the local area network between different operating systems and among them, the two most important components are described below [5].

- **Access Points**: A special type of routing device that is used to transmit the data between wired and wireless networking device is called as AP. It is connected to the Internet with the help of wire or optical fiber. It only transmits or transfers the data between WLAN clients and Internet by using infrastructure mode of the network. One AP can only support small numbers of clients and works more efficiently. It is operated in a radius around 200 meters.

- **Clients**: Any kind of communicating device such as personal computer, notebook or mobile phone which is interlinked with a WLAN is referred as a client of the WLAN.

1.1.3 Advantages and Disadvantages of WLAN

The advantages [6] of WLANs are stated below:

(i) Easier to provide connectivity in areas that are difficult to lay cable.

(ii) Easier to add or move workstations.

(iii) Installation is quick and easy and can eliminate the need to pull the cable through walls or ceilings.

(iv) Access to the network can be accomplished from anywhere within the range of the access point.

(v) Portable or semi-permanent buildings can be connected using WLAN.

(vi) While the initial investment required for WLAN hardware similar to the cost of wired LAN hardware, in long run installation costs can be significantly lower.

(vii) When the facility is located on more than one site (like the two sides of the road), directional antennas can be used to avoid digging trenches under roads to connect to the site.

(viii) Long-term cost benefits can be found in the dynamic environment that requires the frequency of motion and change.

The disadvantages [6] of WLANs are as follows:

(i) When the number of stations that use the same network increases, the data transfer to the each station will be decreased very rapidly.

(ii) When standards change, it may be necessary to replace the wireless card and/or access point.

(iii) Security is more difficult to guarantee.

(iv) The device of a user operates within a limited distance from the access point.

(v) Electrical interference which probably causes degradation in throughput.

(vi) A LAN cable is most likely required to provide a backbone to WLAN. So WLAN should be a supplement to the LAN cable and it is not a complete solution.

(vii) The initial cost for a WLAN is more expensive than that of a wired LAN.

1.2 Medium Access Control in Local Area Network

Medium access control (MAC) [4] protocols for wireless network can be broadly classified into two types, conflict free and contention based protocols. Conflict free protocols establish transmission schedules statically or dynamically. It can be categorized into three types based on access mechanism, namely frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA). Schedule based protocols are also regarded as conflict free protocols. These protocols are mainly used in cellular and satellite networks. The node management in these protocols are centralized and protocols manifest very good throughput performance in the heavy loaded network. However, cost involvement in management is huge.

On the other hand, contention based MAC protocols, mainly used in WLAN, have distributed node management system. These protocols exhibit higher collision in data packet transmission and provide poor performance in heavy traffic. It can mainly be divided into two popular types, ALOHA and Carrier-sense multiple access (CSMA). ALOHA, which was initially conceived by Norman Abramson and his colleagues at University of Hawaii in 1970 [7], is a simple random access mechanism which allows its users to transmit their data regardless of the condition of other users. If data transmission is successful, the base station sends an acknowledgment over a feedback channel. If the user does not receive an acknowledgment, the user retransmits the message after waiting for a random time. There are two types of ALOHA namely pure and slotted ALOHA. In pure ALOHA, the users transmit asynchronously and the efficiency of the protocol is only 18.40%. In slotted ALOHA, users are allowed to transmit only at starting of a slot and hence, the efficiency of the protocol is increased to 36.78%. Unlike ALOHA where users just talk whenever they need to, in carrier sensing protocols the users listen before talk (or transmit). The performance of CSMA MAC protocols is superior than the ALOHA MAC protocols. In this thesis, we consider CSMA type access mechanism.

1.2.1 CSMA and Its Types

When using CSMA, a user/ a station has to wait for sending a packet until the channel is free. Otherwise, the station needs to wait for some time and tries again for transmission. When the channel is sensed as idle, the station can take one of three different approaches [4] (depending on the network design) to send a packet. They are stated below.

(i) **1-persistent CSMA**: If the medium is idle, a station transmits if it has a data packet to send. If the medium is found busy, the station continues the sensing process until the channel becomes free and it transmits as soon as the channel is free. However, when a transmission of a node is unsuccessful then the packet is sent again according to a randomly distributed retransmission delay.

(ii) **Non-persistent CSMA**: When a station has a packet, can transmit if the medium is free, otherwise it has to wait for a random period of time. The station repeats the process until the medium is free at the accessing time. Non-persistent CSMA is less greedy than 1-persistent CSMA because a node in this protocol does not continually sense the medium for the purpose of seizing the channel immediately upon detecting the end of the previous transmission. Consequently, this protocol leads to better channel utilization but has longer delays than 1-persistent CSMA.

(iii) **p-persistent CSMA**: p-persistent CSMA applies to slotted channels and works as follows. Upon sensing an idle channel, each station transmits with a probability p and waits with a probability $1-p$ until the next slot. The process is repeated until either the data packet has been transmitted or another user has begun transmitting. The other stations act as if there had been a collision (i.e., it waits for a random time and tries again). If the station initially senses the channel busy, it waits until the next slot and applies the above algorithm. It has better throughput than the other schemes with a higher delay.

1.2.2 Carrier sensing multiple access with collision avoidance (CSMA/CA)

The IEEE 802.11 standard defines two channel accessing methods which are the basic distributed coordination function (DCF) and the optional point coordination function (PCF). The DCF is contention based and PCF is contention free. DCF is the fundamental medium access scheme of IEEE 802.11 based WLANs. It relies on carrier sensing multiple access with collision avoidance (CSMA/CA) [8] to detect and share the wireless channel among stations. DCF is classified into two categories: basic CSMA/CA and RTS/CTS CSMA/CA.

1.2.2.1 Basic CSMA/CA

Basic CSMA/CA MAC protocol uses a physical carrier sensing mechanism. CSMA/CA is essentially p-persistence, with the twist that when the medium becomes idle, a station must wait for a time period DCF (or distributed) interframe space (DIFS) to learn about the fate of the previous transmission before contending for the medium which is shown in Fig. 1.3. If any station senses the medium free for more than DIFS time then it sends its data packet immediately. If the medium is busy then the station sets a value of contention window (CW) which randomly choosing from (0, $CW_{min} - 1$), where CW_{min} is the minimum CW of the stations. Then the station senses the medium in each mini-slot. If the medium is free in a mini-slot, it reduces its CW value by one and remains unchanged otherwise. The station transmits its data packet when its CW becomes zero. This is called back-off process. After transmitting a packet, the station waits for the receiver to send an acknowledgment (ACK) packet. If no ACK is received, the packet is assumed to be lost and the station sets its CW value randomly choose from (0, $2^m CW_{min} - 1$) and retransmits the data packet by using this process, where m is the number of retransmission of the packet.

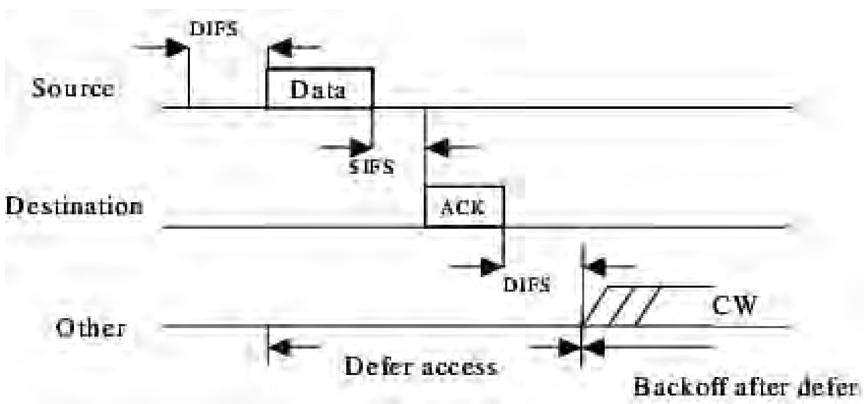


Figure 1.3: Basic CSMA/CA protocol [9].

1.2.2.2 RTS/CTS CSMA/CA

RTS/CTS CSMA/CA MAC protocol uses a physical as well as virtual carrier sensing mechanism. In RTS/CTS CSMA/CA, a station willing to transmit a packet will first send a short control packet called request to send (RTS), which will include the source, destination and the duration of the data and respective ACK packet. The destination station will give feedback if the medium is free with a response control packet called clear to send (CTS), which will also include the same duration information. Two stations exchanging RTS/CTS packet set their network allocation vector (NAV) [8] and this information will be used by other stations while sensing the medium. Fig. 1.4 depicts the virtual carrier sensing process for CSMA/CA. The RTS/CTS CSMA/CA performs better in WLANs. In our thesis work, we consider the RTS/CTS CSMA protocol as the traditional MAC protocol for multi-user multiple input multiple output (MU-MIMO) WLANs.

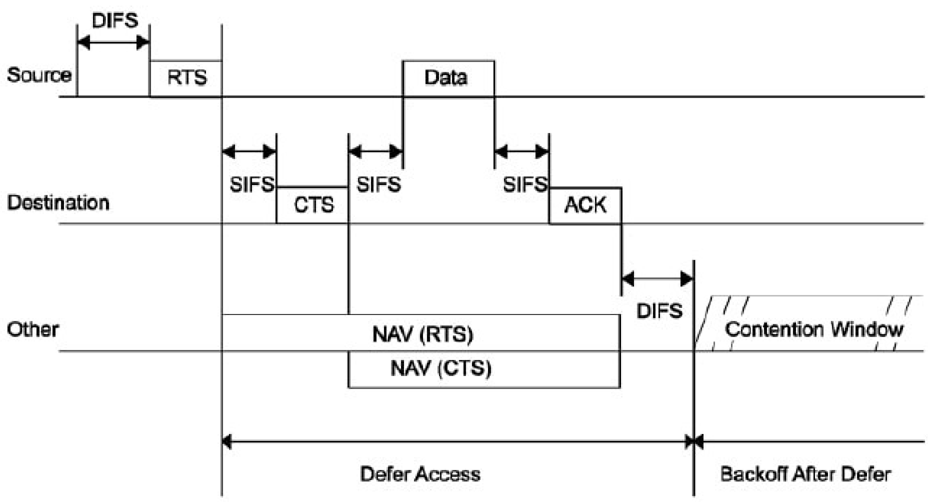


Figure 1.4: CSMA/CA protocol with RTS/CTS packet exchange [10].

1.3 MIMO

In the last two decades, multiple-input multiple-output (MIMO) techniques have become popular among the researchers in the domain of wireless communication with great interests. MIMO has been adopted as a key technology in various new generation wireless communication standards, such as long-term evolution (LTE), WLAN, worldwide interoperability for microwave access (WIMAX) etc. MIMO is an effective antenna technology for wireless communications which utilizes multiple antennas at both transmitter and receiver, not only to transfer multiple streams at the same time but also to enhance spectral efficiency [11]. MIMO technique can be categorized as single user MIMO (SU-MIMO) and multi-user MIMO (MU-MIMO) which are stated below.

1.3.1 SU-MIMO

SU-MIMO technology was first introduced with the 802.11n wireless standard in 2007 [12]. With SU-MIMO, multiple streams of data can be transferred simultaneously between one transmitter and one receiver (point-to-point) using multiple antennas which as a result helps to increase the data speed. The most obvious feature of SU-MIMO is that the multiple streams of data must be sent or received between just a pair of nodes at a time. However, SU-MIMO requires both the transmitting and receiving process to support the MIMO technology, along with having multiple antennas to facilitate more streams. The multiple antennas add cost, weight, and size to the transceivers and the processing of the MIMO signals requires more resources as well. SU-MIMO scheme is illustrated in Fig. 1.5.

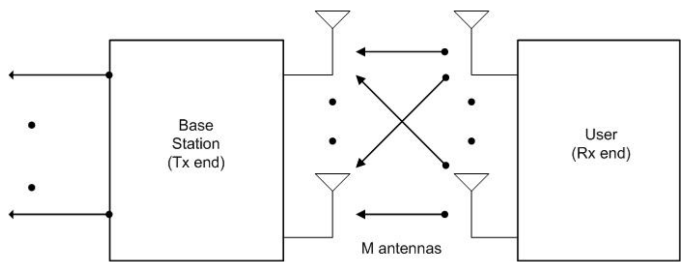
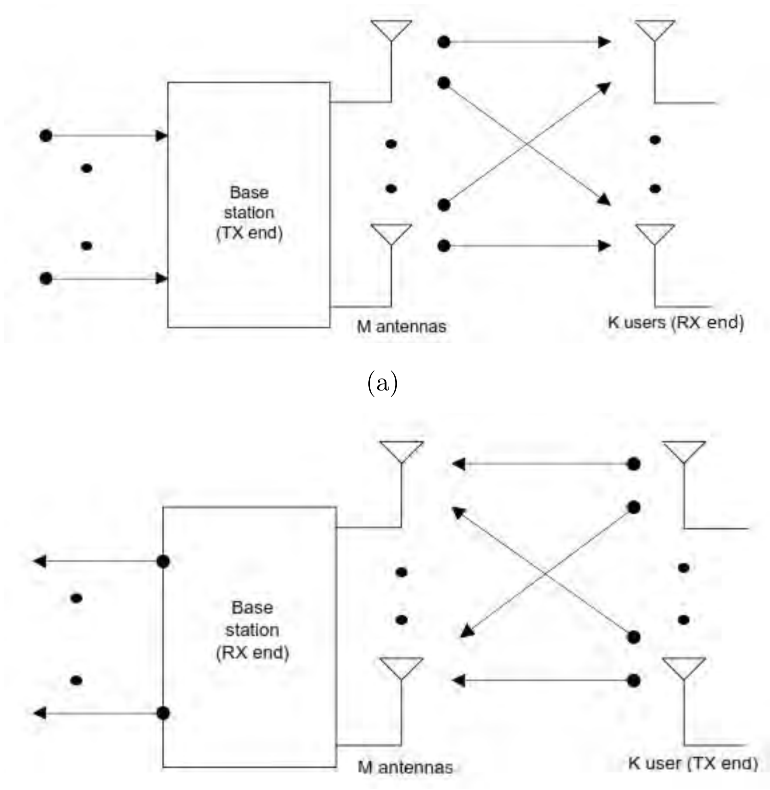


Figure 1.5: A SU-MIMO scheme.

1.3.2 MU-MIMO

MU-MIMO, utilized in IEEE 802.11ac standard [13] is an effective antenna technology for wireless communications. According to MU-MIMO technique, multiple antennas in the transmitter can send parallel data streams to multiple users at the same time which increases the system throughput significantly [14]. Moreover, it allows a receiver of multiple antennas to receive multiple data streams from multiple transmitters simultaneously. Compared to SU-MIMO, MU-MIMO technique can increase MIMO capacity and spectral efficiency. With the help of MU-MIMO scheme, the base station (BS) with M-antennas can transmit K data streams to the K users (or terminals). MU-MIMO scheme also allows K users to transmit K data streams to the BS. MU-MIMO scenarios are depicted in Fig. 1.6.



(b)

Figure 1.6: A MU-MIMO scheme.

1.4 MIMO Decoding and Pre-coding

MU-MIMO transmissions in WLANs have two communication paths, the uplink one where stations simultaneously transmit frames to the AP and the downlink one in which the AP sends data to a group of stations in parallel. For utilizing the benefits of MU-MIMO scheme, the stations are enabled with a MIMO decoding technique and the AP is enabled with a pre-coding technique. Different decoding and pre-coding techniques are mentioned below.

1.4.1 Decoding Schemes for Simultaneous Reception

In the uplink, the AP needs to separate the simultaneously transmitted signals from stations, which is regarded as the multi-user detection (MUD) problem. An illustration of MU-MIMO uplink transmissions is given in Fig. 1.7.

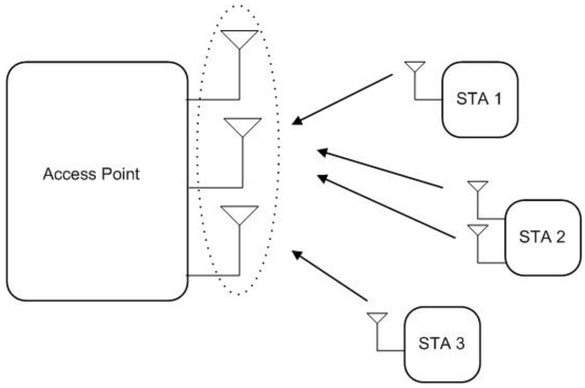


Figure 1.7: Uplink multi-user transmissions.

Here, we are going to provide a brief description of the most popular MUD schemes adopted in literature.

(i) *Zero Forcing (ZF):* In the ZF scheme, the received signal is multiplied by a pseudo-inverse of the channel matrix to completely null the multi-user interference. It assumes that the AP has the full Channel State Information (CSI) and the channel is invertible. By multiplying the pseudo-inverse weight, the ZF scheme also increases the error rate because the noise vector is also amplified. The amplified noise vector indicates that ZF can only perform well in the high signal-to-noise ratio (SNR) region. However, this scheme is very simple and easy to implement.

(ii) *Minimum Mean Square Error (MMSE):* In this scheme, the received signals at each antenna of the AP are multiplied by a complex weight and after that, they are summed up. The weight is adjustable through minimizing the difference between the summation of the output signal and a reference that is known by both the AP and stations. The performance of the MMSE MUD scheme improves as the number of AP's antennas increases and degrades as the network scales up.

(iii) *Successive Interference Cancellation (SIC):* The SIC MUD is regarded as an enhancement to MMSE. According to this scheme, a detection algorithm is utilized by estimating the received power at the AP. The signal with the highest power, which is the least interfered by others, is detected. This detected signal is then subtracted from mixed signals, and the next highest signal is singled out using the same process until the lowest station signal is determined.

(iv) *Maximum Likelihood (ML):* The ML MUD searches exhaustively for receiving the transmitted signals. It provides the best detection performance but comes with the highest complexity that increases exponentially with the number of stations. For that reason, this scheme is infeasible in practical systems.

(v) *Sphere Decoding (SD):* Some SD based MUD algorithms have been proposed to reduce the complexity of the pure ML MUD. The idea is to decrease the radius of the search scope by focusing on the vicinity of the ML solution.

1.4.2 Pre-coding Schemes for Simultaneous Transmission

In the downlink, the AP has to precode the outgoing data frames to avoid the interference among concurrent spatial streams, which is called the multi-user interference cancellation (MUIC) problem. An example of MU-MIMO downlink transmissions is provided in Fig. 1.8.

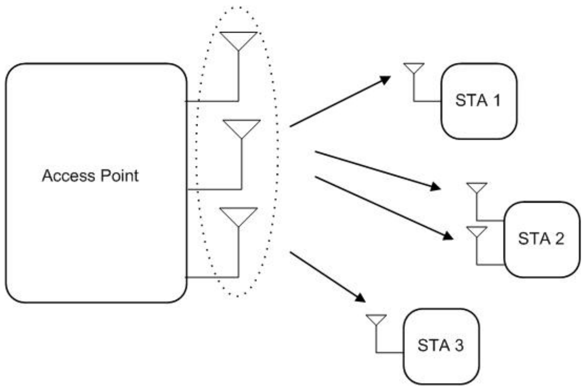


Figure 1.8: Downlink multi-user receptions.

Although simultaneous downlink transmissions from the AP to multiple stations can be seen as a combination of several single-user transmissions, stations' random and independent locations make it very challenging to jointly avoid the multi-user interference at the station side. For that reason, the outgoing signals are precoded at the AP before transmission to minimize interference among the simultaneous streams. The various pre-coding schemes used in the literature are described below:

(i) *Block diagonalization (BD):* BD is a generalized channel inversion technique, especially when receivers have multiple antennas. Singular value decomposition (SVD) is employed to remove unitary matrices, which makes the computational complexity of BD higher than MMSE.

(ii) *Dirty Paper Coding (DPC):* DPC is a non-linear pre-coding scheme, which can gain the optimum performance at the cost of significant computing complexity. The idea is to add an offset (the negative value of the interference that is known at the AP) to the transmitted signal, which hints that (1) the AP has to know the interference in advance, and (2) the AP always has available codewords, i.e., an infinite length of codewords, which make DPC not suitable for practical use.

(iii) *Zero Forcing (ZF):* ZF technique can also be used as a pre-coder. Here, the transmitted signal is multiplied with a pseudo-inverse of channel matrix to counter the multi-user interference.

The MMSE scheme is also used for pre-coding to nullify multi-user interference.

1.5 Channel State Information

It is necessary to have the CSI at the AP for performing decoding and pre-coding schemes properly. Most proposals in the literature integrate the CSI acquisition into MAC operations. There are generally two types of CSI: the statistical CSI and the instantaneous CSI. The former one is using statistical characteristics of the channel to decide the CSI and in the latter one, the CSI is estimated repeatedly on a short-term basis. Due to the time-varying nature of the wireless channel, the transmitter can adapt its outgoing signal using this CSI.

The acquisition of CSI is done by estimating a training sequence known by both transmitter and receiver. In the uplink, the AP can easily extract the uplink CSI from the PHY preambles of received frames. But, for downlink transmissions, the acquisition of the CSI is not that simple. Depending on who computes the CSI, there are two CSI feedback schemes: implicit and explicit feedback. The implicit feedback scheme is shown in Fig. 1.9, where the AP computes the CSI by estimating training sequences sent from stations and it assumes the reciprocity of up/down-link channels. aggregated- MAC protocol data unit (A-MPDU) is a part of physical layer (PHY) preamble (referred to Chapter 3 for more details).

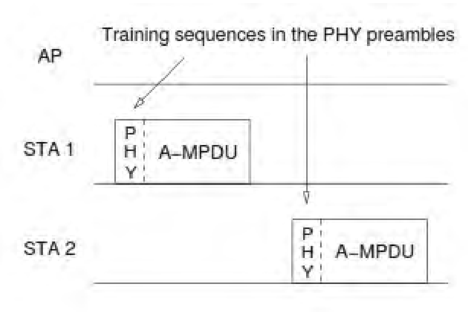


Figure 1.9: Implicit CSI feedback procedures [15].

In the explicit feedback, stations calculate the CSI by estimating the training sequence sent from the AP and then send it to the AP. The explicit feedback process is shown in 1.10. It provides higher resolution in CSI than the implicit scheme with higher overhead compared to implicit one.

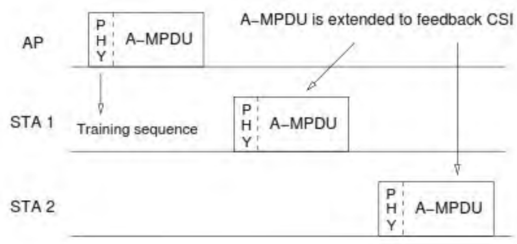


Figure 1.10: Explicit CSI feedback procedures [15].

1.6 Wireless Propagation

Wireless propagation is the fastest growing segment in the communication sector which has captured the attention of researchers. The wireless radio channel poses a severe challenge as a medium for reliable high-speed communication. It is not only susceptible to noise, interference and other channel impediments but these impediments change over time in unpredictable ways due to user movement [16]. An understanding of wireless propagation is necessary for coming up with appropriate design, deployment and management strategies for any wireless network. Accurate characterization of the radio channels through key parameters and the mathematical model is important for predicting signal coverage, achievable data rates, specific performance attributes and reception schemes, analysis of interference from different systems and other associated matters. Some of the important characteristics of wireless propagation are described below [16].

1.6.1 Path Loss

Path loss is caused by dissipation of the power radiated by the transmitter as well as effects of the propagation channel. It includes losses caused by natural expansion of the radio wave-front in free space, absorption (penetration) losses (when the radio passes through media not transparent to electromagnetic waves), diffraction/scattering losses etc. The path loss causes 'large-scale' effects which depend on radio frequency, the distance between transmitter and receiver, antenna characteristics (height, location, gains), nature of the terrain (urban/rural, vegetation/clear) and propagation medium (dry/moist air). The impact on signal strength due to path loss is shown in Fig. 1.11. It can be seen that received signal strength reduces exponentially with the increase of the distance between transmitter and receiver.

Figure 1.11: Effect of path loss [17].

1.6.2 Fading

Variation of signal due to multi-path propagation occurs on the order of the signal wavelength. These variations are sometimes referred to as small-scale propagation effects or multi-path fading. Fading is often modeled as a random process. Multi-path propagation may be caused by reflection, diffraction, and scattering. It is also called fast fading which occurs due to interference between multiple versions of the same transmitted signal arriving at the receiver at slightly different times [16]. Fading can be modeled with different types of distribution like Rayleigh, Rician, Nakagami, Weibull and so on. The effect of fading on received signal strength is shown in Fig. 1.12.

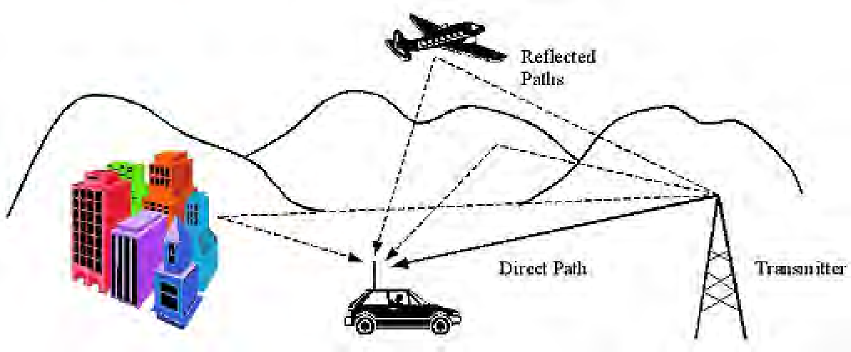


Figure 1.12: Example of fading effect [18].

1.6.3 Shadowing

Shadowing [16] is caused by obstacles between the transmitter and the receiver that absorb power, for example, transmitter outside a building, receiver inside a building, walls blocking transmission etc. Variation due to shadowing occurs over distances proportional to the length of the obstructing object (10-100 meters in outdoor environments and less in indoor environments). It is modeled with the log-normal distribution. The impact of shadowing on the received signal strength is shown in Fig. 1.13.

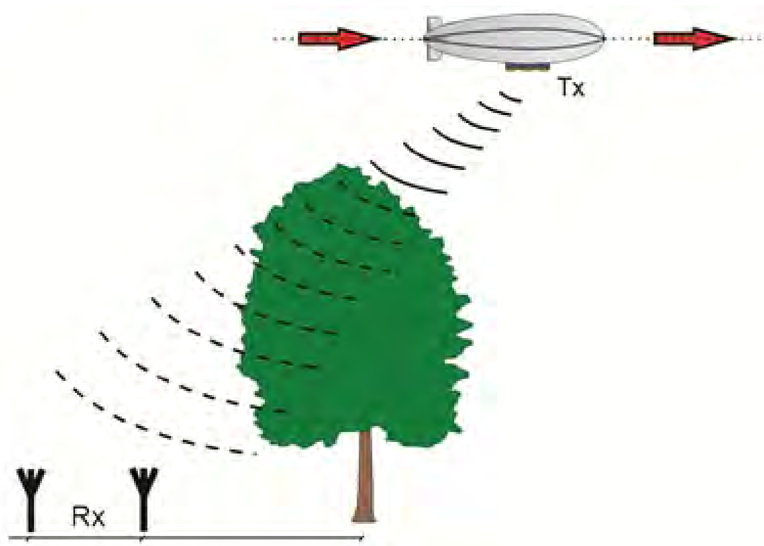


Figure 1.13: Illustration of shadowing effect [19].

1.7 Interference Model

When a set of transmitters transmit in a shared medium, then the desired signal from a particular transmitter to the receiver experiences the presence of signals from other transmitters which are treated as interference. So interference is a major concern in WLANs since a common wireless medium is shared by all users in a WLAN. An accurate model for interference is certainly important from the analytical standpoint to get the right insights in designing and optimizing wireless networks. There are two main types of interference models exist in the literature. They are as follows:

1.7.1 Protocol Interference Model

According to this model [20], a packet reception is successful if the distance between the interferer and receiver is greater than a fixed quantity, the *interference range*. In this model, the received signal strengths are assumed equal for all the received signals. Here, the interference power is not additive and *capture effect* is absent [21]. The network simulator *ns2* [22] software uses this model for inferring collision.

1.7.2 Physical Interference Model

According to the physical interference model [23], a wireless signal transmission is successful if the received signal to interference plus noise ratio (SINR) perceived by the receiver, exceeds an SINR-threshold for the entire duration of the signal transmission. So this model considers all the received power levels as interference except the desired signal's power. The SINR accounts for the cumulative interference power and is a more natural metric for deciding the packet decoding success. This model is regarded as more practical than the protocol interference model because of considering capture effect [21].

1.8 Motivation

Carrier sensing technique has been widely considered for designing MAC protocol because of its utilization advantage in random access based wireless networks. IEEE 802.11 based CSMA/CA is adapted in existing WLANs [12]. MU-MIMO, introduced by IEEE 802.11ac (only in downlink) [13], is one of the most vital techniques that directs WLANs towards the gigabit era. It builds on IEEE 802.11n [12] and facilitates more spatial streams and higher-order modulation than IEEE 802.11n specifications. Unfortunately, the traditional CSMA/CA MAC protocol has the capacity to process multiple streams (up to the number of the antennas in the AP) but it is unable to utilize its full potential due to the random nature of the users for accessing the medium. This leads to ineffective utilization of the resources [24] as illustrated in Fig. 1.14. Let, a MIMO enabled AP with four antennas situated at the center of a WLAN. The AP is surrounded with many distributed single antenna users in a random manner. According to CSMA/CA protocol, if CWs of two or more users become equal then they can get access to the channel at a time. Thus, most of the time less than four users may participate in contention for uplink transmission shown in Fig. 1.14. In that case, the AP will have the unused antenna(s) if the number of the contending stations are less than four, which leads to unutilized resources. However, random access based protocol is popular for designing MAC protocol due to its design flexibility, less complexity and relative ease of implementation. Hence, it becomes more important to design random access based MAC protocol for WLANs which can effectively utilize all the available resources at the same time.

Recently, designing MU-MIMO based MAC protocol has gained immense interest to the researchers of wireless LAN. There are some good works on proposing MAC protocol in recent years. The work in [29] demonstrates two contention round based uplink MAC protocol. The author in [26] shifts contention round from two to multiple for uplink transmission where multiple data packets are transmitted by the

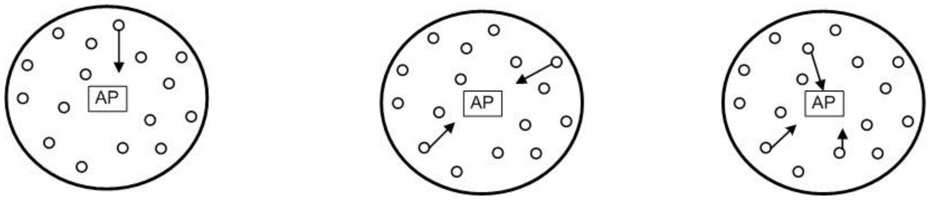


Figure 1.14: Limitation of conventional CSMA/CA in uplink.

users synchronously. Downlink throughput has been improved significantly through the utilization of extended RTS/CTS frames proposed in [30] and [32] where the AP can transmit multiple data packets concurrently. In [38], the authors propose a joint uplink-downlink MU-MIMO supported MAC protocol which is compatible with IEEE 802.11ac WLANs. The authors show that the performance of their proposed protocol is superior than the conventional one. However, the authors consider the protocol interference model in performance analysis. The performance of these protocols may degrade under the physical interference model.

To illustrate this, we consider a scenario shown in Fig. 1.15 where an AP of four antennas is situated at the center of a WLAN surrounded with randomly distributed single antenna users. Assume, after winning the contention, the AP sends a common RTS packet to users 1, 3, 5 and 6 and waits for a certain time which is 4 $\times$ (CTS packet time + one short interframe space (SIFS) time) in this case. If the users 2 and 4 get the access to the channel at the same time with the AP and send their RTS packets to the AP, their transmissions will not be successful due to the half duplex receiver. Hence, the AP will not receive any packet. The RTS packet sent by the AP to the users 1 and 3 will be unsuccessful because of high interference from the users 2 and 4 as they are close to the users 1 and 3. But the packet sent to the users 5 and 6 may be successful due to low interference created by the users 2 and 4 as they are close to the users 5 and 6. All transmissions from the AP are considered as a failure by MAC protocols proposed in [34],[38]. Additionally, most of the joint uplink-downlink proposals tackle this collision issue by spending the waiting time of the AP. It leads to increase of system overhead and wastage of transmitting power of the AP. Thus, a new MAC protocol needs to be designed to overcome the problem in joint uplink and downlink transmissions under physical interference model.

Throughput determination through analytical model is one of the effective ways for realizing, assessing and differentiating the performance and credibility of a MAC protocol in WLANs. Besides, it comes in handy to achieve different insights for different wireless and network parameters on throughput performance. Utilization of an appropriate interference model is very crucial during the development of an analytical model because the power of the received signal differs from one user to

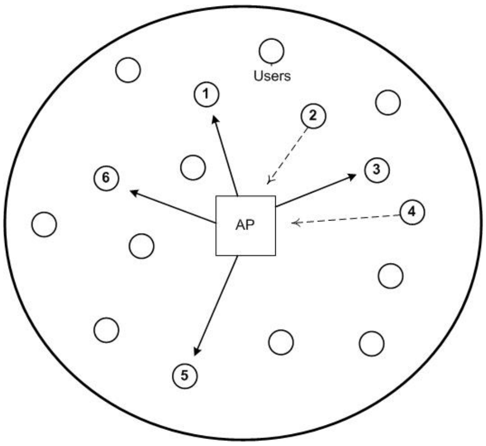


Figure 1.15: Collision created by the AP and users.

another user due to path loss, fading and shadowing in the most WLAN communication environments. So, the utilization of the physical interference model plays a vital role in developing a throughput model. For making the throughput model more realistic, one also needs to consider two essential features of the wireless medium, the fading and shadowing effect.

In light of above discussion, it is evident that we need to revisit the random access based joint uplink-downlink MAC protocol for WLANs which can employ all the available resources at the same time and can be efficiently adopted with MU-MIMO technique while considering practical interference model. Besides, designing analytical model while considering the path loss, fading and shadowing effect will make the model more realistic. Finally, the model having realistic wireless characteristics to determine the throughput of the WLAN system employing MAC protocol helps to realize different insights and importance of the protocol.

1.9 Contributions

In this thesis work, a single channel and single rate WLAN is considered. We employ the physical interference model with path loss, Rayleigh fading and log-normal shadowing of the wireless channel. Motivating from the work [24] where the throughput comparison between SU-MIMO and MU-MIMO technique for uplink is shown by varying transmission probability, we also investigate the performance of our proposed protocol with varying transmission probability. Our contributions in this paper are as follows.

- We propose a carrier sensing based uplink-downlink MAC protocol exploiting full benefits of MU-MIMO technique.

- We model a discrete time Markov chain of a WLAN under the proposed MAC protocol and develop an analytical model to compute the throughput of a MU-MIMO WLAN considering path loss, Rayleigh fading, and log-normal shadowing.
- The analytical model is verified via simulation.
- We compare the performance of the proposed MAC protocol compared with conventional MU-MIMO MAC and Uni-MUMAC protocol[38]. We demonstrate that our proposed protocol provides significant throughput improvement than the conventional MU-MIMO MAC protocol. Besides, the throughput gain under the proposed protocol has little improvement than Uni-MUMAC protocol.
- We also analyze the impact of the proposed MAC protocol with some of the wireless channel and network parameters and get some interesting insights which prove performance enhancement of our protocol than conventional MU-MIMO MAC and Uni-MUMAC protocol.

1.10 Thesis Organization

The rest of thesis paper is arranged as follows. Chapter 2 contains the review of related previous works on MU-MIMO based uplink, downlink, and integrated uplink-downlink MAC protocols. The review of related works on modeling of throughput under MAC protocols is also provided here. Furthermore, the ZF scheme used in this thesis for pre-coding and decoding process along with its use in interference model are described here. The proposed MAC protocol is described in details along with the description of the frames structure in Chapter 3. Different advantages and disadvantages of the proposed protocol are also included in this chapter. In Chapter 4, the system model and transmission policies of different packets are described. A discrete time Markov chain based model of a WLAN under the proposed MAC protocol along with the analytical model for throughput determination for MU-MIMO WLAN are also described here. In Chapter 5, we verify the analytical model via simulation. Performance comparisons between the proposed, CSMA MU-MIMO based MAC and Uni-MUMAC protocol, based on different network and wireless parameters are described in Chapter 6. Finally, Chapter 7 draws the conclusion of the work along with the possible future drive for research.

Chapter 2

Background and Related Work

In this chapter, we provide an overview of the MAC protocols designed for MU-MIMO WLANs. We also review the analytical developed for computing throughput in WLANs. The ZF scheme for MIMO decoding and pre-coding process along with the utilization of interference model on them are described in this chapter.

2.1 MU-MIMO MAC Protocols

MAC protocols for MU-MIMO WLANs can be categorized into three types: uplink, downlink, and integrated uplink-downlink protocols. In the following, we briefly describe the MAC protocols according to categories of MAC protocol.

2.1.1 Uplink Protocols

There are a good number of proposals of MAC protocol on multiple packets reception to exploit the benefits of MU-MIMO technique, where control frames are used to maintain coordination among stations in uplink. In [25], Barghi et al. describe a MAC protocol which supports Multi-Packet Reception (MPR) to receive two concurrent frames by using a waiting time window t_w at the AP. The authors in [26] propose a MAC protocol for WLANs by introducing Two-Round RTS Contention (TRRC) to facilitate MPR capability. In [27], the authors propose two contention rounds based MAC protocol with modified RTS frame. The novelty of this protocol lies in first contention round where the AP broadcasts MU-RTS frame (RTS frame with added antenna information) to all the stations after getting a RTS packet from any station to inform other stations about the remaining spatial streams, that can be processed by the AP. A MAC protocol is proposed in [28] which prolongs the contention rounds from two to multiple rounds utilizing a simple threshold based stopping algorithm. The algorithm makes a trade-off between channel utilization and contention overhead for choosing an optimal time to stop the contention process and start the transmissions. Zhou et al. in [29] present a multi-contention based MAC protocol which has two modes: *timeout* and *without timeout*. Data transmission phase is initiated as soon as the AP retrieves M_{random} (the maximum allowed number of stations that can transmit simultaneously) RTS packets successfully one after another in the case of *without timeout* mode. In the *timeout mode*, the AP dose not wait longer than $T_{timeout}$ time regardless of the number of successful RTS packets reception, then starts transmission process. The AP sends two types of modified CTS frames to the stations, (i) Pending CTS (PCTS) is used to notify RTS transmitting stations and (ii) Final CTS (FCTS) is used to inform the stations to start the data transmission process.

2.1.2 Downlink Protocols

In [30], the authors propose a distributed MU-MAC protocol with extended RTS/CTS frames where the AP transmits multiple data packets simultaneously. By exchanging RTS/CTS frames, the CSI is achieved. Kartsakli et al. in [31] present four scheduling schemes for concurrent transmissions where the users send CTS packets for scheduling. The first one is the MU-Basic scheme that is considered as a reference; the second one is the MU-Deterministic scheme which guarantees collision-free CTS transmissions; the third is the MU-Probabilistic scheme that splits the contention window into slots and nodes randomly select a slot for the CTS transmission, which may lead to collisions and the fourth scheme named the MU-Threshold Selective which is like the third one. The dissimilarity between the third and fourth scheme is due to a SINR threshold which permits the nodes having only good channel condition in the contention phase. A space division multiple access (SDMA) enhanced MAC protocol is proposed for downlink transmission in [32] which supports MU-MIMO technique with some minor changes in DCF. CSI is extracted from the training sequence included in CTS preamble. The authors in [33] investigate the performance of MU-MIMO based downlink with packet aggregation and the system throughput and packet delay are also explored with the help of the buffer size and the number of antennas at the AP.

2.1.3 Integrated Uplink and Downlink Protocols

Only a very few works were done on MAC protocols with both uplink and downlink access is considered. In [34], a MAC protocol is proposed with the facility of opportunistic medium access as well as multiuser MIMO techniques (MAC-OMA/MM) in Multi-channel Multi-radio WLANs. The stations are informed to begin transmissions using a Group CTS message after a RTS/CTS exchange in the uplink. In the downlink, a Group RTS is used to notify the selected stations and they respond one after another with CTS packets before the AP transmits to them simultaneously. Most interesting part is the use of different channels for uplink and downlink so that they can transmit concurrently and a common channel is used for exchanging information about the packet status and the set of available channels for next transmissions. The authors in [35] propose a Multi-user based MAC protocol, which supports both Multi-Packet Transmission (MPT) and MPR in downlink and uplink, respectively which applies OFDM as the preamble for CSI acquisition. Kim et al. in [36] present a back-to-back MU-MIMO based joint transmission method where the AP transmits a special frame Ready to Receive (RTR) immediately after a successful downlink transmission to inform the wireless nodes about the starting of the uplink transmission. The limitation of the protocol is the starting of uplink activities are only allowed after the downlink one, which may be unacceptable in general cases. An experimental multi-point to multi-point MIMO system is proposed in [37] where both uplink and downlink are implemented in software-defined radio platforms. Considering leader concept for both uplink and downlink medium access, they propose synchronization mechanism for both uplink and downlink phase by adopting trigger frame broadcasting by the leader who first won the channel contention. Then, the co-senders send preambles orderly as stated in the trigger frame for the CSI estimation. The authors in [38] devise a joint MAC protocol called Uni-MUMAC which is suitable for IEEE 802.11ac WLANs. It is a combined work of their previous published work [27] and [32] where slight modification is brought in frame extension. They use a Group Identifier (Group-ID) field introduced in IEEE 802.11ac physical layer frame instead of receiver address field in case of CTS and ACK frame.

2.2 Throughput Modeling in WLANs

Researchers show a lot of interest on modeling throughput as it is one of the crucial parameters for performance measurement in WLANs. There are numerous studies which give analytical models of throughput for WLANs by modeling CSMA MAC protocols as Markov chains. The pioneer work of G. Bianchi in [20], gives an analytical model for throughput of IEEE 802.11 based WLANs under the protocol interference model based on DTMC. Like [20], throughput modeling in [38],[39],[49] consider the protocol interference model. There are very few works that consider the physical interference model for modeling the throughput in WLANs. The authors in [40] only consider Rayleigh fading under physical interference model. Path loss and Rayleigh fading are both considered in the analytical analysis under physical interference model in [41]. In [42]-[44], the authors use only path loss under the physical interference model to model the throughput while the studies in [45]-[47], consider fading and shadowing of the wireless channel in addition to path loss for CSMA based wireless networks.

There are a number of studies that propose not only MU-MIMO based MAC protocols but also provide the analytical model of throughputs. In [30],[38],[39], the authors extend the Markov chain model in [20] to model the throughput for their proposed MAC protocols. In [48], the authors develop an analytical model of throughput using Markov chain for asynchronous MPR. In [49], the authors develop an analytical model of throughput for asynchronous uplink transmissions based on the Bianchi Markov chain model [20].

2.3 MU-MIMO Decoding and Pre-coding Model

We consider that the AP consists of a receiver which employs the ZF decoding scheme [50] as described below to retrieve at most M data packets concurrently for facilitating MU-MIMO technique. The AP has a transmitter which has a pre-coder also utilizes the ZF scheme [51] for avoiding inter-user interference at the users for downlink data packet transmission.

2.3.1 ZF Decoding Scheme

Here, the ZF decoding scheme is described for determining SNR of receiving signal. The channel gain between transmitter antenna i to a receiver antenna j is denoted by h_{ij} and expressed as,

$$h_{ij} = \sqrt{g_{ij}} h'_{ij} \tag{2.1}$$

where g_{ij} is the path loss between the two antennas and h'_{ij} is an independent zero mean, complex Gaussian random variable with unit variance and with Rayleigh fading. g_{ij} can be expressed as

$$g_{ij} = \left(\frac{r_{ij}}{r_0} \right)^{-\eta} \tag{2.2}$$

where r_{ij} is the distance between transmitter and receiver antenna and r_0 is the far field crossover distance.

As stated earlier, N users are transmitting concurrently each through one antenna and AP has M antennas. The channel matrix can be expressed as $\boldsymbol{H} = [\boldsymbol{h}_1, \boldsymbol{h}_2, ..., \boldsymbol{h}_N]$ where $\boldsymbol{h}_i = (h_{1i}, h_{2i}, ..., h_{Mi})^T$ denotes the channel gain vector from the i-th transmitter antenna to the M antennas of AP. The received signal at the AP can be written as

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n} \tag{2.3}$$

where $\boldsymbol{s} = (s_1, s_2, ...s_M)^T$ and $\boldsymbol{y} = (y_1, y_2, ..., y_M)^T$ represent the transmitted and received signal vectors, respectively and $\boldsymbol{n}$ is a complex Gaussian vector with zero mean which represent the combination of interference and inherent other noises. A ZF receiver can extract data successfully if number of received data streams $M' \leq M$. A ZF receiver multiplies the receiver signal $\boldsymbol{y}$ by a pseudo-inverse matrix [52]. This pseudo-inverse matrix is denoted as $\boldsymbol{G}$ and can be expressed as

$$\boldsymbol{G} = \boldsymbol{H}^{\dagger} = (\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H})^{-1}\boldsymbol{H}^{\boldsymbol{H}} \tag{2.4}$$

where $\boldsymbol{H}^{\dagger}$ denotes the pseudo-inverse matrix of $\boldsymbol{H}$ and $\boldsymbol{H}^{\boldsymbol{H}}$ is a Hermitian matrix which is the conjugate transpose of matrix $\boldsymbol{H}$.

The output of the ZF receiver is given by

$$\hat{\boldsymbol{s}} = \boldsymbol{G}\boldsymbol{y} = \boldsymbol{H}^{\dagger}(\boldsymbol{H}\boldsymbol{s} + \boldsymbol{n}) = \boldsymbol{s} + \boldsymbol{z} \tag{2.5}$$

where $\boldsymbol{z} = \boldsymbol{H}^{\dagger}\boldsymbol{n}$ is considered as noise. According to [53], the covariance matrix of $\boldsymbol{z}$, $\boldsymbol{K_z}$ is obtained as

$$\boldsymbol{K_z} = \boldsymbol{E}[\boldsymbol{z}\boldsymbol{z}^*] = \boldsymbol{H}^{\dagger}(\boldsymbol{H}^{\dagger})^{\boldsymbol{H}}\boldsymbol{E}[\boldsymbol{n}\boldsymbol{n}^*] = (\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H})^{-1}N_0 \tag{2.6}$$

According to [52], from the definition of co-variance matrix $\boldsymbol{K_z}$, we can obtain

$$\boldsymbol{E}[\boldsymbol{z_i}\boldsymbol{z_i}^*] = \boldsymbol{E}[|\boldsymbol{z_i}|^2] = \boldsymbol{k_{ii}} = (\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H})^{-1}_{\boldsymbol{ii}}N_0 \tag{2.7}$$

$[A]_{ii}$ is the element in i-th row and i-th column. According to [50],[53], the post detection SNR for the i-th data symbol, γ_i can be expressed as,

$$\gamma_i = \frac{E[|s_i|^2]}{E[|z_i|^2]} = \frac{E[|s_i|^2]}{[(\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H})^{-1}]_{ii}N_0} = \frac{\gamma_0}{[(\boldsymbol{H}^{\boldsymbol{H}}\boldsymbol{H})^{-1}]_{ii}} \tag{2.8}$$

where, $\gamma_0 = \frac{E[|s_i|^2]}{N_0}$ is the SNR of the transmitted i-th stream. Now, equation 2.8 can be expressed as

$$\gamma_i = \gamma_0 x \tag{2.9}$$

where x is a Chi-square distributed random variable with D degree of freedom. The probability distribution function (PDF) of γ_i is given as

$$f_D(\gamma_i) = \frac{exp\left(-\frac{\gamma_i}{g_{ii}\gamma_0}\right)}{(M-N)!(g_{ii}\gamma_0)^{M-N+1}}\left(\frac{\gamma_i}{g_{ii}\gamma_0}\right)^{M-N} \tag{2.10}$$

2.3.2 ZF Pre-coding Scheme

In the ZF pre-coding scheme, the transmitted signal is multiplied with precoding matrix and utilize inverse of $\boldsymbol{H}$, $\boldsymbol{H}^{\dagger}$ to nullify the inter-user interference at the receiver/users [51].

2.3.3 Interference Model for MIMO Decoding/Pre-coding

The power of the received signal differs from one user to another due to path loss, fading and shadowing in most WLAN communication environments. For that reason, in physical interference model, the decoding of a desired signal is accomplished by considering rest of the ongoing signals as interference. Decoding success is probabilistic, and the success or failure of a signal transmission can be expressed in terms of a bit/packet error probability (BER) which depends on the SINR. For a certain acceptable BER, the SINR found from the MIMO decoder has to exceed an appropriate threshold. According to this model, a transmission is treated as successful if the received SINR is greater than a required threshold [21], [54].

For a given modulation and coding scheme, BER can be expressed as a function of $g_{ii}\gamma_0$ as described in the previous section. We assume that a certain BER is required to provide a certain quality of service and hence, for a data stream i, the value of $g_{ii}\gamma_0$ must be greater from a certain threshold. This threshold is denoted by β. So for successful reception of the i-th data stream at the receiver, the following relation is required

$$g_{ii}\gamma_0 \geq \beta \tag{2.11}$$

Using $\gamma_0 = \frac{E[|s_i|^2]}{N_0}$, we can rewrite the above equation as

$$\frac{g_{ii}E[|s_i|^2]}{N_0} \geq \beta \tag{2.12}$$

which indicates the condition for successful reception of the i-th data stream where $E[|s_i|^2] = P_{tr}$ for our system.

In this work, we consider path loss, Rayleigh fading and log-normal shadowing in physical interference model (described in Chapter 4) and all the users in the WLAN are assumed to use the same modulation and coding scheme for all types of packet transmission, hence data rate is denoted as R and the SINR required for successful decoding of a signal is β, that means SINR $> \beta$.

2.4 Summary

In this chapter, the literature related with the thesis work have been reviewed. There are many proposals of MU-MIMO based MAC proposals for both uplink and downlink. However, the proposals of joint uplink-downlink based MAC proposals are very limited. Most of the previous works on throughput modeling consider error free channel or only fading in their analytical model under the conventional CSMA/CA MAC protocol. To the best of our knowledge, the throughput modeling of a MU-MIMO aware integrated uplink and downlink MAC protocol with consideration of path loss, fading and shadowing along with physical interference model has not been done yet. In this thesis, a joint uplink and downlink MAC protocol is presented and also an analytical model is developed to investigate throughput performance of the MAC protocol. We consider path loss, fading and shadowing under physical interference model while developing the analytical model which is regarded as more practical than protocol interference model. Moreover, the ZF based MIMO decoding and pre-coding scheme are discussed here. The condition for successful packet transmission based on interference model is also provided in this chapter.

Chapter 3

Proposed MAC Protocol

In this chapter, we describe the proposed MU-MIMO MAC protocol along with the structure of the control frames. Different operations of the proposed MAC protocol with various transmission conditions are also presented. The advantages and disadvantages of the proposed MAC protocol are also provided in this chapter.

3.1 Overview of the Proposed MAC Protocol

We consider joint uplink and downlink transmission scheme where multiple round contentions in uplink are used. We develop the protocol by combining the uplink protocols in [26], [29] and downlink protocols in [30], [32] with necessary modifications such that the problem occurred due to capture effect during uplink and downlink accesses is solved.

There are several assumptions in our proposed protocol such as the time is divided into mini-slots and the data packet sizes of all the users and the AP are considered to be equal. The transmit power for all the nodes and the AP is considered to be very high compared to the carrier sensing threshold (CST). Perfect carrier sensing is also assumed such that if a node transmits, all the other nodes sense the channel as busy although fading and shadowing are present in the channel. In our protocol, the AP and all users access the medium with a certain probability when the channel is free. If the AP wins the channel then it completes the whole downlink process. Otherwise, if any user wins the channel then the uplink process is initiated and continued until finishing of the whole uplink process. We assume that the users and the AP use half-duplex antenna system, i.e. they cannot transmit and receive simultaneously.

3.2 Frame Structure

In this section, we describe the PHY and MAC layer frame structure used in the proposed protocol on the basis of IEEE 802.11ac [13] specification.

3.2.1 *PHY* Frame Structure

The frame structure for physical layer (PHY) of IEEE 802.11ac is illustrated in Fig. 3.1, where VHT PLCP, PPDU, and MPDU stand for Very High Throughput Physical Layer Convergence Protocol, PLCP Protocol Data Unit, and MAC Protocol Data Unit, respectively. It depicts from the frame structure that PPDU consists of the PHY preamble and MPDUs. IEEE 802.11ac states that transmission of all MPDUs must be in Aggregated-MPDU (A-MPDU) format, where aggregated MPDUs are divided with MPDU delimiters. After preamble field, a service field and a tail field are attached to the A-MPDU. The PHY preamble consists of 3 legacy fields for the backward compatibility (i.e., L-STF, L-LTF, and L-SIG) and some newly introduced VHT fields [13].

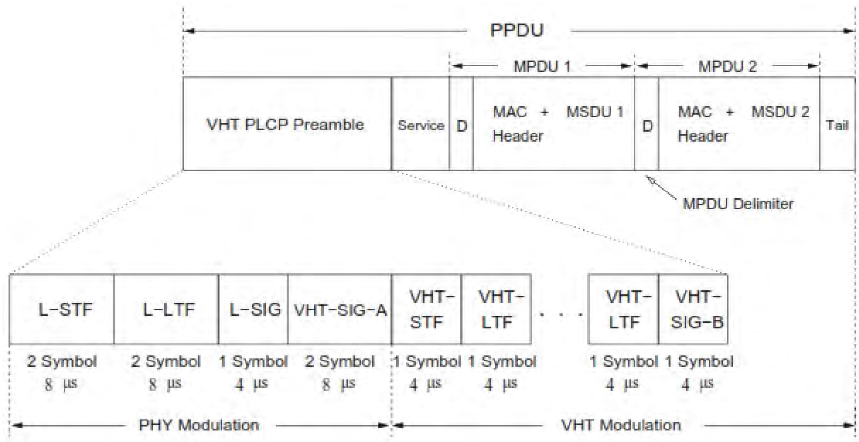


Figure 3.1: PHY frame format of IEEE 802.11ac [38].

Introducing these VHT fields by IEEE 802.11ac to help WLANs in achieving better performance. A Group Identifier (Group-ID) field is included in VHT Signal Field-A (VHT-SIG-A), which is used to inform the targeted stations about the followed MU-MIMO transmission, the order and the position of each stations' corresponding stream. A complete Group-ID table is created and circulated by the AP and will be recomputed as stations associate or de-associate to the AP. Since the number of stations' combinations can exceed the available number of Group-ID in a large basic service set, and the down/up-link channel may be different. Thus, we assume a single Group-ID like in [38], can refer to multiple transmission sets along with other PHY preamble features that could be used to resolve the intended stations which indicate that there will be always at least one proper Group-ID entry that can be mapped to the intended transmission set [55].

VHT Long Training Field (VHT-LTF) can accommodate an orthogonal training sequence that is familiar by both the transmitter and the receiver to estimate the MIMO channel. For estimating the channel precisely, the number of VHT-LTF fields should not be less than the number of transmitted spatial streams. The legacy and VHT-SIG-A fields adopt the low rate modulation scheme to make the preamble understandable to all stations, while the rest VHT fields and A-MPDU are transmitted using the VHT modulation scheme. In this thesis work, a single modulation is considered for all frames' transmissions to simplify the simulation.

3.2.2 *MAC* Frame Structure

The control frames of the proposed protocol follow standard structure of RTS and CTS frames with some modifications. The standard structure of RTS and CTS frame are shown in Fig. 3.2 and 3.3, respectively. All the frame modifications are confined to the AP side.

In uplink, the requests from the users are taken by using the conventional RTS frame. The modified control frames in the uplink process are U-CTS (Uplink CTS) and U-ACK (Uplink ACK) and they have the identical frame structure. Only the receiver address field is removed and replaced by the Group-ID field as used in the IEEE 802.11ac PHY frame. We use a new frame reception confirmation (RC) frame which is same as CTS frame. The U-CTS frame is utilized to notify stations the beginning of the data transmission and U-ACK is used to indicate the successful reception of data. The RC frame is used to notify a user about the successful reception of RTS frame by the AP among the contending stations.

In the downlink, the modified control frame is D-RTS (Downlink RTS) which has two parts: dummy and information. The size of the dummy part is exactly same as the RTS packet. The information part consists of the addresses, timing and header information, are also equal to the size of standard RTS frame. Like U-CTS and U-ACK, the AP can also utilize the Group-ID field in the D-RTS frame to notify the selected receiving users. So D-RTS frame has double size compared to the standard RTS frame. In downlink process, we use the conventional CTS and ACK frames to response the AP by the users.

2 bytes	2 bytes	6 bytes	6 bytes	4 bytes
Frame Control	Duration	Receiver Address	Transmitter Address	Frame Check Sequence

Figure 3.2: Frame structure of standard RTS packet [38].

2 bytes	2 bytes	6 bytes	4 bytes
Frame Control	Duration	Transmitter Address	Frame Check Sequence

Figure 3.3: Frame structure of standard CTS packet [38].

3.3 Medium Access Strategy

If a node is in the idle state (they do not transmit/receive/wait) and wants to send data packet(s), it needs to sense the medium in each mini-slot. A node does not try to transmit if the channel is found busy in a mini-slot. If the status of the channel is found to be free, the users try to send a RTS packet with a transmission probability p and the AP tries to send a modified RTS packet (D-RTS) including the Group-ID which indicates targeted M users with transmission probability p_a. It is possible for more than one user to launch transmission of their RTS packets to the AP because they try to send RTS packets with a transmission probability p. If a user sends a RTS packet, it waits for a RC packet. If a user receives a RC packet from the AP, it waits to receive a U-CTS packet for a certain period of time. If any user sends a RTS packet but dose not receive a RC packet after SIFS time, it will enter into idle mode and try to access the medium as before. So interference model described later predicts the success or failure of a RTS packet transmission because the AP cannot utilize MIMO technique to decode due to the absence of the CSIs of the users. If the AP receives a RTS packet, it performs the "Uplink Process" described in the next sub-section.

If the AP gets the access of the channel before any of the users, it randomly selects M users to which it wants to send data packets and then sends a D-RTS packet including the addresses and the CTS packet transmission times for each of the M users. Like uplink, the determination of the success or failure of D-RTS (sent by the AP) reception by the users solely depends on interference model described later. In this case, the users and the AP perform the "Downlink Process" described in the next sub-section.

However, if any user and the AP get the access of the medium at the same time, then the AP transmits D-RTS packet and hence, the AP is unable to receive any RTS packets transmitted by the users because the AP uses the half duplex system. Moreover, the D-RTS transmission will be always successful because collision will happen between RTS packets and the dummy part of D-RTS packet and hence the information part of the D-RTS packet is free from the collision.

3.3.1 Uplink Transmission Process

(U1) A user waits for a RC after sending RTS packet. The AP transmits a RC packet to the user after a SIFS time when it receives a RTS packet from the user. A user which received a RC packet waits for a certain period of time to receive a U-CTS packet.

(U2) The waiting time is taken remarkably large so that during this period the AP can retrieve M RTS packets. If the AP is unable to receive M RTS packets during the waiting time of the first RTS transmitting user, it will take attempt to transmit U-CTS packet to the users from which it gets RTS packets.

(U3) If any user has transmitted RTS packet but does not receive RC packet after SIFS time, it will enter into idle mode and try again to access the medium to send RTS packet.

(U4) We consider that after receiving M RTS packets from M users, the AP sends U-CTS packet to each M users including the addresses of all the M users. We also consider that the AP updates the CSIs of the M users by receiving M RTS packets from them.

(U5) A user will send a data packet if it receives a U-CTS packet. On the contrary, a user will not transmit any data packet if it does not get any U-CTS packet and try to access the medium again for sending RTS packet based on the method described previously.

(U6) The AP will decode the data packets using the ZF MIMO decoding with the CSIs of the users. The AP will transmit a common U-ACK packet to the users after a SIFS time after getting the data packets. If a user gets the U-ACK packet, it will try to send a RTS packet for next data packet according to the described method.

3.3.2 Downlink Transmission Process

(D1) The AP waits for CTS packets for a time equal to $M(L_{CTS} + SIFS)$ after sending a D-RTS packet, where L_{CTS} is the transmission time of a CTS packet.

The users included in the Group-ID transmit CTS packets individually and sequentially as the indicated order to the AP with adding a SIFS time. If any user does not send CTS packet that means it cannot able to extract the D-RTS packet. We consider that when AP receives a CTS packet from a user, it updates CSI of the user.

(D2) If the AP does not receive any CTS packet during the waiting time, it will enter into idle mode and again try to access the medium to transmit D-RTS packet.

(D3) The AP transmits data packets to the users simultaneously from which it receives CTS packets by using ZF pre-coding.

(D4) The users employ the ZF decoding to decode the data packets. If a user can decode the data packet, it transmits ACK packet after a SIFS time and then it tries to access the channel for uplink transmission.

(D5) The AP uses the ZF MIMO decoding to decode the ACK packets transmitted by the users and then tries to access the channel.

3.3.3 Illustration of the Protocol

Fig. 3.4 portrays the proposed MAC protocol with $M = 3$, where A, B, C and D are 4 users in a WLAN with one AP. A mini-slot without any shadow means that a node senses the medium as free in that mini-slot, but the users and the AP do not get access to send RTS and D-RTS packet, respectively in that mini-slot. A mini-slot with dark shadow indicates that in that mini-slot, the user senses the medium as busy. Cross-striped mini-slot of a user refers that the user has already received RC packet and it is waiting for U-CTS packet. The solid and dotted rectangles mean the transmission and reception of different types of packets. Different types of transmissions are described below for better understanding of our proposed protocol.

3.3.3.1 Successful Uplink Transmissions

It is illustrated in Fig. 3.4 that the users A, C, and D transmit their RTS packets, get RC packets and expect for U-CTS packet. The users A and D get U-CTS packet while the user B does not get any U-CTS packet. The users A and D transmit their DATA packets and get U-ACK packet from the AP. The users B and C try to transmit their RTS packets for the next data packet transmission after completing this chunk of packet transmissions. We consider that during a chunk of packet transmission, the channel state of a user is unchanged.

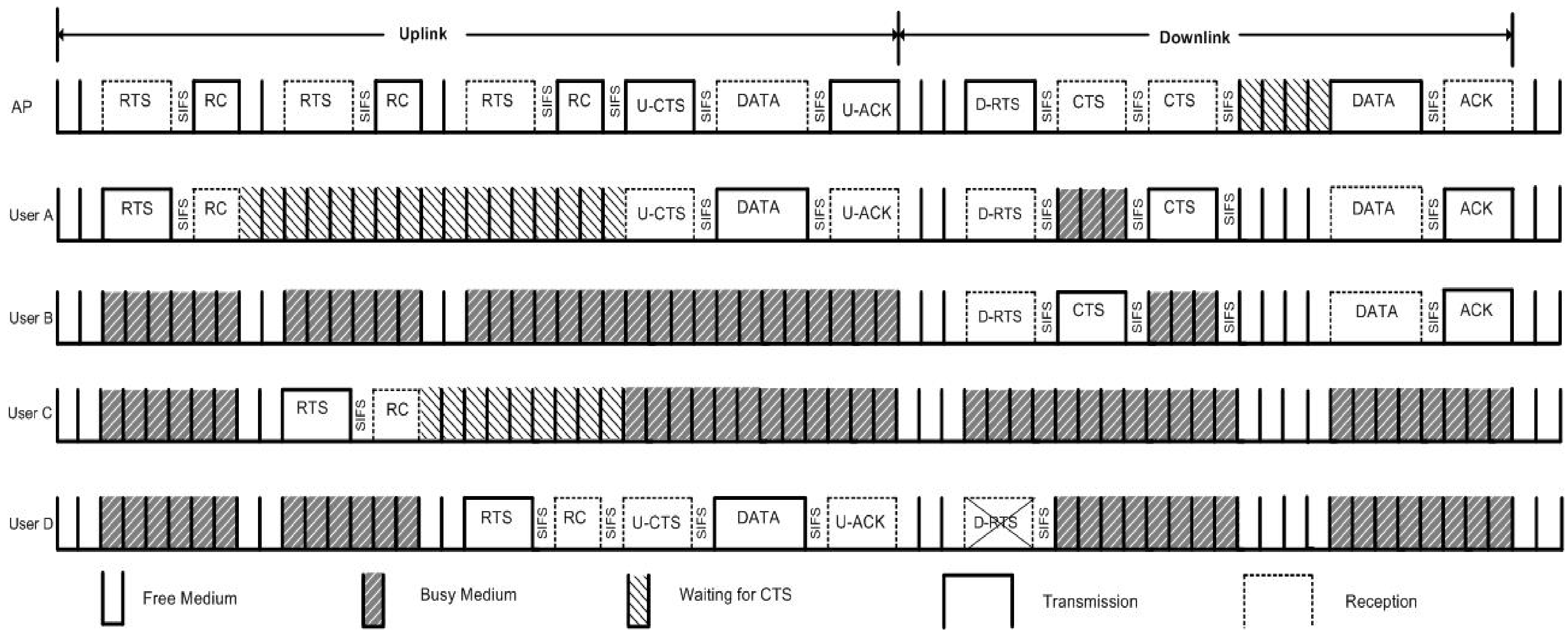


Figure 3.4: Illustration of proposed MAC protocol for $M = 3$.

3.3.3.2 Successful Downlink Transmissions

In downlink, we can see from Fig. 3.4 that the AP transmits D-RTS packet to users A, B and D and the AP is waiting for CTS packets. The users A and B send their CTS packets to the AP and the user D does not send CTS packet because of unsuccessful reception of D-RTS packet. The users A and B receive DATA packets and they send ACK packets to the AP to notify about the reception of the data packet.

3.3.3.3 Collision between the AP and Users

The collision of RTS frames will happen when both user and the AP get the access to the channel and try to send their respective RTS packet. Fig. 3.5 illustrates this situation where both user B and the AP transmit RTS and D-RTS packet, respectively. In this case, RTS packet transmission of the user B will be unsuccessful due to half-duplex nature of the receiver but D-RTS packet transmission will be successful. Because the dummy portion in the packet which will collide with the RTS packet sent from the user but the information part of a D-RTS packet is free from interference. Therefore, the AP initiates the downlink process. It signifies that if the AP gets the access to the channel, it completes the downlink process whether users access the channel or not, which will help to decrease the overhead and save the power of the AP (explained in Chapter 1).

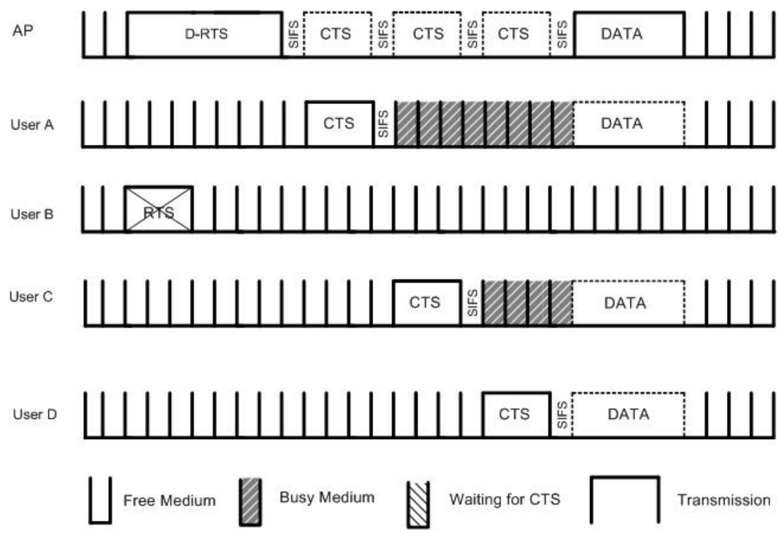


Figure 3.5: Illustration of collision of the AP and users' RTS packet transmission.

3.4 Advantages and Disadvantages of the Proposed Protocol

There are several advantages of our proposed protocol. They are as follows:

- Our proposed protocol facilitates MU-MIMO technique in both uplink and downlink transmissions.

- The frame size of the D-RTS which includes targeted users addresses is same as a standard RTS frame. Same goes for U-CTS and U-ACK packet. So total transmission time is decreased. As a result, overhead is decreased and throughput is improved.

- Our protocol extracts CSIs in each uplink and downlink phase before data reception or transmission, respectively, which will help to perform the de/precoding process efficiently.

- This protocol addresses the issue created by collision due to joint access by both the users and the AP to the channel at the same time, very efficiently by using D-RTS packet in downlink. Most of the joint uplink-downlink MAC proposals tackle it by spending the waiting time of the AP with no data transmission which will degrade the performance of the protocol.

There are also some disadvantages of our proposed protocol. They are as follows:

- Exhaustive search of users to select for data transmission in uplink may cause overhead.

- Utilization of RC packets to inform successful RTS transmitted users will increase the overhead.

3.5 Summary

The proposed integrated uplink and downlink protocol has been described in this chapter. Multiple contention based user selection is incorporated in uplink so users get more opportunity to participate in selection process for data transmission. Synchronization of stations for data transmission to the AP is ensured through control packet (U-CTS). The AP also transmits multiple packets simultaneously to the users in downlink. Despite having some disadvantages, our proposed protocol has interesting features. The frame size of modified RTS and CTS packet remains same compared to basic RTS and CTS frame. Our protocol introduces a crucial and effective way to counter the issue created for accessing the channel by both the AP and users at the same time which will help to enhance throughput.

Chapter 4

System Model and Throughput Modeling

In this chapter, we develop the analytical model of total throughput of a WLAN system under the proposed MAC protocol in presence of path loss, Rayleigh fading and log-normal shadowing. We consider that the sizes of all kinds of the CTS and ACK packets are the same and also same goes for all the RC and DATA packets. We assume that D-RTS packet is double in size than the RTS packet. The SIFS time is assumed to be equal to one mini-slot.

4.1 Description of System Model

4.1.1 Network Configuration

We consider a MU-MIMO WLAN with one AP and N users. The AP consists of M antennas and each user has a single antenna. The users are distributed randomly in a circle of unity radius surrounded to the AP located at the center as shown in Fig. 4.1. The position of a user is (r, θ). The probability density functions (PDFs) of r and θ are considered as

$$f_r(r) = 2r,\ 0 \leq r \leq 1 \tag{4.1}$$

and

$$f_\theta(\theta) = \frac{1}{2\pi},\ 0 \leq \theta \leq 2\pi \tag{4.2}$$

respectively. All the nodes are assumed to be half-duplex, i.e., a node cannot transmit and receive simultaneously. We assume that the transmit power of the each antenna of the AP is P_{tr}. The transmit power of the users is also assumed to be P_{tr}. Radiations from all the antennas are assumed to be omni-directional. We consider both uplink and downlink communication, i.e., the users send data packets to the AP and the AP sends data to the users. We assume that all the nodes in the WLAN are saturated, i.e., they always have data packets to send.

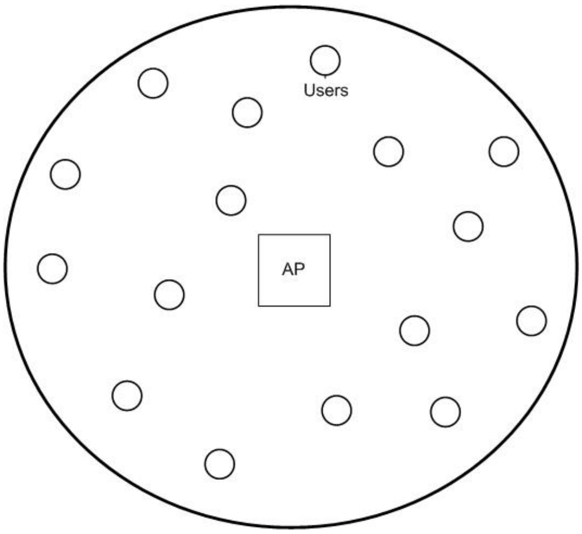


Figure 4.1: The considered WLAN scenario consists of an AP with M antennas and single-antenna users.

4.1.2 Wireless Propagation Model

The wireless propagation becomes more realistic by considering attenuation, fading and shadowing. In our system, attenuation, Rayleigh fading and log-normal distributed random variable for shadowing are taken into consideration. So, the received power of a receiver from a transmitter at distance r is given as

$$P_r = F^2 e^{\xi} \left(\frac{r}{r_0}\right)^{-\eta} P_{tr} \tag{4.3}$$

where, F is a Rayleigh distributed random variable with unit power, e^{ξ} is for shadowing with Gaussian distributed ξ with zero mean and variance σ^2 , η is the path loss exponent and r_o is the far field crossover distance. P_{tr} and η will be assumed constant for all users where ξ and F is considered to be independent from user to user as well as from one data packet transmission to another. The PDFs of ξ and F are given as

$$f_{\xi}(\xi) = (e^{\frac{-\xi^2}{2\sigma^2}})/\sqrt{2\pi}\sigma \tag{4.4}$$

and

$$f_F(x) = 2xe^{-x^2} \tag{4.5}$$

respectively.

4.2 Interference Model

The interference models for different packets for both uplink and downlink transmissions are stated below:

4.2.1 Transmission of RTS Packet by the Users

Let a set of users y are transmitting their RTS packets to the AP at a time. According to the MAC protocol, the transmissions of the RTS packets begin at the same time and end simultaneously. According to the physical interference model, the SINR at the AP for the RTS transmission of user $d \in y$ from the RTS transmitting user-set can be expressed as

$$SINR_d = \frac{P_r^d}{\sum_{i \in y \backslash d} P_r^i + N_o} \tag{4.6}$$

where, P_r^i is the received power by the AP from a user i and N_o is the background noise power. The RTS packet transmission of the user d is successful for the transmitting user-set y if

$$\frac{P_r^d}{\sum_{i \in y \backslash d} P_r^i + N_o} > \beta. \tag{4.7}$$

4.2.2 Transmission of D-RTS Packet by the AP

Let the AP is transmitting a D-RTS packet to M users at a time. The transmissions of the D-RTS packet begin at the same time and end simultaneously. When AP sends a D-RTS packet to a set of users then a user does not experience interference for transmission to the other users because of utilizing the ZF pre-coding at the AP. The SINR at a user $d' \in \mathcal{N}$ for a D-RTS transmission from the AP can be expressed as

$$SINR_{d'} = \frac{P_r^{d'}}{N_o} \tag{4.8}$$

where, $P_r^{d'}$ is the received power by the user d' from the AP and N_o is the background noise power. The D-RTS packet transmission to the user d' is successful if

$$\frac{P_r^{d'}}{N_o} > \beta. \tag{4.9}$$

4.2.3 Transmission of RC, U-CTS, DATA and U-ACK Packets by the AP

The AP transmits the data packets with ZF pre-coding and hence, there is no interference for the data packet transmissions. Further, there is no interference for the transmissions of RC, U-CTS and U-ACK packets by the AP. For simplicity of modeling, we assume that all the RC, DATA, U-CTS and U-ACK packet transmissions by the AP are successful.

4.2.4 Transmission of CTS, DATA and ACK Packets by the Users

The AP uses the ZF MIMO decoding for the DATA and ACK packets sent by the users and hence, there is no interference for the DATA and ACK packets. Since CTS packets are transmitted by the users in different times, their receptions are not hampered by interference. Thus, transmissions of CTS, DATA and ACK packets are assumed to always be successful.

4.3 Model of the WLAN System using Discrete Time Markov Chain

The proposed MAC protocol of the WLAN system can be modeled as a discrete time Markov chain where the duration of each state of the Markov chain is equal to a mini-slot. We assume that, the set of users are denoted by $\mathcal{N}$ and the users are arranged in ascending order according to arbitrary number e.g., $\mathcal{N} = \{1, 2, ..., N\}$. Let, the power set of user set $\mathcal{N}$ excluding the null set is $\mathcal{P}'(\mathcal{N})$. We consider that (i) the transmission time of a RTS packet including one SIFS time is L_{RTS} mini-slots and the set $\mathcal{L}_{RTS} = \{1, 2, ..., L_{RTS}\}$, (ii) the transmission time of a D-RTS packet including one SIFS time is L_{D-RTS} mini-slots and the set $\mathcal{L}_{D-RTS} = \{1, 2, ..., L_{D-RTS}\}$, (iii) the transmission time of M CTS packets including M SIFS times is L_{CTS} mini-slots and the set $\mathcal{L}_{CTS} = \{1, 2, ..., L_{CTS}\}$, (iv) the transmission time of a RC packet including one SIFS time is L_{RC} mini-slots and the set $\mathcal{L}_{RC} = \{1, 2, ..., L_{RC}\}$, (v) the total transmission time for transmitting U-CTS packet by the AP, DATA packets by M users and U-ACK packet by the AP including three SIFS times is L_{DT} mini-slots and the set $\mathcal{L}_{DT} = \{1, 2, ..., L_{DT}\}$ and (vi) the total transmission time for transmitting DATA packets by the AP and ACK packets by the users including two SIFS times is $L_{DT'}$ mini-slots and the set $\mathcal{L}_{DT'} = \{1, 2, ..., L_{DT'}\}$. For better understanding of model, we first take $M = 3$ and later the model is extended for general case. The states of the DTMC for $M = 3$ are defined as follows.

1. S_0: all the nodes are in idle state

2. $(RT_m, l) \quad \forall m \in \mathcal{P}'(\mathcal{N}), \forall l \in \mathcal{L}_{RTS}$: the users of user-set m are transmitting the l-th mini-slot RTS packets and the other nodes find the medium as busy

3. $(S_d, l) \quad \forall d \in \mathcal{N}, \forall l \in \mathcal{L}_{RC}$: RTS packet transmitted by the user d is successfully received by the AP and it is sending the l-th mini-slot RC packet

4. $S_d \quad \forall d \in \mathcal{N}$: the user d is waiting for U-CTS packet and all the other nodes are in idle state

5. $(S_d, RT_n, l) \quad \forall d \in \mathcal{N}, \forall n \in \mathcal{P}'(\mathcal{N} \backslash d), \forall l \in \mathcal{L}_{RTS}$: the user d is waiting for U-CTS packet, the users of user-set n are transmitting the l-th mini-slot RTS packets and other nodes find the medium as busy

6. $(S_{d,e}, l) \quad \forall d \in \mathcal{N}, \forall e \in \mathcal{N} \backslash d, \forall l \in \mathcal{L}_{RC}$: the user d is waiting for U-CTS packet, RTS packet transmitted by the user e is successfully received by the AP and the AP is sending the l-th mini-slot RC packet to the user e

7. $S_{d,e} \quad \forall d \in \mathcal{N}, \forall e \in \mathcal{N} \backslash d$: the users d and e are waiting for U-CTS packet and all the other nodes are in idle state

8. $(S_{d,e}, RT_k, l) \quad \forall d \in \mathcal{N}, \forall e \in \mathcal{N} \backslash d, \forall k \in \mathcal{P}'(\mathcal{N} \backslash \{d, e\}), \forall l \in \mathcal{L}_{RTS}$: the users d and e are waiting for U-CTS packet, the users of user-set k are transmitting the l-th mini-slot RTS packets and other nodes find the medium as busy

9. $(S_{d,e,f}, l) \quad \forall d \in \mathcal{N}, \forall e \in \mathcal{N} \backslash d, \forall f \in \mathcal{N} \backslash \{d, e\}, \forall l \in \mathcal{L}_{RC}$: the users d and e are waiting for U-CTS packet, RTS packet transmitted by the user f is successfully received by the AP and the AP is sending the l-th mini-slot RC packet to the user f

10. $(S_{d,e,f}, DT_{d,e,f}, l) \quad \forall d \in \mathcal{N}, \forall e \in \mathcal{N} \backslash d, \forall f \in \mathcal{N} \backslash \{d, e\}, \forall l \in \mathcal{L}_{DT}$: the users d, e and f are requested to transmit their DATA packets and they are transmitting/receiving the l-th mini-slot U-CTS, DATA and U-ACK packets

11. $(RT_{d',e',f'}, l) \quad \forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \backslash d', \forall f' \in \mathcal{N} \backslash \{d', e'\}, \ \forall l \in \mathcal{L}_{D-RTS}$: the AP is transmitting the l-th mini-slot D-RTS packet to the users d', e' and f' and the other users find the medium as busy

12. $(S_{d'}, l) \quad d' \ \in \mathcal{N}, \ \forall l \in \mathcal{L}_{CTS}$: the user d' receives D-RTS packet successfully from the AP and it is transmitting l-th mini-slot CTS packet to the AP

13. $(S_{d',e'}, l) \quad \forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \backslash d', \ \forall l \in \mathcal{L}_{CTS}$: D-RTS packet transmitted from the AP is successfully received by the users d' and e' and they are transmitting l-th mini-slot CTS packets to the AP

14. $(S_{d',e',f'}, l)$ $\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \backslash d', \forall f' \in \mathcal{N} \backslash \{d', e'\}$, $\forall l \in \mathcal{L}_{CTS}$: the users d', e' and f' receive D-RTS packet successfully from the AP and they are transmitting l-th mini-slot CTS packets to the AP

15. $(S_{d'}, DT'_{d'}, l)$ $d' \in \mathcal{N}$, $\forall l \in \mathcal{L}_{DT'}$: the AP is transmitting DATA packet to the user d' and after successful reception of DATA packet, the user d' is transmitting l-th mini-slot ACK packet to the AP

16. $(S_{d',e'}, DT'_{d',e'}, l)$ $\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \backslash d'$, $\forall l \in \mathcal{L}_{DT'}$: DATA packets are transmitted by the AP to the users d' and e' and after successful reception of DATA packets, the users d' and e' are transmitting l-th mini-slot ACK packets

17. $(S_{d',e',f'}, DT'_{d',e',f'}, l)$ $\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \backslash d', \forall f' \in \mathcal{N} \backslash \{d', e'\}$, $\forall l \in \mathcal{L}_{DT'}$: the AP is transmitting DATA packets to the users d', e' and f' and after successful reception of DATA packets, they are transmitting l-th mini-slot ACK packets to the AP

In uplink, when RTS packets are transmitted by a set of users simultaneously, one of the transmission may be successful. The success of a transmission depends on its power level among the powers from other users received at the AP. Let the probability of RTS packet transmission for the user $d \in m$ is successful be $P^c_{m,d}$. Further, let P^c_m be the probability that one of the RTS transmission of the users in the user-set m is successful, i.e., $\sum_{d \in m} P^c_{m,d} = P^c_m$.

In downlink, AP transmits D-RTS packet to M users and it can be successfully received by the users based on their respective SNR. We assume that the probability of receiving RTS packet successfully by at least one user and two users are P^{cp}_1 and P^{cp}_2, respectively. P^s_1, P^s_2 and P^s_3 are the probabilities, for receiving D-RTS packet successfully by exactly one, two and three users respectively. Moreover, P_s is the probability of one D-RTS packet reception is successful and this probability is useful to calculate above-mentioned probabilities. In Table I and II, we illustrate the transition probability p_{s_1,s_2} from a state s_1 to a state s_2 of the Markov chain for uplink and downlink, respectively with considering $M = 3$.

Table 4.1: Transition probability p_{s_1,s_2} from a state s_1 to a state s_2 for uplink

SN.	**State** s_1	**State** s_2	**State Detail**	p_{s_1,s_2}
1	S_0	$(RT_m, 1)$	$\forall m \in \mathcal{P}'(\mathcal{N})$	$p^{\lvert m\rvert}(1-p)^{N-\lvert m\rvert}$ $(1-p_a)$
2	(RT_m, l)	$(RT_m, l+1)$	$\forall m \in \mathcal{P}'(\mathcal{N}),\ \forall l \in \mathcal{L}_R \backslash\ L_{RTS}$	1
3	(RT_m, L_{RTS})	S_0	$\forall m \in \mathcal{P}'(\mathcal{N})$	$1 - P_m^c$
4	(RT_m, L_{RTS})	$(S_d, 1)$	$\forall m \in \mathcal{P}'(\mathcal{N}), \forall d \in m$	$P_{m,d}^c$
5	(S_d, l)	$(S_d, l+1)$	$\forall d \in \mathcal{N},\ l \in \mathcal{L}_{RC} \backslash\ L_{RC}$	1
6	(S_d, L_{RC})	S_d	$\forall d \in \mathcal{N}$	1
7	S_d	$(S_d, RT_n, 1)$	$\forall d \in \mathcal{N}, \forall n \in \mathcal{P}'(\mathcal{N}\backslash d)$	$p^{\lvert n\rvert}(1-p)^{N-\lvert n\rvert-1}$
8	(S_d, RT_n, l)	$(S_d, RT_n, l+1)$	$\forall d \in \mathcal{N}, \forall n \in \mathcal{P}'(\mathcal{N}\backslash d),\ \forall l \in \mathcal{L}_{RTS} \backslash\ L_{RTS}$	1
9	(S_d, RT_n, L_{RTS})	S_d	$\forall d \in \mathcal{N}, \forall n \in \mathcal{P}'(\mathcal{N}\backslash d)$	$1 - P_n^c$
10	(S_d, RT_n, L_{RTS})	$(S_{d,e}, 1)$	$\forall d \in \mathcal{N}, \forall n \in \mathcal{P}'(\mathcal{N}\backslash d), \forall e \in \mathcal{N}\backslash d$	$P_{n,e}^c$
11	$(S_{d,e}, l)$	$(S_{d,e}, l+1)$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall l \in \mathcal{L}_{RC} \backslash\ L_{RC}$	1
12	$(S_{d,e}, L_{RC})$	$S_{d,e}$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d$	1
13	$S_{d,e}$	$(S_{d,e}, RT_k, 1)$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall k \in \mathcal{P}'(\mathcal{N}\backslash\{d,e\})$	$p^{\lvert k\rvert}(1-p)^{N-\lvert k\rvert-2}$
14	$(S_{d,e}, RT_k, l)$	$(S_{d,e}, RT_k, l+1)$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall k \in \mathcal{P}'(\mathcal{N}\backslash\{d,e\}), \forall l \in \mathcal{L}_{RTS} \backslash\ L_{RTS}$	1
15	$(S_{d,e}, RT_k, L_{RTS})$	$S_{d,e}$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall k \in \mathcal{P}'(\mathcal{N}\backslash\{d,e\})$	$1 - P_k^c$
16	$(S_{d,e}, RT_k, L_{RTS})$	$(S_{d,e,f}, 1)$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall f \in \mathcal{N}\backslash\{d,e\}, \forall k \in \mathcal{P}'(\mathcal{N}\backslash\{d,e\})$	$P_{k,f}^c$
17	$(S_{d,e,f}, l)$	$(S_{d,e,f}, l+1)$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall f \in \mathcal{N}\backslash\{d,e\}, \forall l \in \mathcal{L}_{RC} \backslash\ L_{RC}$	1
18	$(S_{d,e,f}, L_{RC})$	$(S_{d,e,f}, DT_{d,e,f}, 1)$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall f \in \mathcal{N}\backslash\{d,e\}$	1
19	$(S_{d,e,f}, DT_{d,e,f}, l)$	$(S_{d,e,f}, DT_{d,e,f}, l+1)$	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall f \in \mathcal{N}\backslash\{d,e\}, \forall l \in \mathcal{L}_{DT} \backslash\ L_{DT}$	1
20	$(S_{d,e,f}, DT_{d,e,f}, L_{DT})$	S_0	$\forall d \in \mathcal{N}, \forall e \in \mathcal{N}\backslash d, \forall f \in \mathcal{N}\backslash\{d,e\}$	1

Table 4.2: Transition probability p_{s_1,s_2} from a state s_1 to a state s_2 for downlink

SN.	State s_1	State s_2	State Detail	p_{s_1,s_2}
1	S_0	$(RT_{d',e',f'},1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d', \forall f' \in \mathcal{N}\backslash\{d',e'\}$	$1/\binom{N}{3}p_a$
2	$(RT_{d',e',f'},1)$	$(RT_{d',e',f'},l+1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d', \forall f' \in \mathcal{N}\backslash\{d',e'\}, \forall l \in \mathcal{L}_{D-RTS}\backslash\ L_{D-RTS}$	1
3	$(RT_{d',e',f'},L_{D-RTS})$	S_0	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d', \forall f' \in \mathcal{N}\backslash\{d',e'\}$	$(1-P_s)^3$
4	$(RT_{d',e',f'},L_{RTS})$	$(S_{d'},1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d', \forall f' \in \mathcal{N}\backslash\{d',e'\}, \forall l \in \mathcal{L}_{D-RTS}\backslash\ L_{D-RTS}$	P_1^{cp}
5	$(S_{d'},1)$	$(S'_d,l+1)$	$d' \in \mathcal{N},\ \forall l \in \mathcal{L}_{CTS}\backslash\ L_{CTS}$	1
6	$(S_{d'},L_{CTS})$	$(S_{d',e'},1)$	$\{d',e'\} \in \mathcal{N}$	P_2^{cp}
7	$(S_{d',e'},1)$	$(S_{d',e'},l+1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d',\ \forall l \in \mathcal{L}_{CTS}\backslash\ L_{CTS}$	1
8	$(S_{d',e'},L_{CTS})$	$(S_{d',e',f'},1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d'$	P_3^s
9	$(S_{d',e',f'},1)$	$(S_{d',e',f'},l+1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d', \forall f' \in \mathcal{N}\backslash\{d',e'\}, \forall l \in \mathcal{L}_{CTS}\backslash\ L_{CTS}$	1
10	$(S_{d',e',f'},L_{CTS})$	$(S_{d',e',f'},DT'_{d',e',f'},1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d', \forall f' \in \mathcal{N}\backslash\{d',e'\}$	1
11	$(S_{d',e',f'},DT'_{d',e',f'},1)$	$(S_{d',e',f'},DT'_{d',e',f'},$ $l+1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d', \forall f' \in \mathcal{N}\backslash\{d',e'\}, \forall l \in \mathcal{L}_{DT'}\backslash\ L_{DT'}$	1
12	$(S_{d',e',f'},DT'_{d',e',f'},$ $L_{DT'})$	S_0	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d', \forall f' \in \mathcal{N}\backslash\{d',e'\}$	1
13	$(S_{d',e'},L_{CTS})$	$(S_{d',e'},DT'_{d',e'},1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d'$	P_2^s
14	$(S_{d',e'},DT'_{d',e'},1)$	$(S_{d',e'},DT'_{d',e'},l+$ $1)$	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d',\ \forall l \in \mathcal{L}_{DT'}\backslash\ L_{DT'}$	1
15	$(S_{d',e'},DT'_{d',e'},L_{DT'})$	S_0	$\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N}\backslash d'$	1
16	$(S_{d'},L_{CTS})$	$(S_{d'},DT'_{d'},1)$	$d' \in \mathcal{N}$	P_1^s
17	$(S_{d'},DT'_{d'},1)$	$(S_{d'},DT'_{d'},l+1)$	$d' \in \mathcal{N},\ \forall l \in \mathcal{L}_{DT'}\backslash\ L_{DT'}$	1
18	$(S_{d'},DT'_{d'},L_{DT'})$	S_0	$d' \in \mathcal{N}$	1

4.4 Analysis of the Markov Chain

Let, $\psi(s)$ is the stationary probability of a state s. The total throughput of a WLAN system depends on the stationary probabilities of the data transmission states. Here, we are going to calculate stationary probabilities for every stage under the modeled Markov chain for both uplink and downlink transmissions.

4.4.1 Markov Chain Analysis for Uplink Transmission

The Markov chain for uplink is illustrated in Fig. 4.2. From the transition probabilities of serial number 1 in Table 4.1, we obtain

$$\begin{aligned}\sum_{m\in\mathcal{P}'(\mathcal{N})}\psi(RT_m,1) &= \psi(S_0)\sum_{m\in\mathcal{P}'(\mathcal{N})}p^{|m|}(1-p)^{N-|m|}(1-p_a)\\ &= \psi(S_0)(1-p_a)[1-(1-p)^N]. \end{aligned} \tag{4.10}$$

We can find from the transition probabilities of serial number 4 shown in Table 4.1 that

$$\sum_{d\in\mathcal{N}}\psi(S_d,1) = \sum_{d\in\mathcal{N},m\in\mathcal{P}'(\mathcal{N})}\psi(RT_m,L_{RTS})P^c_{m,d}. \tag{4.11}$$

By using transition probabilities of serial numbers 1, 2 and 4 shown in Table 4.1, we obtain

$$\psi(RT_m,L_{RTS}) = \psi(RT_m,l) = \psi(RT_m,1). \tag{4.12}$$

So we can modify equation (4.11) using equation (4.12) as

$$\begin{aligned}\sum_{d\in\mathcal{N}}\psi(S_d,1) &= \sum_{m\in\mathcal{P}'(\mathcal{N})}\psi(RT_m,1)P^c_m\\ &= \psi(S_0)(1-p_a)\sum_{m\in\mathcal{P}'(\mathcal{N})}p^{|m|}(1-p)^{N-|m|}P^c_m\\ &= \psi(S_0)(1-p_a)K_N \end{aligned} \tag{4.13}$$

where,

$$K_N = \sum_{m\in\mathcal{P}'(\mathcal{N})}p^{|m|}(1-p)^{N-|m|}P^c_m. \tag{4.14}$$

The balance equation for state S_d can be expressed as

$$\begin{aligned}\psi(S_d) &= \psi(S_d,L_{RC})+\psi(S_d)(1-p)^{N-1}+\sum_{n\in\mathcal{P}'(\mathcal{N}\backslash d)}\psi(S_d,RT_n,L_{RTS})(1-P^c_n)\\ &= \psi(S_d,1)+\psi(S_d)(1-p)^{N-1}+\psi(S_d)\sum_{n\in\mathcal{P}'(\mathcal{N}\backslash d)}p^{|n|}(1-p)^{N-|n|-1}(1-P^c_n). \end{aligned} \tag{4.15}$$

After some mathematical manipulation, from equation (4.15) we can find

$$\psi(S_d) = \frac{\psi(S_d, 1)}{K_{N-1}} \tag{4.16}$$

where,

$$K_{N-1} = \sum_{n \in \mathcal{P}'(\mathcal{N}\backslash d)} p^{|n|}(1-p)^{N-|n|-1} P_n^c. \tag{4.17}$$

It can be shown by putting value of equation (4.13) into equation (4.16) that

$$\begin{aligned} \sum_{d \in \mathcal{N}} \psi(S_d) &= \frac{\sum_{d \in \mathcal{N}} \psi(S_d, 1)}{K_{N-1}} \\ &= \frac{\psi(S_0) K_N (1-p_a)}{K_{N-1}}. \end{aligned} \tag{4.18}$$

From the transition probabilities shown in serial number 7 of Table 4.1 and equation (4.18), we get

$$\begin{aligned} \sum_{d \in \mathcal{N}, n \in \mathcal{P}'(\mathcal{N}\backslash d)} \psi(S_d, RT_n, 1) &= \sum_{d \in \mathcal{N}, n \in \mathcal{P}'(\mathcal{N}\backslash d)} p^{|n|}(1-p)^{N-|n|-1} \psi(S_d) \\ &= \frac{[1-(1-p)^{N-1}] \psi(S_0) K_N (1-p_a)}{K_{N-1}}. \end{aligned} \tag{4.19}$$

Now we can obtain from the transition probabilities shown in serial numbers 7, 8 and 10 in Table 4.1 and equations (4.18) and (4.19),

$$\begin{aligned} \sum_{d \in \mathcal{N}, e \in \mathcal{N}\backslash d} \psi(S_{d,e}, 1) &= \sum_{d \in \mathcal{N}, e \in \mathcal{N}\backslash d, n \in \mathcal{P}'(\mathcal{N}\backslash d)} \psi(S_d, RT_n, L_{RTS}) P_{n,e}^c \\ &= \sum_{d \in \mathcal{N}, n \in \mathcal{P}'(\mathcal{N}\backslash d)} \psi(S_d, RT_n, 1) P_n^c \\ &= \sum_{d \in \mathcal{N}, n \in \mathcal{P}'(\mathcal{N}\backslash d)} p^{|n|}(1-p)^{N-|n|-1} P_n^c \psi(S_d) \\ &= K_{N-1} \times \frac{\psi(S_0) K_N (1-p_a)}{K_{N-1}} \\ &= K_N \psi(S_0)(1-p_a). \end{aligned} \tag{4.20}$$

The balance equation for state $S_{d,e}$ can be written as

$$\begin{aligned}\psi(S_{d,e}) &= \psi(S_{d,e}, L_{RC}) + \psi(S_{d,e})(1-p)^{N-2} \\ &+ \sum_{k\in\mathcal{P}'(\mathcal{N}\setminus\{d,e\})} \psi(S_{d,e}, RT_k, L_{RTS})(1-P_r^c) \\ &= \psi(S_{d,e}, L_{RC}) + \psi(S_{d,e})(1-p)^{N-2} \\ &+ \psi(S_{d,e}) \sum_{k\in\mathcal{P}'(\mathcal{N}\setminus\{d,e\})} p^{|k|}(1-p)^{N-|k|-2} \times (1-P_k^c) \\ &= \frac{\psi(S_{d,e},1)}{K_{N-2}} \qquad (4.21)\end{aligned}$$

where,

$$K_{N-2} = \sum_{k\in\mathcal{P}'(\mathcal{N}\setminus\{d,e\})} p^{|k|}(1-p)^{N-|k|-2}P_k^c. \qquad (4.22)$$

From equations (4.20) and (4.21), it can be shown that

$$\sum_{d\in\mathcal{N},k\in\mathcal{N}\setminus d} \psi(S_{d,e}) = \frac{\psi(S_0)K_N(1-p_a)}{K_{N-2}}. \qquad (4.23)$$

From the transition probabilities shown in serial number 13 of Table 4.1 and equation (4.23), we can write

$$\begin{aligned}&\sum_{d\in\mathcal{N},e\in\mathcal{N}\setminus d,k\in\mathcal{P}'(\mathcal{N}\setminus\{d,e\})} \psi(S_{d,e}, RT_k, 1) \\ =& \sum_{d\in\mathcal{N},e\in\mathcal{N}\setminus d,k\in\mathcal{P}'(\mathcal{N}\setminus\{d,e\})} p^{|k|}(1-p)^{N-|k|-2}\psi(S_{d,e}) \\ =& \frac{[1-(1-p)^{N-2}]\psi(S_0)K_N(1-p_a)}{K_{N-2}}. \qquad (4.24)\end{aligned}$$

Using the transition probabilities shown in serial numbers 13, 14 and 16 of Table 4.1 and equations (4.22) and (4.23), we get

$$\begin{aligned}&\sum_{d\in\mathcal{N},e\in\mathcal{N}\setminus d,f\in\mathcal{N}\setminus\{d,e\}} \psi(S_{d,e,f}, 1) \\ =& \sum_{d\in\mathcal{N},e\in\mathcal{N}\setminus d,f\in\mathcal{N}\setminus\{d,e\},k\in\mathcal{P}'(\mathcal{N}\setminus\{d,e\})} \psi(S_{d,e}, RT_k, L_{RTS})P_{k,f}^c \\ =& \sum_{d\in\mathcal{N},e\in\mathcal{P}'(\mathcal{N}\setminus d),k\in\mathcal{P}'(\mathcal{N}\setminus\{d,e\})} \psi(S_{d,e}, RT_k, 1)P_k^c \\ =& \sum_{d\in\mathcal{N},e\in\mathcal{N}\setminus d,k\in\mathcal{P}'(\mathcal{N}\setminus\{d,e\})} p^{|k|}(1-p)^{N-|k|-2}P_k^c\psi(S_{d,e}) \\ =& K_N\psi(S_0)(1-p_a). \qquad (4.25)\end{aligned}$$

4.4.2 Markov Chain Analysis for Downlink Transmission

In downlink, the AP can choose any users set between $\binom{N}{M}$. If we assume equal probability of choosing one of the set of users, the probability of choosing any user-set would be $1/\binom{N}{M}$. So we find unity after taking summation of state probabilities for all paths. The Markov chain for downlink is illustrated in Fig. 4.3 for $M = 3$.

From the transition probabilities shown in serial number 1 of Table 4.2, we can write

$$\begin{aligned} \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\}} \psi(RT_{d',e',f'}, 1) &= \psi(S_0) \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\}} \frac{1}{\binom{N}{3}} p_a \\ &= \psi(S_0) p_a. \end{aligned} \tag{4.26}$$

Using the transition probabilities of serial numbers 2, 3 and 4 of Table 4.2 and equation (4.26), we get

$$\begin{aligned} \sum_{\forall d' \in \mathcal{N}} \psi(S_{d'}, 1) &= \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\}} \psi(RT_{d',e',f'}, L_{RTS}) P_1^{cp} \\ &= \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\}} \psi(RT_{d',e',f'}, 1) P_1^{cp} \\ &= \psi(S_0) p_a P_1^{cp}. \end{aligned} \tag{4.27}$$

From the transition probabilities of serial number 6 of Table 4.2 and by using equation (4.27),we can find

$$\begin{aligned} \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d'} \psi(S_{d',e'}, 1) &= \sum_{\forall d' \in \mathcal{N}} \psi(S_{d'}, L_{CTS}) P_2^{cp} \\ &= \sum_{\forall d' \in \mathcal{N}} \psi(S_{d'}, 1) P_2^{cp} \\ &= \psi(S_0) p_a P_1^{cp} P_2^{cp}. \end{aligned} \tag{4.28}$$

Now we can obtain from the transition probabilities of serial number 8 of Table 4.2 as well as from equation (4.28) that

$$\begin{aligned} \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\}} \psi(S_{d',e',f'}, 1) &= \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d'} \psi(S_{d',e'}, L_{CTS}) P_3^{cp} \\ &= \psi(S_0) p_a P_1^{cp} P_2^{cp} P_3^{s}. \end{aligned} \tag{4.29}$$

From equation (4.27) and the transition probabilities of serial number 16 of Table

4.2, we get

$$\begin{aligned}\sum_{\forall d'\in\mathcal{N}} \psi(S_{d'}, DT'_{d'}, 1) &= \sum_{d'\in\mathcal{N}} \psi(S_{d'}, L_{CTS})P_1^s \\ &= \sum_{\forall d'\in\mathcal{N}} \psi(S_{d'}, 1)P_1^s \\ &= \psi(S_0)p_a P_1^{cp} P_1^s. \end{aligned} \tag{4.30}$$

Using the transition probabilities of serial number 13 of Table 4.2 and equation (4.28), we can find

$$\begin{aligned}\sum_{\forall d'\in\mathcal{N},\forall e'\in\mathcal{N}\setminus d'} \psi(S_{d',e'}, DT'_{d',e'}, 1) &= \sum_{\forall d'\in\mathcal{N},\forall e'\in\mathcal{N}\setminus d'} \psi(S_{d',e'}, L_{CTS})P_2^s \\ &= \sum_{\forall d'\in\mathcal{N},\forall e'\in\mathcal{N}\setminus d'} \psi(S_{d',e'}, 1)P_2^s \\ &= \psi(S_0)p_a P_1^{cp} P_2^{cp} P_2^s. \end{aligned} \tag{4.31}$$

By using the transition probabilities of serial number 10 of Table 4.2 along with help of equation (4.29), we get

$$\begin{aligned} &\sum_{\forall d'\in\mathcal{N},\forall e'\in\mathcal{N}\setminus d',\forall f'\in\mathcal{N}\setminus\{d',e'\}} \psi(S_{d',e',f'}, DT'_{d',e',f'}, 1) \\ =& \sum_{\forall d'\in\mathcal{N},\forall e'\in\mathcal{N}\setminus d',\forall f'\in\mathcal{N}\setminus\{d',e'\}} \psi(S_{d',e',f'}, L_{CTS}) \\ =& \sum_{\forall d'\in\mathcal{N},\forall e'\in\mathcal{N}\setminus d',\forall f'\in\mathcal{N}\setminus\{d',e'\}} \psi(S_{d',e',f'}, 1) \\ =& \ \psi(S_0)p_a P_1^{cp} P_2^{cp} P_3^s. \end{aligned} \tag{4.32}$$

4.4.3 Throughput Model

The total throughput of the users in the WLAN under the proposed MAC protocol with $M = 3$ is given by

$$\begin{aligned}\Omega_{up} &= 3\rho_{up}R \sum_{d\in\mathcal{N},e\in\mathcal{N}\setminus d,f\in\mathcal{N}\setminus\{d,e\},l\in\mathcal{L}_{DT}} \psi(S_{d,e,f}, DT_{d,e,f}, l) \\ &= 3\rho_{up}RL_{DT} \sum_{d\in\mathcal{N},e\in\mathcal{N}\setminus d,f\in\mathcal{N}\setminus\{d,e\}} \psi(S_{d,e,f}, DT_{d,e,f}, 1) \end{aligned} \tag{4.33}$$

where ρ_{up} is the efficiency for uplink transmission, defined as $\rho_{up} = \frac{L_{dt}}{L_{DT}}$ with the transmission time of a DATA packet for uplink to be L_{dt} in mini-slots. From the transition probabilities of serial numbers 17 and 18 shown in Table 4.1, we can write

$$\psi(S_{d,e,f}, DT_{d,e,f}, 1) = \psi(S_{d,e,f}, 1). \tag{4.34}$$

So we can rewrite equation (4.33) according to equation (4.34) as

$$\Omega_{up} = 3\rho_{up} R L_{DT} \sum_{d\in\mathcal{N}, e\in\mathcal{N}\backslash d, f\in\mathcal{N}\backslash\{d,e\}} \psi(S_{d,e,f}, 1). \quad (4.35)$$

For general case, the total throughput of the users can be found from equation (4.35) by using equation (4.25) as

$$\Omega_{up} = \rho_{up} R M L_{DT} K_N \psi(S_o)(1-p_a) \quad (4.36)$$

where the value of $\psi(S_0)$ can be obtained as [See Appendix A]

$$\psi(S_0) \approx \Big[M - (M-1)p_a + L_{RTS} M[1-(1-p)^N](1-p_a) \\ +(ML_{RC} + L_{DT})K_N(1-p_a) + (L_{D-RTS} + ML_{CTS} + L_{DT'})p_a \Big]^{-1}. \quad (4.37)$$

For $M = 3$, the total throughput obtained by the AP is given as

$$\begin{aligned} \Omega_{dn} &= \rho_{dn} R\{ \sum_{d'\in\mathcal{N},\ \forall l\in\mathcal{L}_{DT'}} \psi(S_{d'}, DT'_{d'}, l) + \sum_{\forall d'\in\mathcal{N}, \forall e'\in\mathcal{N}\backslash d',\ \forall l\in\mathcal{L}_{DT'}} \psi(S_{d',e'}, DT'_{d',e'}, l) \\ &+ \sum_{\forall d'\in\mathcal{N}, \forall e'\in\mathcal{N}\backslash d', \forall f'\in\mathcal{N}\backslash\{d',e'\},\ \forall l\in\mathcal{L}_{DT'}} \psi(S_{d',e',f'}, DT'_{d',e',f'}, l)\} \\ &= \rho_{dn} R L_{DT'}\{ \sum_{d'\in\mathcal{N}} \psi(S_{d'}, DT'_{d'}, 1) + 2 \sum_{\forall d'\in\mathcal{N}, \forall e'\in\mathcal{N}\backslash d'} \psi(S_{d',e'}, DT'_{d',e'}, 1) \\ &+ 3 \sum_{\forall d'\in\mathcal{N}, \forall e'\in\mathcal{N}\backslash d', \forall f'\in\mathcal{N}\backslash\{d',e'\}} \psi(S_{d',e',f'}, DT'_{d',e',f'}, 1)\} \end{aligned} \quad (4.38)$$

By using equations (4.30), (4.31) and (4.32) into equation (4.38), we can get

$$\Omega_{dn} = \rho_{dn} R L_{DT'} \psi(S_0) p_a P_1^{cp} \{P_1^s + 2P_2^{cp} P_2^s + 3P_2^{cp} P_3^s\} \quad (4.39)$$

where the efficiency for downlink transmission is ρ_{dn}, defined as $\rho_{dn} = \frac{L_{dt'}}{L_{DT'}}$ with the transmission time of a DATA packet for downlink to be $L_{dt'}$ in mini-slots. We find that $P_1^{cp}\{P_1^s + 2P_2^{cp}P_2^s + 3P_2^{cp}P_3^{cp}\} \approx 3$ [See Appendix B]. So equation (4.39) can be expressed as

$$\Omega_{dn} \approx 3\rho_{dn} R L_{DT'} \psi(S_0) p_a. \quad (4.40)$$

For general case, the total throughput of the AP can be expressed as

$$\Omega_{dn} = M\rho_{dn} R L_{DT'} \psi(S_0) p_a. \quad (4.41)$$

4.5 Computation of K_N

So far, we develop the analytical model for determining the total throughput of the users as well as the AP. However, to calculate the total throughput, K_N needs to be computed. From equation (4.14), it is clear that we need to calculate P^c_m for computing K_N. P^c_m is the capture probability when the users of the user-set m transmit RTS packets simultaneously. Let r_d, ξ_d and F_d are the distance, shadowing and fading parameter, respectively for a user $d \in \mathcal{N}$. We intend to compute the total throughput by averaging over positions of the users. The value of K_N can be computed after finding P^c_m for all m in $\mathcal{P}'(\mathcal{N})$. So by using equation (4.7), we have

$$\begin{aligned} P_m(r_d) &= P\left[P^d_r > \beta \sum_{i \in y \backslash d} P^i_r + N_o\right] \\ &= P\left[F^2_d > \beta \sum_{i \in y \backslash d} F^2_d e^{\xi_i - \xi_d} \left(\frac{r_i}{r_d}\right)^{-\eta}\right] \\ &= P\left[F^2_d > \beta \sum_{i \in m \backslash d} b_{i,d} x^2_i\right] \end{aligned} \tag{4.42}$$

where only the dependence on distance r_d is expressed and $b_{i,d} = e^{\xi_i - \xi_d}\left(\frac{r_i}{r_d}\right)^{-\eta}$. N_o is omitted here because we assume transmitted power is appreciably greater than noise power.

Conditioning on r_i and ξ_i for all $i \in m$, the probability that the transmission of the user $d \in m$ is successful is given as

$$\begin{aligned} P^c_{m,d} &= \int_0^\infty \int_0^\infty ... \int_0^\infty P(F^2_d > \beta \sum_{i \in m \backslash d} b_{i,d} x^2_i) \prod_{i \in m \backslash d} (2x_i) exp(-\sum_{i \in m \backslash d} x^2_i) \prod_{i \in m \backslash d} dx_i \\ &= \int_0^\infty \int_0^\infty ... \int_0^\infty \exp(-\beta \sum_{i \in m \backslash d} b_{i,d} x^2_r) \prod_{r \in m \backslash d} (2x_r) exp(-\sum_{r \in m \backslash d} x^2_r) \prod_{r \in m \backslash d} dx_i \\ &= \prod_{i \in m \backslash d} \frac{1}{1 + \beta b_{i,d}}. \end{aligned} \tag{4.43}$$

Averaging over $\forall \xi_i$ and $\forall r_i$ where $i \in m \backslash d$, $P^c_{m,d}$ can be expressed as

$$P^c_{m,d} = G_d^{|m|-1} \tag{4.44}$$

where,

$$G_d = \int_{-\infty}^{\infty} \int_0^1 \frac{1}{1 + \beta b_{i,d}} f_r(r_i) f_\xi(\xi_i) dr_i d\xi_i. \tag{4.45}$$

Further, averaging over ξ_d and r_d, the average value of $P^c_{m,d}$ can be found as

$$\overline{P}^c_{m,d} = \int_0^1 \int_{-\infty}^{\infty} G_d^{|m|-1} f_r(r_d) f_\xi(\xi_d) dr_d d\xi_d. \tag{4.46}$$

Since, the success probability of all the RTS transmitting users are equal, the value of P^c_m can be computed as

$$P^c_m = |m| \overline{P}^c_{m,d}. \tag{4.47}$$

4.6 Summary

In this chapter, we have described the system model which considers different wireless and network parameters for our analytical analysis. Here, path loss, Rayleigh fading, and log-normal shadowing are considered which affect the received signal(s). The ZF scheme has been utilized in both pre-coding and decoding process for taking the benefit of MU-MIMO technique. The physical interference model has been adopted to decide the success of a RTS/D-RTS packet transmission by checking its SINR, which must be greater than a certain threshold. Rest of the control packets along with DATA packet transmissions are always considered successful. Furthermore, discrete time Markov chain has been used to model a WLAN system under the proposed MAC protocol. Finally, we have calculated the stationary probabilities of all states which lead to the development of the analytical model for calculating the total throughput of the users and the AP.

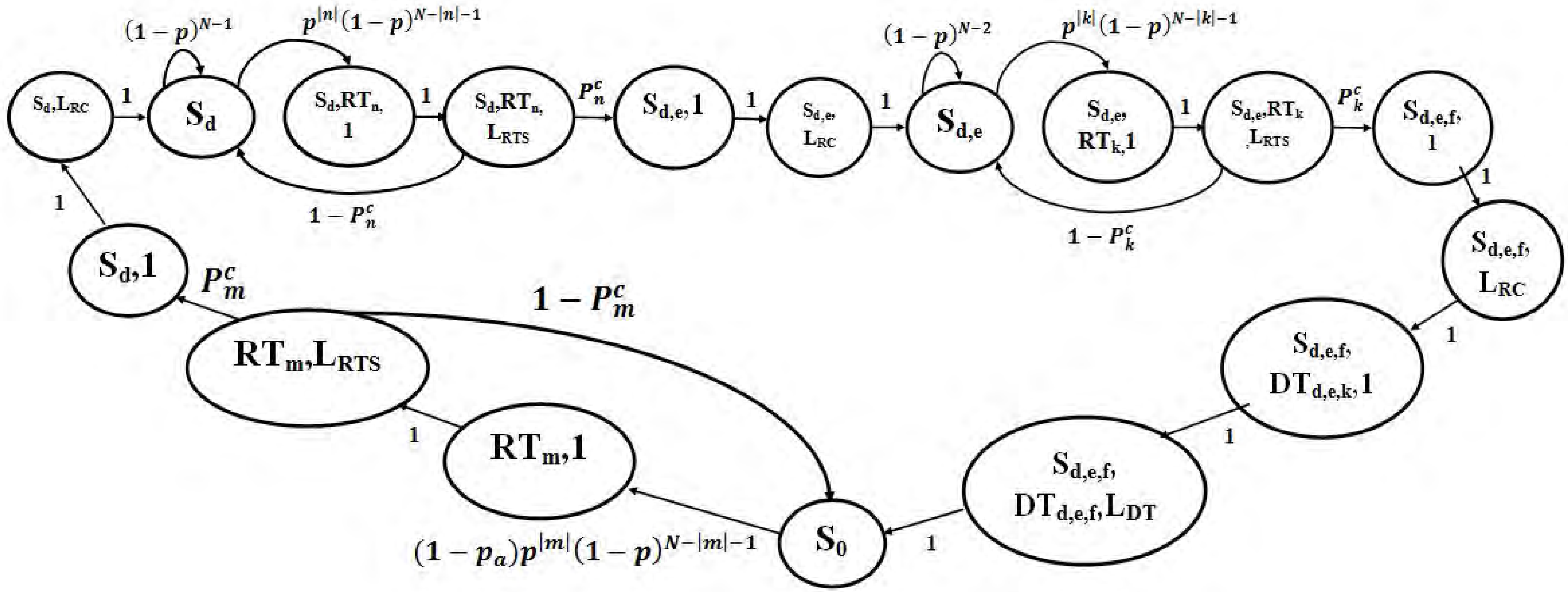


Figure 4.2: Illustration of the Markov chain model for uplink MAC protocol for $M = 3$.

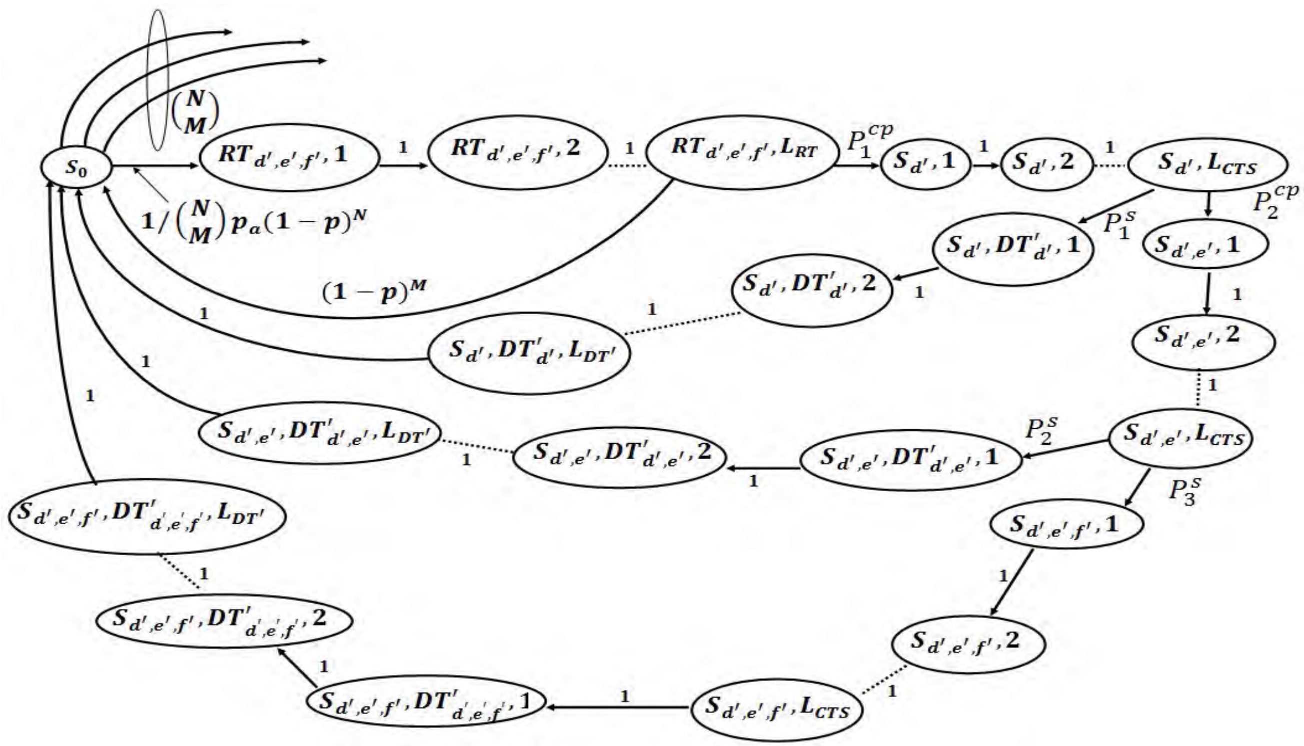


Figure 4.3: Illustration of the Markov chain model for downlink MAC protocol for $M = 3$.

Chapter 5

Verification of Developed Analytical Model

In this chapter, the process for making a simulator is described, which is utilized to validate our analytical model. The necessary settings and parameters used in the simulator are also provided. The impact of transmission probability on throughput under the proposed method is also discussed here.

5.1 Model Verification

5.1.1 Network Setup and Assumptions

For validation of our analytical model, it is necessary to compare the results produced from the analytical model developed in Chapter 4 with the simulation results. In the simulation, a WLAN system consists of an AP with 20 users is considered. This WLAN system is used to compute the total throughput under different configurations of WLAN parameters. Due to the freedom of configuring the WLAN and channel parameters, MATLAB is used for building the custom simulator to get the simulation results. The value of P_m^c for each $m \in \mathcal{P}'(\mathcal{N})$ is calculated using the Gauss-Hermit quadrature [56] under different configurations of WLAN parameters. Besides the value of P_m^c is considered same for two transmitting user-sets m_1 and m_2 if $|m_1| = |m_2|$ for averaging over the positions of the users. The value of P_s is numerically calculated with the help of MATLAB software. Three different modulation and coding schemes are considered with their corresponding threshold value, β which is shown in Table 5.1. The path loss component, η is considered to be 4 for indoor WLAN environment in the simulation. The duration of different packets used in simulation along with other parameters are listed in Table 5.2.

5.1.2 Simulator Set up

For averaging over the positions of 20 users, 300 instances of WLANs are considered. The distance of a user from the AP is determined as $\sqrt{Z}$ for a WLAN instance where Z is a uniform random variable between (0,1). The angle between a user and the AP is defined as $Z \times 2\pi$ for an instance. Traffic has saturation condition which is ensured by considering that the nodes always have packets to send.

To implement perfect carrier sensing, we consider all the other nodes except the transmitting and receiving nodes stay in the current state during the transmission. If an idle node finds the medium as free in a mini-slot, its decision on RTS packet transmission is determined by generating a random variable with Bernoulli distribution. Note that the parameter of Bernoulli distribution of a node is the transmission probability of that node, i.e., p for each user and p_a for the AP.

If the outcomes of random variables for a set of users are greater than zero and the random variable for the AP gives no outcome, then simulator enters into the uplink mode. In uplink, more than one user may transmit RTS packet simultaneously according to our proposed MAC protocol. When a set of users start transmitting RTS packets, their received power at the AP are determined by independently generated shadowing and fading parameters based on their distributions. The AP determines a successful RTS transmitted user with the help of SINR of the user. If the SINR of a user is greater than the threshold SINR, AP receives the RTS packet successfully and sends a RC packet to the user after a mini-slot. The AP receives packets without comparing its SINR with the threshold SINR if only one user sends RTS packet because interference is absent and we consider the transmit power is very high compared to noise. If one user is successful from these above-mentioned process then simulator again tries to find $M-1$ successful RTS transmitting users and also sends RC packets after finding them. Otherwise, the simulator enters into the idle mode which means users, as well as the AP, contend to access the channel. After accumulation of M RTS packets, the AP sends U-CTS packet to notify RC packet received users to start data transmission. We consider that the received power level from each user at the AP remains same during RTS to DATA packet transmission. All the DATA packet transmissions are considered to be successful and the AP sends

Table 5.1: Values of β for different R

Data Rate(Mbps)	SINR, β(dB)
2	6.4
5.5	9.4
11	12.4

Table 5.2: Simulation parameters

A mini-slot, Φ	20 μs
SIFS time	1 mini-slot
L_{RTS}	7 mini-slots
L_{D-RTS}	15 mini-slots
L_{RC}	6 mini-slots
L_{ACK}/L_{U-ACK}	6 mini-slots
L_{CTS}/L_{U-CTS}	6 mini-slots
$L_{dt}/L_{dt'}$	500 mini-slots
Waiting time for CTS	5000 mini-slots
P_{tr}	12 watts
r_o	0.01 m

a U-ACK packet to inform the users from which it receives the DATA packet. Like DATA packet, we also assume U-ACK packet transmission is successful.

If the outcome of the random variable for the AP is one then the simulator enters into the downlink mode. In this phase, AP selects M users uniformly from N users. After that, AP sends a D-RTS packet to the selected M users and their received power at the users are determined by generating the shadowing and fading parameters of the packet transmissions independently. According to our protocol, there is no interference in downlink. So users can successfully receive D-RTS packet sent from the AP if received signal SNR is greater than the threshold SINR. After successful reception of D-RTS packet, users send CTS packets to the AP. The waiting time for the AP is M $\times$ (one CTS packet time + one SIFS time) after transmitting D-RTS packet. During this time, the AP completes the reception of CTS packets from the targeted stations. Likewise, the received power level from the AP at each user remains unchanged during D-RTS to DATA packet transmission. All the DATA packet transmissions are considered to be successful. The users who receive DATA packets successfully send an ACK packet to inform the AP. ACK packet transmissions are also considered successful.

On the other hand, if the outcomes for all the nodes are zero which indicates that the AP or any user is unable to access the channel, then a slot time is added with simulation time. After that, simulator enters into the idle mode.

5.1.3 Determination of Total Throughput

We conduct our simulation for two types of antenna configurations, $M = 4$ and $M = 8$. We consider the simulation time of a WLAN instance to be 100 s. We set the downlink access probability, $p_a = Np$. The total number of successful DATA packet reception by the AP is calculated at the end of all instances and the total throughput of the users in uplink is computed as $\frac{N_{pk}\Phi RL_{dt}}{T_{sm}}$ where T_{sm} is the total number of simulation time and N_{up} is the total number of the packets received by the AP. For downlink, the total number of the successful DATA packet, transmitted by the AP is also calculated at the end of all instances and the total throughput is computed as $\frac{N_{dn}\Phi RL_{dt}}{T_{sm}}$ where N_{dn} is the total number of the packets sent by the AP.

5.1.4 Validation of Model

Fig. 5.1 to Fig. 5.5 show the comparison between simulated and analytical results for different wireless channel parameters. The abbreviations “ana” , “simu”, “up” and “dn” in the figures stand for analytical result, simulated result, uplink and downlink respectively. From all these figures, it is evident that the simulated results are well fitted with the analytical results for different configurations of the wireless channel. We also observe the performance of the proposed protocol for different configurations of the wireless channel. It is found that the maximum percentage difference between analytical and simulation results for all considered configurations are below 2% and 6% for $M = 4$ and $M = 8$, respectively. The possible reason for this difference is due to the fact that, we do not consider about SIFS time in analytical analysis but in simulation, SIFS time has been taken into account. Hence, the simulated result validates the model developed analytically in this work.

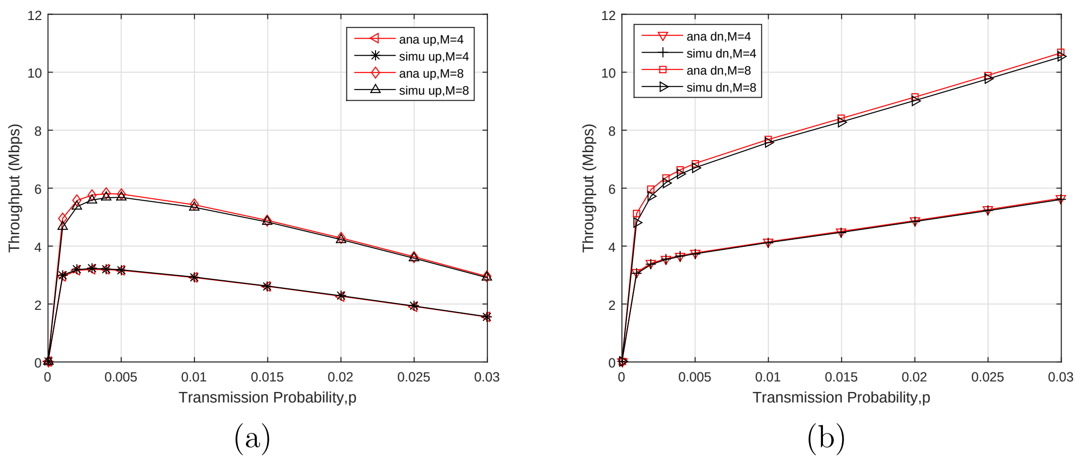
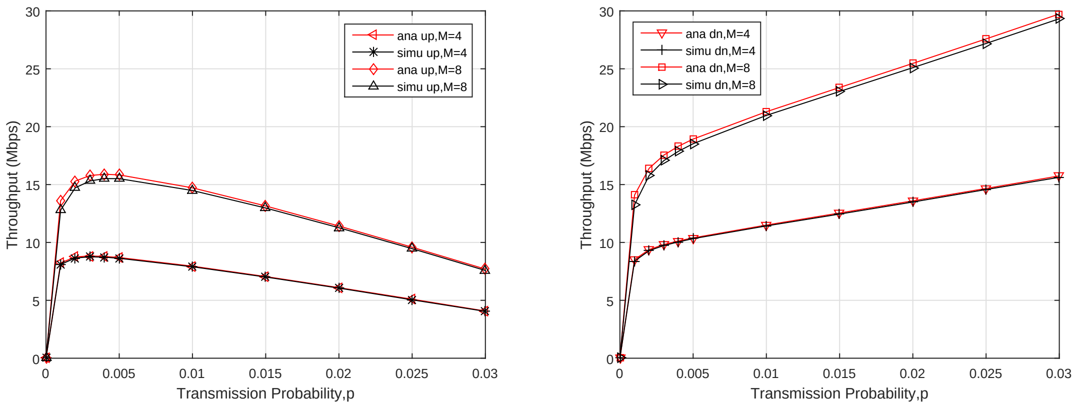


Figure 5.1: (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 6.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$.

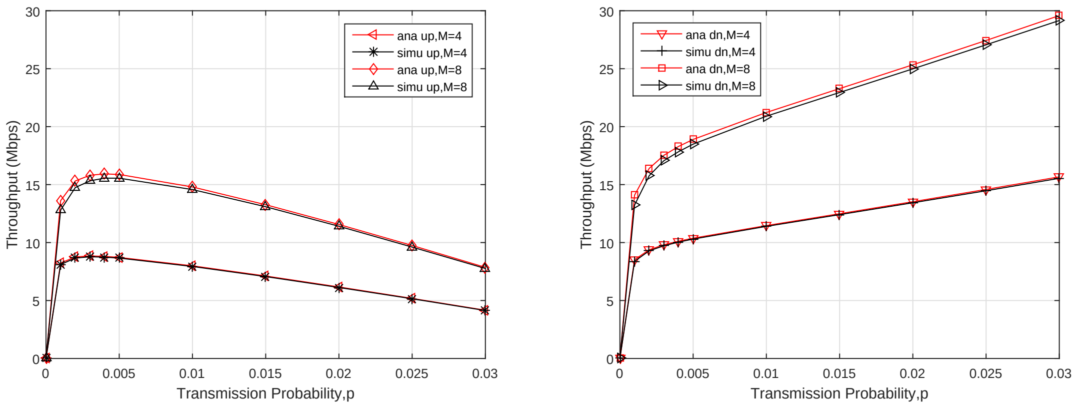
5.1.5 Effect of Transmission Probability

It is illustrated in Fig. 5.1 to Fig. 5.5 that after a certain value of p, the throughput for uplink decreases and on the other hand, the throughput for downlink is incremental in nature. We define this value of p as optimum transmission probability,



(a) (b)

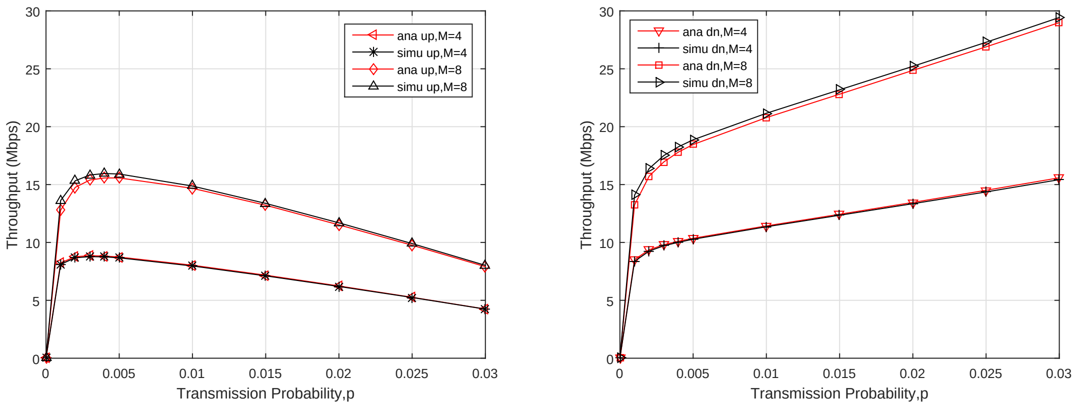
Figure 5.2: (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 9.4dB$ and $\sigma = 0dB$ for $M = 4$ and $M = 8$.



(a) (b)

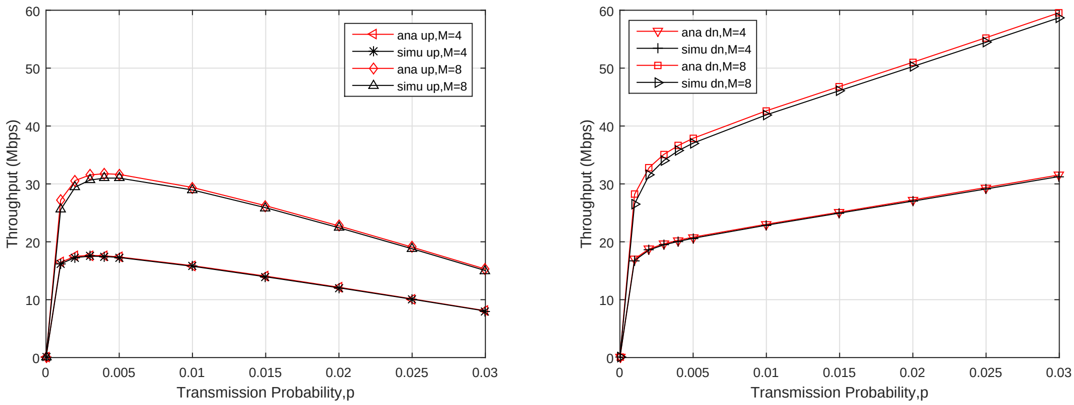
Figure 5.3: (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$.

$p_{optimal}$. At this transmission probability, maximum throughput is found for uplink. After optimum transmission probability, the collision between users will be increased with increase in p, so the time needed for accumulating M RTS packets increases in uplink phase which results in the decrease of throughput. Besides, throughput is increased after $p_{optimal}$ in downlink. The possible reason for this nature is that the probability for accessing medium for the AP, p_a is N times higher than p. For this reason, the AP can access more to the channel with higher probability. Moreover, the probability of receiving D-RTS packet by the M users successfully is high due to the absence of interference.



(a) (b)

Figure 5.4: (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 9.4dB$ and $\sigma = 10dB$ for $M = 4$ and $M = 8$.



(a) (b)

Figure 5.5: (a) Uplink and (b) Downlink throughput comparison between the analytical and simulation results with $\beta = 12.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$.

5.2 Summary

The verification process is needed to validate our analytical model. For that purpose, we have to compare the results from analytical analysis with simulation results. We have built a custom simulator written in MATLAB for achieving simulation results. We choose MATLAB due to its flexibility for configuring WLAN and channel parameters. Comparison of throughput between simulation and analytical results for different wireless configurations depict the validation of our analytical model. Results show that the uplink throughput has the highest value in optimum transmission probability. After that transmission probability, throughput is decreased due to the increase of collisions between the users. On the other hand, the downlink throughput is increased after the optimum transmission probability because the AP can access more to the channel due to higher transmission probability. Additionally, the success for D-RTS transmission by the AP is high because of the absence of interference.

Chapter 6

Performance Analysis of Proposed MAC Protocol

In this chapter, we compare the performances of the proposed protocol with CSMA RTS/CTS MU-MIMO and Uni-MUMAC protocol to find out different insights of the proposed protocol on basis of different wireless and network parameters.

6.1 Description of the Baseline MAC and Uni-MUMAC Protocol

We observe the throughput performance of the proposed protocol compared with and Uni-MUMAC protocol to realize the improvements made by the proposed MAC protocol. CSMA RTS/CTS MU-MIMO protocol is considered as the baseline protocol in this thesis work. Here, these protocols are described below in brief.

6.1.1 Baseline MAC Protocol

In the baseline protocol, an idle node senses the medium in each mini-slot. If a node finds the medium as free, it accesses the medium with same probability as in the proposed MAC protocol. In uplink, when the number of the RTS transmitting users is less than or equal to M, the AP selects all RTS packet transmitted users to send a common CTS packet. Because we consider employment of MIMO technique in receiving RTS packets by using ZF decoder so that the AP can easily receive them successfully. But if the number of the RTS transmitting users are greater than M, the AP calculates SINR of the M strongest signals considering the other signals as interference. If the SINR of a RTS packet is higher than the threshold β, the RTS packet is considered as successful. The AP then transmits a common CTS packet to the users from which it successfully receives RTS packet(s). A common CTS packet received users send DATA packet and after receiving them, the AP transmits a common ACK packet to notify the users. When the AP gets the access to the channel, the “downlink process” is started which is same as in the proposed MAC protocol except the ACK packets are transmitted in different time for notifying the AP about DATA packet reception.

6.1.2 Uni-MUMAC Protocol

In this protocol, all the idle nodes are sensing the channel to access. According to this protocol, users selection are completed within two contention rounds in uplink phase. If any user wins in the 1st contention round by sending RTS packet successfully to the AP, the AP broadcasts an Ant-CTS packet. The functions of the Ant-CTS packet are to inform the user about the successful reception of the RTS packet and to notify other users about the number of available antennas at the AP. This packet also indicates the beginning of 2nd contention round. In the 2nd contention round, users participate in the contention which have packets to send. The AP sends notification packet only once after receiving first RTS packet successfully. After that, the AP does not send any more notification packet to inform users about the successful reception of RTS packets. After accumulating M RTS packets, the AP transmits a G-CTS packet for starting DATA packet transmission by the RTS transmitted users. If the AP cannot receive a RTS packet from any user, the AP will not start the 2nd contention round. Then users again try to access the channel for transmitting RTS packets. When the AP gets the access, the “downlink process” is initiated which is also similar as in our proposed MAC protocol.

6.2 Advantages of the Proposed Protocol

MATLAB is again used to develop the simulator for both the baseline and Uni-MUMAC protocol, with the same parameters used in the simulator of the proposed protocol except $L_{RC} = 0$ and $L_{D-RTS} = L_{RTS}$ are considered. The process of accessing the medium for both users and the AP is same. Comparison of throughput performances between proposed, baseline and Uni-MUMAC protocols for both uplink and downlink transmissions are shown in Fig. 6.1 and 6.2 for $M = 4$ and $M = 8$, respectively.

The uplink throughput of Uni-MUMAC is higher than proposed protocol while baseline throughput is lower compared to the proposed one, as shown in Fig. 6.1(a) and 6.2(a). The throughput under the baseline protocol has a lower value than the proposed one in uplink because data reception of the AP is higher under the proposed protocol than the baseline one. This happens because the number of users sending

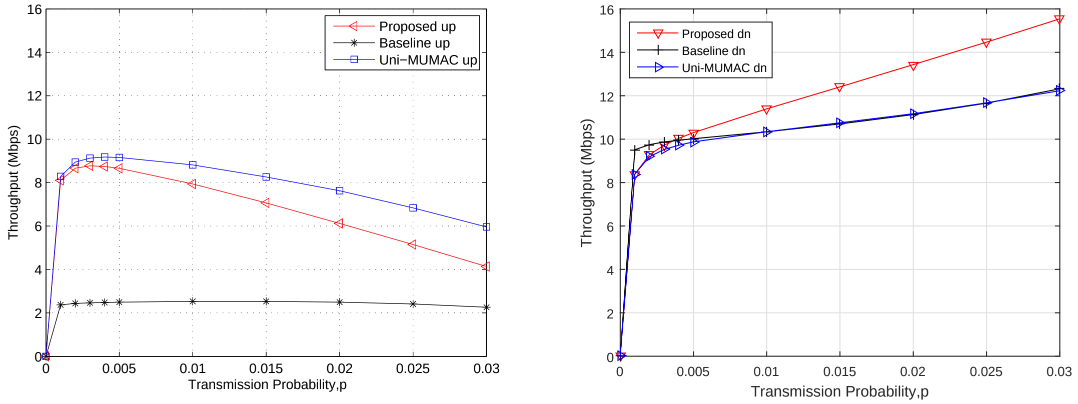
DATA packets to the AP may vary up to M according to the baseline protocol. On the contrary, according to our proposed protocol, M users send DATA packets to the AP every time. At lower transmission probability, the throughput in downlink under the baseline protocol is higher than the proposed protocol. The reduction of medium accessing time of the AP under the proposed protocol is responsible for that. It occurs because the AP has to wait for more time to collect M RTS packets due to the low participating rate of the users to transmit RTS packets. But the scenario is changed with the increase in transmission probability. For the case of Uni-MUMAC protocol, throughput in uplink is greater than the proposed protocol because of using RC packet by our proposed protocol to notify about the successful reception of RTS packet by the AP for each successful user. This increases overhead during the uplink transmission process. But in the case of Uni-MUMAC protocol, the AP stops sending the notification to the users after sending notification for first successful RTS reception.

It is clear from Fig. 6.1(b) and 6.2(b) that the downlink throughput of the proposed protocol is greater than the two other protocols. A significant difference between downlink throughputs is also created for higher transmission probabilities because the time needed to complete whole downlink phase under proposed protocol is less than the baseline protocol. The reason being that the ACK packets are sent from DATA packet recipient users together at the same time in proposed protocol whereas they are sent consecutively from DATA packet recipient users according to the baseline protocol. However, the throughput in downlink is lower than the proposed one because according to our protocol, the AP transmits DATA packets to the M users when it gets the access. This process is unaffected even if users get the access with the AP to the channel at the same time. But Uni-MUMAC protocol tackles this joint access issue by waiting for $M \times$ (one CTS packet time + one SIFS time) without any data transmission. This will lead to an increase in overhead of the system and decrease in the throughput.

Now, we want to observe the throughput improvement under the proposed MAC protocol with respect to the baseline MAC and Uni-MUMAC protocol based on *% Throughput Gain*. The percentage throughput gain of our proposed protocol compared to the baseline protocol which is defined as

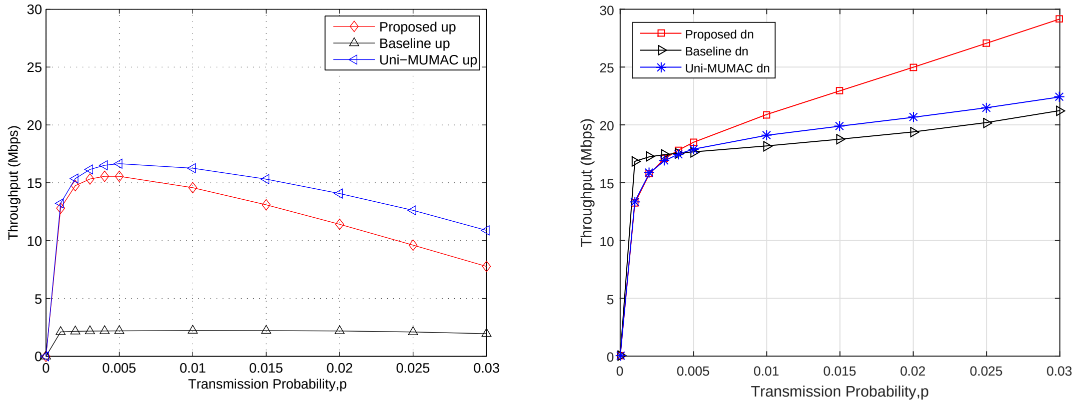
$$Gain_b = 100 \times \frac{\lambda_p - \lambda_b}{\lambda_b}$$

and the percentage throughput gain of our proposed protocol compared to Uni-



(a) (b)

Figure 6.1: (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocols with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$, when $p_a = Np$.



(a) (b)

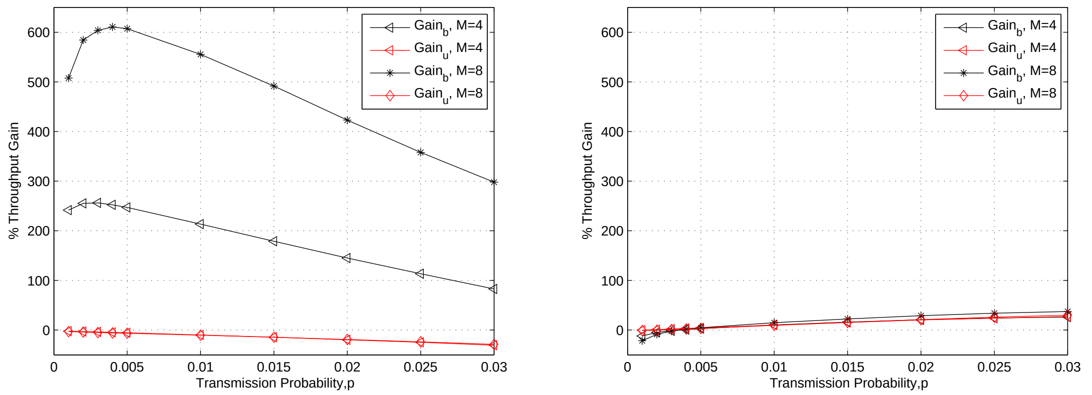
Figure 6.2: (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocols with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 8$, when $p_a = Np$.

MUMAC protocol is defined as

$$Gain_u = 100 \times \frac{\lambda_p - \lambda_u}{\lambda_u}$$

where, λ_p, λ_b and λ_u stands for the throughput under proposed, baseline and Uni-MUMAC protocols, respectively. These two gains are illustrated in Fig. 6.3 for both $M = 4$ and $M = 8$, respectively. From the Fig. 6.3(a), it is evident that the proposed MAC protocol provides a significant throughput gain compared to the baseline protocol in uplink and it is increased with increasing number of antennas. However, there is no improvement in uplink throughput under the proposed protocol compared to Uni-MUMAC protocol. Fig. 6.3(b) indicates that our proposed protocol improves the downlink throughput compared to both the baseline and Uni-

MUMAC protocols and the gains are increased with the increase of transmission probability. However, Fig. 6.4 depicts the percentage gains comparison for total throughput. From this figure, it is obvious that the proposed MAC protocol gives a significant throughput gain compared to the baseline protocol and a little improvement compared to the Uni-MUMAC protocol. Finally, the throughput gains are increased by increasing the number of antennas in the AP.



(a) (b)

Figure 6.3: Percentage gains comparison for (a) uplink and (b) downlink with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$, when $p_a = Np$.

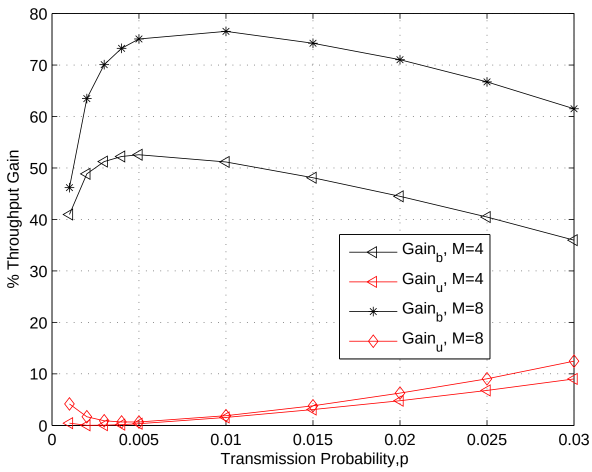
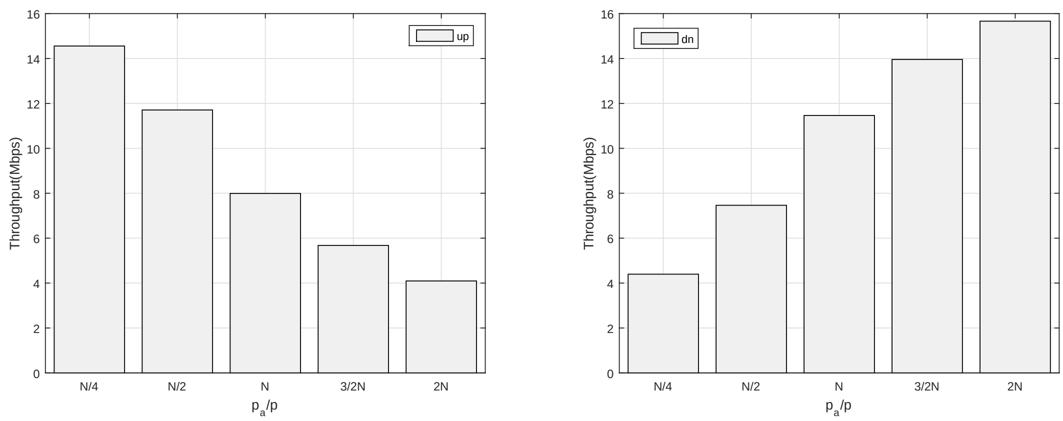


Figure 6.4: Percentage gains comparison for total throughput with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$, when $p_a = Np$.

6.2.1 Effect of Access probability

Fig. 6.5 depicts the effect of access probability on both uplink and downlink throughput for our proposed protocol. The throughput for uplink decreases with the increase of the access probability of the AP, which is shown in Fig. 6.5(a). On the other hand, it is clearly evident from Fig. 6.5(b) that with the increase of the access probability of the AP, the downlink throughput increases. It happens because the AP can access the channel more with increasing probability. So time staying in the downlink phase is increasing with the increase of access probability of the AP. For this reason, the time for staying in uplink phase is also decreasing so the uplink throughput is decreased because the users cannot access the channel more with lower probability compared to the AP. Furthermore, Fig. 6.6 shows the effect of access probability on both uplink and downlink throughputs for proposed, the baseline and Uni-MUMAC protocols when the AP accesses the medium with fixed probability. Here, the throughput of uplink increases with the increase in uplink access probability which is true for all these protocols, shown in Fig. 6.6(a). However, Fig. 6.6(b) shows that the throughput of downlink decreases for all protocols with increase in access probability of user. It happens because with fixed access probability of the AP, users can access more to the channel. So the time staying in uplink phase is increasing. For this reason, the downlink throughput is decreasing.

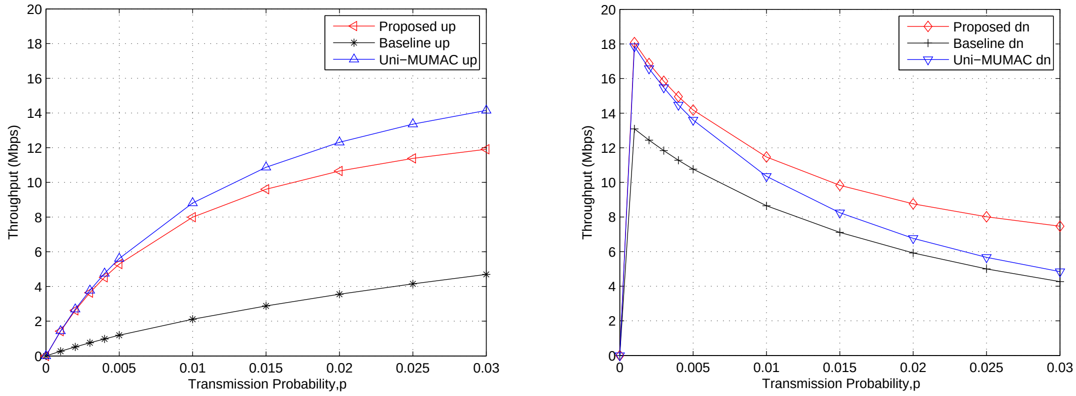


(a) (b)

Figure 6.5: Effect of access probability on (a) uplink and (b) downlink throughput under the proposed protocol for $\beta = 9.4dB$ and $\sigma = 6.4dB$ when $M = 4$.

6.2.2 Effect of Shadowing

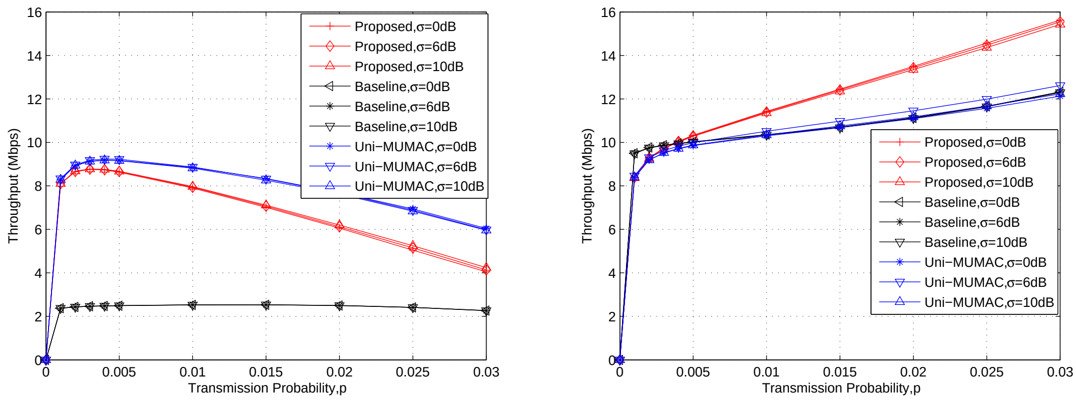
Fig. 6.7 represents the throughput performances for both uplink and downlink under proposed, baseline and Uni-MUMAC protocol for different values of σ with $M = 4$. There is minimal change in both uplink and downlink throughput for all three protocols for varying the values of σ as shown in Fig. 6.7 and their throughputs decrease with the increase of σ. The reason for showing a small change in uplink throughput under our proposed and Uni-MUMAC protocol due to shadowing is due to considering physical interference model to choose M users each time for data transmission. So these protocols select users with good SINR regardless of



(a) (b)

Figure 6.6: (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocol for $\beta = 9.4dB$ and $\sigma = 6.4dB$ when $M = 4$ and $p_a = 0.2$.

the condition of the users' signal affected due to shadowing. Uplink throughput under the baseline protocol also shows small change due to shadowing because we consider employing MIMO in RTS packets reception. Thus the AP can facilitate up to M users for sending DATA packets. Besides, physical interference model is applied when the RTS transmitting users are greater than M. But it is highly unlikely to have more than M RTS transmitting users due to lower transmission probability. The impact of the shadowing on uplink throughputs are shown in Fig. 6.7(a). For downlink case, the effect of shadowing on throughput is not significant for all protocols which is illustrated in Fig. 6.7(b) because of taking the account the absence of interference.

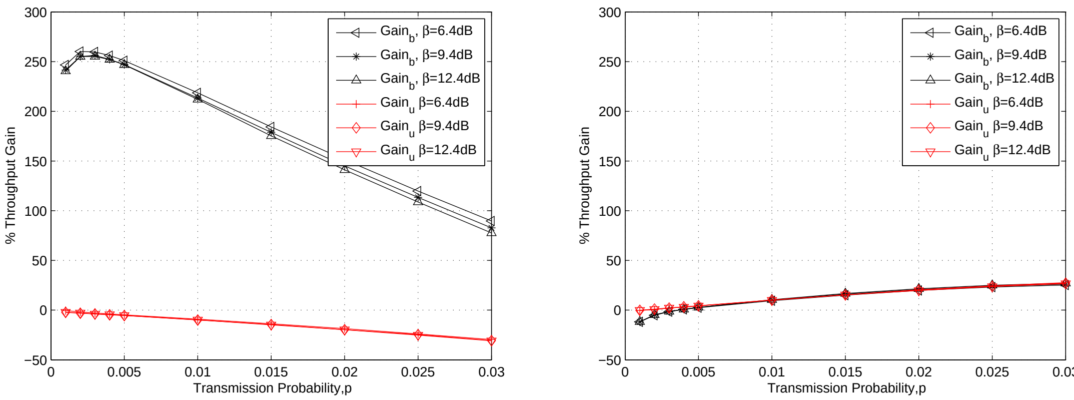


(a) (b)

Figure 6.7: (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocols with $\beta = 9.4dB$ and varying σ for $M = 4$, when $p_a = Np$.

6.2.3 Effect of Transmission Rate

The impacts of different transmission rate on throughputs for our proposed protocol with respect to the baseline and Uni-MUMAC protocol are illustrated in Fig. 6.8 for $M = 4$ through the percentage throughput gain. It is easy to infer from the figure that throughput gains compared to both baseline and Uni-MUMAC protocol exhibit decreasing nature when the transmission rate is changed from lower to a higher rate. With the increase of transmission rate, the SINR requirement is also increased. For this reason, the percentage throughput gains are reduced with the higher transmission rate.

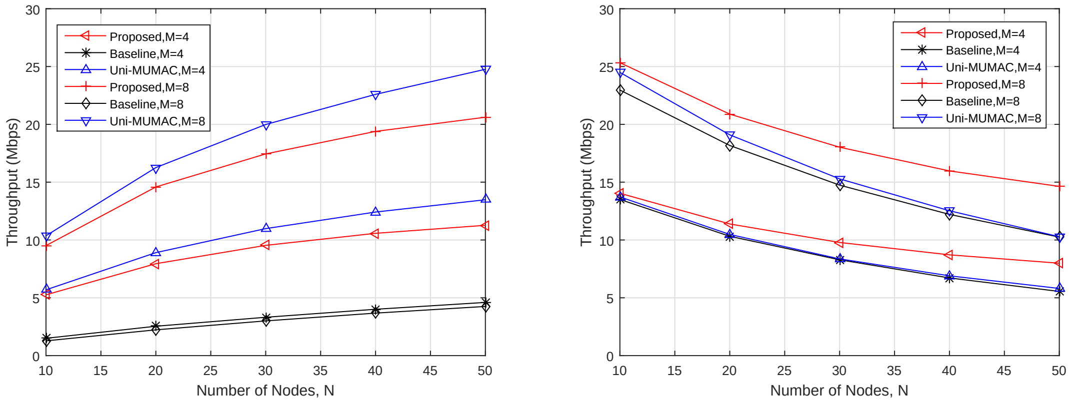


(a) (b)

Figure 6.8: Percentage gains comparison for (a) uplink and (b) downlink with $\sigma = 6dB$ and varying β for $M = 4$, when $p_a = Np$.

6.2.4 Effect of Number of Users

We calculate the throughput for both uplink and downlink of WLAN system by changing the number of users under the proposed, baseline and Uni-MUMAC protocols for both $M = 4$ and $M = 8$, respectively. The impact on throughput performance due to the change in the number of users in the system with fixed access probability for both the AP and the user is shown in Fig. 6.9. Fig. 6.9(a) indicates that with the increase in the number of users, the uplink throughput increases under all protocols. It occurs for both the proposed and Uni-MUMAC protocol because the time taken by the AP to gather M successful RTS transmitted users is increasing with the increase of the number of users in WLANs. The level of interference is increasing because collisions between RTS transmitted users are increased due to the increase of participating users in the contention. For the baseline protocol, with increasing the number of users, the participation of users for transmitting RTS packets are also increasing in the contention although users try to access the channel with lower probability. Therefore, the uplink throughput under the baseline protocol is increasing. On the other hand, the downlink throughput decreases for all protocols with the increase in number of the users, which is shown in Fig. 6.9(b). It happens because the duration of the AP for staying in downlink phase is decreasing due to the fact that time taken by the AP for accumulating M RTS transmitted users is gradually increasing in uplink phase when the number of users is increasing. It is also revealed from Fig. 6.9 that with the increase of M, protocols exhibit higher throughputs when both the AP and the users access the channel with fixed probability.



(a) (b)

Figure 6.9: (a) Uplink and (b) Downlink throughput comparison of the proposed, baseline and Uni-MUMAC protocols with $\beta = 9.4dB$ and $\sigma = 6dB$ for $M = 4$ and $M = 8$, when $p = 0.01$ and $p_a = 0.2$.

6.3 Summary

In this chapter, the performance comparisons between the proposed, MU-MIMO CSMA based MAC and Uni-MUMAC protocols have been investigated to explore different insights of the proposed protocol. We have developed simulators for both baseline and Uni-MUMAC protocols in MATLAB considering almost the same settings as used in the simulator of proposed protocol to find out necessary results. It is significant from the results that the throughput of the proposed protocol is remarkably higher than the baseline protocol and also the throughput is increased with the increase of M. Moreover, the proposed protocol provides better throughput compared to the Uni-MUMAC protocol. The performance of the proposed protocol is also compared as well as analyzed based on different shadowing power, data transmission rate and numbers of users and found interesting insights from this comparison. The impact of shadowing on both uplink and downlink throughput under all three protocols are not significant. For the increase in transmission rate, throughput gains of the proposed protocol are decreased compared to both baseline and Uni-MUMAC protocol because of increasing SINR threshold. Furthermore, the uplink throughput for all protocols exhibits increasing nature with the increase in number of users while their downlink throughputs are decreasing. Moreover, when both the AP and the users access the channel with fixed probability, both throughputs are also increased with the increase of M.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

In this thesis, the CSMA-based MAC protocols using MU-MIMO technique are studied. The conventional CSMA/CA MAC protocol has a weakness of not utilizing all the antennas for uplink transmission due to random access nature of the users. In our work, we have presented a MAC protocol which addresses this issue by utilizing additional control frames and results better utilization of all the available resources. In the proposed MAC protocol, multiple contention rounds in uplink and simultaneous multi-packet transmissions in downlink are considered to explore the benefits of MU-MIMO technique. There are a few proposals of random access based MAC protocols where both uplink and downlink transmissions are considered. These proposals have a major limitation in addressing the case when both the AP and the users access the channel simultaneously which causes performance degradation. Our protocol has addressed this issue by modifying the control frames.

We have modeled the proposed MAC protocol of the WLAN system as a discrete time Markov chain. We have developed an analytical model for determining the throughput of the users and the AP with considering path loss, fading and shadowing under physical interference model. Note that the physical interference model is not considered in throughput analysis of the most of the protocols proposed in the literature. Additionally, fading, shadowing and path loss are the most important characteristics of a wireless channel which are not considered in throughput analysis of MU-MIMO WLANs. So our analysis becomes more realistic due to the consideration of physical interference model as well as important wireless channel characteristics.

Throughputs under all three (CSMA/CA, Uni-MUMAC and proposed) MAC protocols are determined with the help of simulators written in MATLAB tool. The developed analytical model under the proposed protocol is verified by comparing analytical and simulation results. By means of analytical and simulation results, it is illustrated that the throughput of the proposed protocol is remarkably higher than the traditional CSMA/CA MAC protocol. Further, our proposed protocol provides better throughput than the Uni-MUMAC protocol.

We have studied the effect of variations of some channel and network parameters on the performance of the proposed MAC protocol. We have found that the uplink and downlink throughputs under the proposed protocol have little change with the variation of shadowing. However, throughput gains decrease with the increase of data transmission rate for increasing SINR threshold. We have also found that the uplink throughput increases and the downlink throughput decreases for increasing the number of users.

7.2 Future Work

In this thesis, we have focused on designing a MU-MIMO supported MAC protocol and developed an analytical model for determining the throughput of the users and the AP of a WLAN. There are several future research scopes worthy for the further investigation related to this thesis. They are as follows:

(i) Performance analysis through practical implementation of the proposed protocol can be carried out. Hardware implementation is one of the major concern for that. Another important concern is CSI acquisition for achieving the knowledge of channel states. Besides, the study for gaining backward compatibility of the proposed protocol needs to be performed to co-exist with legacy IEEE 802.11 WLAN systems.

(ii) Delay, fairness, and energy consumption are regarded as vital performance metrics in any wireless network. Delay is the time of arrival of a packet successfully at a node while fairness calculates the fair proportion of available system resources among users. Besides, the total energy consumption in wireless networks is rising at an incredible rate for rapid growth of modern communication technologies. Thus, these performance metrics under the proposed protocol can also be studied in MU-MIMO WLANs.

(iii) IEEE 802.11 based MAC protocols utilize multiple transmission rates dynamically based on current wireless channel conditions. We have considered a single rate system throughout this thesis. So the performance of proposed protocol can also be investigated for multi-rate WLAN systems.

(iv) Some MAC protocols use multiple channels along with multiple transmission rates in WLANs. In the thesis, we consider that both the AP and the users share a single channel. Thus our proposed protocol may be extended for the multi-channel system and the behavior of the modified protocol can also be studied.

(v) The performance of our proposed protocol can be observed for the multi-hop system. Routing and power allocation for the users need to be addressed under the proposed protocol to cope up with the multi-hop system. Joint design of the physical, medium access and network layers of a wireless network can also be considered to investigate the performance improvement under the proposed protocol.

(vi) We use ZF scheme for both pre-coding and decoding purpose. Perhaps, different types of pre-coding/decoding schemes like MMSE, SIC, and BD can be employed to explore the performance variation of the proposed protocol.

(vii) The network traffic is assumed to be saturated for modeling the throughput and all the performance studies consider the saturation condition. Therefore, the performance of the proposed protocol can be investigated for the non-saturated condition. Nowadays, the demand for uplink throughput is escalating in amazing rate with the increase of using cloud-based applications. Hence, the configurations of the medium access rate of the AP and the users for balanced uplink and downlink traffic under the proposed protocol can be analyzed.

Bibiliography

[1] Cisco, "The Zettabyte Era-Trends and Analysis," in *Cisco White Paper*, pp. 1-36, July 2016.

[2] IEEE 802.11ay, "Enhanced Throughput for Operation in License-Exempt Bands above 45 GHz." http://www.ieee802.org/11/Reports/tgay_update.htm.[Accessed 15 December 2016].

[3] IEEE 802.11ad, "Very High Throughput in 60 GHz." http://www:ieee802:org/11/Reports/tgad_update:htm.[Accessed 15 December 2016].

[4] Marsic, I., "Wireless Networks: Local and Ad Hoc Networks" in 2005, Rutgers University.

[5] http://wifinotes.com/wlan-architecture.html[Accessed 15 December 2016].

[6] "Definition, advantages and disadvantages of WLAN," http://net-cybercrime.blogspot.com.ng/2013/05/definition-advantages-and-disadvantages_9837.html[Accessed 15 December 2016].

[7] Corazza, G., "Digital Satellite Communications," 2007, Springer-Verlag.

[8] Brenner, P., "A Technical Tutorial on the IEEE 802.11 Protocol," Tech. rep., 1997.

[9] Chen, Y., and D. P. Agrawal, "Effect of Contention Window on the Performance of IEEE 802.11 WLANs," in *Proceedings of 3rd Annual Mediterranean Ad Hoc Networking Workshop*, June 27-30, 2004.

[10] Sweedy, A. M., Semeia, A. I., Sayed, S. Y., and Konber, A. H., "The effect of frame length fragmentation and RTS/CTS mechanism on IEEE 802.11 MAC performance," in *10th international conference on intelligent systems design and applications*, pp. 1338-1344, 2010.

[11] Raoof, K., Khalighi, M., and Prayongpun, N., "MIMO systems: Principles, iterative techniques and advanced polarization," in *Adaptive Signal Processing for Wireless Communication*, CRC Press, vol. 2, pp. 95-134, Aug. 2008.

[12] IEEE Std. 802.11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specification," *IEEE, New York, USA*, Nov. 1997.

[13] "IEEE Draft Standard for Information Technology–LAN/MAN–Part 11: Wireless LAN Medium Access Control and Physical Layer Specifications–Amendment: Enhancements for Very High Throughput for Operation in Bands Below 6GHz," *IEEE P802.11ac/D6.0*, pp. 1-446, 2013.

[14] Gesbert, D. , Kountouris, M., Heath Jr.,R. W., Chae, C. B. , and Salzer, S. T., "From single user to multiuser communications: Shifting the MIMO paradigm," *IEEE Sig. Proc. Mag.*, 24(5), pp. 36-46, Oct. 2007.

[15] Liao, R., Bellalta, B., Oliver, M., and Niu., Z.,"MU-MIMO MAC Protocols for Wireless Local Area Networks: A Survey" *IEEE Communications Surveys and Tutorials.*, 2014.

[16] Goldsmith, A., "Wireless Communications" *Cambridge University Press*, New York, USA,2005.

[17] Mostofi, Y., "Compressive Cooperative Sensing and Mapping in Mobile Networks," in *IEEE Transactions on Mobile Computing*, vol. 10, no. 12, pp. 1769-1784, December 2011.

[18] "Chapter 1," `http://www.skydsp.com/publications/4thyrthesis/chapter1.htm`[Accessed 15 December 2016].

[19] `http://old.elmag.org/en/propagation-modeling-of-shadowing-by-vegetation-for-mobile-satcom-%26-satnav-systems`[Accessed 15 December 2016].

[20] Bianchi, G., "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, 2000.

[21] Iyer, A., Rosenberg, C., and Karnik, A., "What is the right model for wireless channel interference?" *IEEE/ACM Trans. on Netw.*, vol. 8, no. 5, May 2009.

[22] "The ns2 network simulator," [online]. Available: `www.isi.edu/nsnam/ns/`

[23] Gupta P., and Kumar, P. R., "The capacity of wireless networks," *IEEE Trans. Inform. Theory*, vol. IT-46, no. 2, pp. 388-404, Mar. 2000.

[24] Chowdhury, M. M. U., Tanveer, M. A., and Uddin, M. F., "Performance analysis of CSMA/CA based MU-MIMO WLANs," in *Proc. International Conference on Electrical and Computer Engineering (ICECE)*, 2014.

[25] Barghi, S., Jafarkhani, H., and Yousefi'zadeh, H., "MIMO-assisted MPR-aware MAC design for asynchronous WLANs," *IEEE/ACM Transactions on Networking*, vol. 19, no. 6, pp. 1652–1665, 2011.

[26] Zheng, P.X., Zhang, Y.J., and Liew, S.C., "Multipacket Reception in Wireless Local Area Networks," in *IEEE International Conference on Communications,*pp. 3670-3675, 2006.

[27] Liao, R., Bellalta, B., and Oliver, M., "DCF/USDMA: Enhanced DCF for uplink SDMA transmissions in WLANs," *8th International Wireless Communications and Mobile Computing Conference (IWCMC)*, Limassol, pp. 263-268, 2012.

[28] Zhang, Y. J., "Multi-round contention in wireless LANs with multipacket reception," *IEEE Transactions on Wireless Communications*, vol. 9, pp. 1503–1513, Apr. 2010.

[29] Zhou, S. and Niu, Z., "Distributed Medium Access Control with SDMA Support for WLANs," *IEICE Transactions*, vol. 93-B, no. 4, pp. 961–970, 2010.

[30] Cai, L. X., Shan,H., Zhuang, W., Shen,X., Mark,J. W., and Wang,Z., "A Distributed Multi-User MIMO MAC Protocol for Wireless Local Area Networks," in *GLOBECOM*, pp. 4976–4980, 2008.

[31] Kartsakli,E., Zorba,N., Alonso,L., and Verikoukis, C. V.,"Multiuser MAC Protocols for 802.11n Wireless Networks," in *ICC*, pp. 1–5, 2009.

[32] Liao,R., Bellalta,B., Cano,C., and Oliver,M., "DCF/DSDMA: Enhanced DCF with SDMA Downlink Transmissions for WLANs," in *BCFIC*, pp. 96–102, 2011.

[33] Bellalta,B. , Barcelo, J., Staehle,D., Vinel,A., and Oliver,M.,"On the performance of packet aggregation in IEEE 802.11 ac MU-MIMO WLANs," *IEEE Communications Letters*, vol. 16, no. 10, pp. 1588-1591, 2012.

[34] Zhao,M., Ma,M., and Yang,Y., "Applying opportunistic medium access and multiuser MIMO techniques in multi-channel multi-radio WLANs," *Mobile Networks and Applications*, vol. 14, no. 4, pp. 486-507, 2009.

[35] Li,H., Attar,A., and Leung, V. C. M., "Multi-User Medium Access Control in Wireless Local Area Network," in *WCNC*, pp. 1–6, 2010.

[36] Kim, T.H., and Vaidya,N.H., “MAC Protocol Design for Multiuser MIMO Wireless Networks,” *Technical Reports, The University of Illinois at Urbana-Champaign*, pp. 1-8, 2008.

[37] Yun,S., Qiu,L., and Bhartia,A., “Multi-point to multi-point MIMO in wireless LANs,” in *INFOCOM*, pp. 125-129, 2013.

[38] Liao,R., Bellalta,B., Minh,T. C., Barcelo,J., and Oliver,M., “Uni-MUMAC: A Unified Down/Up-link MU-MIMO MAC Protocol for IEEE 802.11 ac WLANs,” in *Wireless Networks*, Volume 21, Issue 5, pp 1457-1472, July 2015.

[39] Jin,H., Jung,B. C., Hwang,H. Y., and Sung,D. K., “Performance Comparison of Uplink WLANs with Single-User and Multi-User MIMO Schemes,” in *WCNC*, pp. 1854-1859, 2008.

[40] Han,H., Pei,Z., Zhu, W., and Li,N., “Saturation Throughput Analysis of IEEE 802.11b DCF Considering Capture Effects,” in *8th International Conference on Wireless Communications, Networking and Mobile Computing*, Shanghai, pp. 1-4, 2012.

[41] Kumar, P., and Krishnan,A., “Throughput Analysis of the IEEE 802.11 Distributed Coordination Function Considering Capture Effects,” in *3rd International Conference on Emerging Trends in Engineering and Technology*, Goa, pp. 836-841, 2010.

[42] Jiang,L., and Walrand,J., “Approaching throughput-optimality in a distributed CSMA algorithm: collisions and stability,” *IEEE/ACM Trans. on Netw.*, vol. 19, no. 23, pp. 816-823, Jun. 2011.

[43] Ni, J., Tan,B., and Srikant,R., “Q-CSMA: Queue length-based CSMA/CA algorithms for achieving maximum throughput and low delay in wireless networks,” *Proc.IEEE INFOCOM Mini-Conf.*, pp. 1-5, 2010.

[44] Qian,D., Zheng,D., Zhang,J. , Shroff,N. B., and Joo,C., “Distributed CSMA algorithms for link scheduling in multihop MIMO networks under SINR model,” *IEEE/ACM Trans. Netw.*, vol. 21, no. 3, pp. 746-759, 2013.

[45] Hadzi-Velkov,Z., Spasenovski,B., “Capture effect in IEEE 802.11 basic service area under influence of rayleigh fading and near/far effect,” *IEEE Personal Indoor and Mobile Radio Communications Symposium*, pp. 172-176, 2002.

[46] Kim,J. H., and Lee,J. K., “Capture effects of wirelss CSMA/CA protocols in Rayleigh and shadow fading channels,” *IEEE Trans. Veh. Technol.*, vol. 48, pp. 1277-1286, 1999.

[47] Li,X., and Zeng,Q.,"Performance analysis of the IEEE 802.11 MAC protocols over a WLAN with capture effct,"*Information and Media Technologies 1*, pp. 679-685, 2006.

[48] Babich,F., and Comisso,M., "Theoretical analysis of asynchronous multi-packet reception in 802.11 networks," in IEEE Transactions on Communications, vol. 58, no. 6, pp. 1782-1794, June 2010.

[49] Wu,S., Mao,W., and Wang,X., "Performance Study on a CSMA/CA-Based MAC Protocol for Multi-User MIMO Wireless LANs," in *IEEE Transactions on Wireless Communications*, vol. 13, no. 6, pp. 3153-3166, June 2014.

[50] Wang,C., Au,E. K., Murch,R. D., Mow, W. H., Cheng,R. S., and Lau,V., "On the performance of the MIMO zero-forcing receiver in the presence of channel estimation error," *IEEE Transactions on Wireless Communications*, vol. 6, no. 3, pp. 805-810, 2007.

[51] Cha,J., Jin,H., Jung,B. C. , and Sung,D. K., "Performance Comparison of Downlink User Multiplexing Schemes in IEEE 802.11ac: Multi-user MIMO vs. Frame Aggregation," in *WCNC*, pp. 1514-1519, 2012.

[52] Jin,H., Jung,B. C., Hwang,H. Y., and Sung,D. K., "A Throughput Balancing Problem between Uplink and Downlink in Multi-user MIMO-Based WLAN Systems," in *IEEE Wireless Communications and Networking Conference*, Budapest, pp. 1-6 , 2009.

[53] Jin,H., Jung,B. C., and Sung,D. K., "A Tradeoff Between Single-User and Multi-User MIMO Schemes in Multi-Rate Uplink WLANs," in *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3332-3342, October 2011.

[54] Uddin,M. F., Rosenberg,C., Zhuang, W., Mitran,P., and Girard, A., "Joint Routing and medium access control in fixed random access wireless multihop networks," *IEEE/ACM Trans. on Netw.*, vol. 22, no. 1, Feb. 2014.

[55] Aboul-Magd,O., Kwon,U., Kim,Y., and Zhu,C., "Managing downlink multi-user MIMO transmission using group membership," in *IEEE 10th Consumer Communications and Networking Conference (CCNC)*, Las Vegas, NV, pp. 370-375, 2013.

[56] Rao,S. S.,"Applied numerical methods for engineers and scientists," Prantice Hall, pp. 588-605, 2002.

Appendix A

Computation of $\psi(S_0)$

We can obtain the expression in (A.1) due to the fact that $\sum_s \psi(s) = 1$. We observe from the transition probabilities of Table I and Table II that the steady state probabilities of all the sates are equal for (i) transmitting RTS packets by a set of users or receiving D-RTS packet by a set of users, (ii) receiving RC packet by a user, (iii) transmitting CTS packets by a set of users, (iv) transmitting DATA packets to a set of users or receiving DATA packets from a set of users and (v) receiving ACK packets from a set of users.

Based on the above information, equation (A.1) can be expressed as equation (A.2). By using equations (4.10), (4.13), (4.18)-(4.20), (4.23)-(4.32), equation (A.2) can be written as equation (A.3). After some mathematical manipulation, we can get equation (A.4) from equation (A.3). We can express equation (A.4) into equation (A.5) by using the facts $P_1^s + P_2^{cp} = 1$ and $P_3^s + P_2^s = 1$ (from Fig. 4.3). If $N \gg M$ and p is small, then $K_N \approx K_{N-1} \approx K_{N-2}$ and $(1-p)^N \approx (1-p)^{N-1} \approx (1-p)^{N-2}$. Moreover, we find out $P_1^{cp}\{3-2P_1^s-P_2^s+P_1^sP_2^s\} \approx 3$ and $P_1^{cp}\{P_1^s+P_2^{cp}(P_2^s+P_3^s)\} \approx 1$ [See Appendix B]. By using the above mentioned facts, equation (A.5) can be expressed as (A.6) and after some arrangements equation (A.6) will be like equation (A.7). Now, for general case, the expression of $\psi(S_0)$ can be written as equation (4.37) from equation (A.7).

$$
\begin{aligned}
&\psi(S_0) + \sum_{\forall m \in \mathcal{P}'(\mathcal{N}),\ \forall l \in \mathcal{L}_{RTS}} \psi(RT_m, l) + \sum_{\forall d \in \mathcal{N}, l \in \mathcal{L}_{RC}} \psi(S_d, l) + \sum_{\forall d \in \mathcal{N}} \psi(S_d) + \\
&\sum_{\forall d \in \mathcal{N}, \forall n \in \mathcal{P}'(\mathcal{N} \setminus d),\ \forall l \in \mathcal{L}_{RTS}} \psi(S_d, RT_n, l) + \sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d, \forall l \in \mathcal{L}_{RC}} \psi(S_{d,e}, l) + \sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d} \psi(S_{d,e}) \\
&+ \sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d, \forall k \in \mathcal{P}'(\mathcal{N} \setminus \{d,e\}), \forall l \in \mathcal{L}_{RTS}} \psi(S_{d,e}, RT_k, l) + \sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d, \forall f \in \mathcal{N} \setminus \{d,e\}, \forall l \in \mathcal{L}_{RC}} \psi(S_{d,e,f}, l) \\
&+ \sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d, \forall f \in \mathcal{N} \setminus \{d,e\}, \forall l \in \mathcal{L}_{DT}} \psi(S_{d,e,f}, DT_{d,e,f}, l) + \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\},\ \forall l \in \mathcal{L}_{D-RTS}} \\
&\psi(RT_{d',e',f'}, l) + \sum_{\forall d' \in \mathcal{N},\ \forall l \in \mathcal{L}_{CTS}} \psi(S_{d'}, l) + \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d',\ \forall l \in \mathcal{L}_{CTS}} \psi(S_{d',e'}, l) + \\
&\sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\},\ \forall l \in \mathcal{L}_{CTS}} \psi(S_{d',e',f'}, l) + \sum_{\forall d' \in \mathcal{N},\ \forall l \in \mathcal{L}_{DT'}} \psi(S_{d'}, DT'_{d'}, l) + \\
&\sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d',\ \forall l \in \mathcal{L}_{DT'}} \psi(S_{d',e'}, DT'_{d',e'}, l) + \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\},\ \forall l \in \mathcal{L}_{DT'}} \\
&\psi(S_{d',e',f'}, DT'_{d',e',f'}, l) = 1.
\end{aligned} \tag{A.1}
$$

$$
\begin{aligned}
&\psi(S_0) + L_{RTS} \sum_{\forall m \in \mathcal{P}'(\mathcal{N})} \psi(RT_m, 1) + L_{RC} \sum_{\forall d \in \mathcal{N}} \psi(S_d, 1) + \sum_{\forall d \in \mathcal{N}} \psi(S_d) + L_{RTS} \\
&\sum_{\forall d \in \mathcal{N}, \forall n \in \mathcal{P}'(\mathcal{N} \setminus d)} \psi(S_d, RT_n, 1) + L_{RC} \sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d} \psi(S_{d,e}, 1) + \sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d} \psi(S_{d,e}) + L_{RTS} \\
&\sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d, \forall k \in \mathcal{P}'(\mathcal{N} \setminus \{d,e\})} \psi(S_{d,e}, RT_k, 1) + L_{RC} \sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d, \forall f \in \mathcal{N} \setminus \{d,e\}} \psi(S_{d,e,f}, 1) + L_{DT} \\
&\sum_{\forall d \in \mathcal{N}, \forall e \in \mathcal{N} \setminus d, \forall f \in \mathcal{N} \setminus \{d,e\}} \psi(S_{d,e,f}, DT_{d,e,f}, 1) + L_{D-RTS} \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\}} \psi(RT_{d',e',f'}, 1) \\
&+ L_{CTS} \sum_{\forall d' \in \mathcal{N}} \psi(S_{d'}, 1) + L_{CTS} \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d'} \psi(S_{d',e'}, 1) + L_{CTS} \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\}} \\
&\psi(S_{d',e',f'}, 1) + L_{DT'} \sum_{\forall d' \in \mathcal{N}} \psi(S_{d'}, DT'_{d'}, 1) + L_{DT'} \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d'} \psi(S_{d',e'}, DT'_{d',e'}, 1) \\
&+ L_{DT'} \sum_{\forall d' \in \mathcal{N}, \forall e' \in \mathcal{N} \setminus d', \forall f' \in \mathcal{N} \setminus \{d', e'\}} \psi(S_{d',e',f'}, DT'_{d',e',f'}, 1) = 1.
\end{aligned} \tag{A.2}
$$

$$\psi(S_0) + L_{RTS}\psi(S_0)(1-p_a)[1-(1-p)^N] + L_{RC}\psi(S_0)(1-p_a)K_N + \frac{\psi(S_0)K_N(1-p_a)}{K_{N-1}}$$
$$+ L_{RTS}\frac{[1-(1-p)^{N-1}]\psi(S_0)K_N(1-p_a)}{K_{N-1}} + L_{RC}K_N\psi(S_0)(1-p_a) + \frac{\psi(S_0)K_N(1-p_a)}{K_{N-2}}$$
$$+ L_{RTS}\frac{[1-(1-p)^{N-2}]\psi(S_0)K_N(1-p_a)}{K_{N-2}} + (L_{RC}+L_{DT})K_N\psi(S_0)(1-p_a) + L_{D-RTS}$$
$$\psi(S_0)p_a + L_{CTS} + L_{CTS}\psi(S_0)p_aP_1^{cp}P_2^{cp} + (L_{CTS}+L_{DT'})\psi(S_0)p_a$$
$$P_1^{cp}P_2^{cp}P_3^{cp} + L_{DT'}\psi(S_0)p_aP_1^{cp}P_1^{s} + L_{DT'}\psi(S_0)p_aP_1^{cp}P_2^{cp}P_2^{s} = 1. \tag{A.3}$$

$$\psi(S_0)\Bigg[1 + L_{RTS}\{(1-p_a)[1-(1-p)^N] + \frac{[1-(1-p)^{N-1}]K_N(1-p_a)}{K_{N-1}}$$
$$+ \frac{[1-(1-p)^{N-2}]K_N(1-p_a)}{K_{N-2}}\} + 3L_{RC}(1-p_a)K_N + \frac{K_N(1-p_a)}{K_{N-1}} + \frac{K_N(1-p_a)}{K_{N-2}} +$$
$$L_{DT}K_N(1-p_a) + L_{CTS}p_aP_1^{cp}\{1 + P_2^{cp} + P_2^{cp}P_3^{cp}\} + L_{DT'}p_aP_1^{cp}$$
$$\{P_1^s + P_2^{cp}P_2^s + P_2^{cp}P_3^{cp}\} + p_aL_{D-RTS}\Bigg] = 1. \tag{A.4}$$

$$\psi(S_0)\Bigg[1 + L_{RTS}\{(1-p_a)[1-(1-p)^N] + p_a + \frac{[1-(1-p)^{N-1}]K_N(1-p_a)}{K_{N-1}}$$
$$+ \frac{[1-(1-p)^{N-2}]K_N(1-p_a)}{K_{N-2}}\} + 3L_{RC}(1-p_a)K_N + \frac{K_N(1-p_a)}{K_{N-1}} + \frac{K_N(1-p_a)}{K_{N-2}}$$
$$+ L_{DT}K_N(1-p_a) + L_{CTS}p_aP_1^{cp}\{3 - 2P_1^s - P_2^s + P_1^sP_2^s\} + L_{DT'}p_a$$
$$P_1^{cp}\{P_1^s + P_2^{cp}(P_2^s + P_3^{cp})\} + p_aL_{D-RTS}\Bigg] = 1. \tag{A.5}$$

$$\psi(S_0)\Bigg[3 - 2p_a + L_{RTS}\{3(1-p_a)[1-(1-p)^N] + 2p_a\} + 3L_{RC}(1-p_a)K_N +$$
$$L_{DT}K_N(1-p_a) + 3L_{CTS}p_a + L_{DT'}p_a + p_aL_{D-RTS}\Bigg] \approx 1. \tag{A.6}$$

$$\psi(S_0) \approx [3 - 2p_a + L_{RTS}\{3(1-p_a)[1-(1-p)^N] + 2p_a\} + (3L_{RC} + L_{DT})$$
$$(1-p_a)K_N + (3L_{CTS} + L_{DT'})p_a + p_aL_{D-RTS}\Bigg]^{-1}. \tag{A.7}$$

Appendix B

Computation of P_1^{cp}, P_2^{cp}, P_1^s, P_2^s and P_3^s

At first we need to find out the probability for one RTS reception is successful for calculating above mentioned probabilities. We assume that all links are independent. So the probability for receiving D-RTS packet successfully by the user d' can be calculated by using equation (4.9) as

$$\begin{aligned}
P_s &= P\left[\frac{P_r^{d'}}{N_o} > \beta\right] \\
&= P\left[P_r^{d'} > \beta N_o\right] \\
&= P\left[F_{d'}^2 e^{\xi_{d'}} \left(\frac{r_{d'}}{r_0}\right)^{-\eta} P_{tr} > \beta N_o\right] \\
&= P\left[F_{d'}^2 > \beta N_o e^{-\xi_{d'}} \left(\frac{r_{d'}}{r_0}\right)^{\eta} \frac{1}{P_{tr}}\right] \\
&= \int_{r=0}^{1} \int_{\xi=-\infty}^{\infty} cdf\left(\beta N_o e^{-\xi_{d'}} \left(\frac{r_{d'}}{r_0}\right)^{\eta} \frac{1}{P_{tr}}\right) f_\xi(\xi_{d'}) f_r(r_{d'}) dr_{d'} d\xi_{d'} \\
&= \int_{r=0}^{1} \int_{\xi=-\infty}^{\infty} \exp\left(-\left(\beta N_o e^{-\xi_{d'}} \left(\frac{r_{d'}}{r_0}\right)^{\eta} \frac{1}{P_{tr}}\right)^2\right) \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-\xi^2}{2\sigma^2}\right) 2r_{d'} dr_{d'} d\xi_{d'}.
\end{aligned} \tag{B.1}$$

Now, the probability for receiving D-RTS packet successfully by exactly one user can be found using as

$$\begin{aligned} P_1^s &= \binom{M}{1} P_s(1-P_s)^{M-1} \\ &= \binom{3}{1} P_s(1-P_s)^{3-1} \\ &= 3P_s(1-P_s)^2. \end{aligned} \tag{B.2}$$

The probability for receiving D-RTS packet successfully by exactly two users can be expressed as

$$\begin{aligned} P_2^s &= \binom{M}{2} P_s^2(1-P_s)^{M-2} \\ &= \binom{3}{2} P_s^2(1-P_s)^{3-2} \\ &= 3P_s^2(1-P_s). \end{aligned} \tag{B.3}$$

Besides, the probability for D-receiving RTS packet successfully by all three users can be obtained

$$\begin{aligned} P_3^s &= \binom{M}{3} P_s^3(1-P_s)^{M-3} \\ &= \binom{3}{3} P_s^3(1-P_s)^{3-3} \\ &= P_s^3. \end{aligned} \tag{B.4}$$

Now, the probability for receiving D-RTS packet successfully by at least one user can be expressed as

$$\begin{aligned} P_1^{cp} &= 1 - P\Big[No\ success\Big] \\ &= 1-(1-P_s)^M \\ &= 1-(1-P_s)^3. \end{aligned} \tag{B.5}$$

In addition, the probability for receiving D-RTS packet successfully by at least two user will be

$$\begin{aligned} P_2^{cp} &= 1 - P\Big[No\ success\Big] - P\Big[Exactly\ one\ RTS\ is\ successful\Big] \\ &= 1-(1-P_s)^M - \binom{M}{1} P_s(1-P_s)^{M-1} \\ &= 1-(1-P_s)^3 - \binom{3}{1} P_s(1-P_s)^{3-1} \\ &= 4P_s^2 - 2P_s^3. \end{aligned} \tag{B.6}$$

It is found that the value of P_s from equation (B.1) is close to unity. By observing equations (B.2)-(B.6), we find that the probabilities $P_1^s, P_2^s \ll 1$ while $P_1^s < P_2^s$, $P_3^s < P^s$, $P_3^s > P_2^s$, $P_1^{cp} \approx 1$ and $P_1^{cp} > P_2^{cp}$.

Now, the term $P_1^{cp}\{P_1^s + 2P_2^{cp}P_2^s + 3P_2^{cp}P_3^{cp}\}$ from equation (4.38) can be expressed using the fact $P_3^s + P_2^s = 1$ (from Fig. 4.3) as

$$\begin{aligned} P_1^{cp}\{P_1^s + 2P_2^{cp}P_2^s + 3P_2^{cp}P_3^{cp}\} &= P_1^{cp}\{P_1^s + P_2^{cp}(2P_2^s + 3P_3^{cp})\} \\ &= P_1^{cp}\{P_1^s + P_2^{cp}(2[1 - P_3^s] + 3P_3^{cp})\} \\ &= P_1^{cp}\{P_1^s + P_2^{cp}(2 + P_3^{cp})\}. \end{aligned} \tag{B.7}$$

By using the above mentioned information about the probabilities, we can write $\{P_1^s + P_2^{cp}(2 + P_3^{cp})\} \approx 3$. So the right side of equation (B.7) can be approximated by 3.

However, the term $P_1^{cp}\{3 - 2P_1^s - P_2^s + P_1^s P_2^s\}$ from equation (A.5) can be written by using the fact $P_3^s + P_2^s = 1$ (from Fig. 4.3) as

$$\begin{aligned} P_1^{cp}\{3 - 2P_1^s - P_2^s + P_1^s P_2^s\} &= P_1^{cp}\{3 - 2P_1^s + P_1^s(P_2^s - 1)\} \\ &\approx P_1^{cp}\{3 - 2P_1^s - P_2^s\} \\ &\approx P_1^{cp}\{3 - (2P_1^s + P_2^s)\}. \end{aligned} \tag{B.8}$$

Though $(2P_1^s + P_2^s) \ll 1$ so the right side of equation (B.8) can be approximated by 3.

Furthermore, the term $P_1^{cp}\{P_1^s + P_2^{cp}(P_2^s + P_3^s)\}$ from equation (A.5) can be can be approximated by 1 using the facts $P_1^s + P_2^{cp} = 1$ and $P_3^s + P_2^s = 1$ (from Fig. 4.3).