AN EFFICIENT CSMA/CA PROTOCOL FOR IEEE 802.11

ALI MUHAMMAD HUSSEIN ABBAS

MASTER OF COMPUTER SCIENCE

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

DECLARATION OF THESIS AND COPYRIGHT

Author's Full Name : ALI MUHAMMAD HUSSEIN ABBAS

Date of Birth : 14/03/1981

Title : An Efficient CSMA/CA Protocol for IEEE 802.11

Academic Session : SEM 2 2017/2018

I declare that this thesis is classified as:

☐ CONFIDENTIAL (Contains confidential information under the Official Secret Act 1997)*

☐ RESTRICTED (Contains restricted information as specified by the organization where research was done)*

☑ OPEN ACCESS I agree that my thesis to be published as online open access (Full Text)

I acknowledge that Universiti Malaysia Pahang reserves the following rights:

1. The Thesis is the Property of Universiti Malaysia Pahang
2. The Library of Universiti Malaysia Pahang has the right to make copies of the thesis for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by:

(Student's Signature)

A9996475
Date: JULY 2018

(Supervisor's Signature)

DR. MD. ARAFATUR RAHMAN
Date: JULY 2018

SUPERVISOR'S DECLARATION

I declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree in Master of Computer Science.

(Supervisor's Signature)

Full Name : Dr. MD. ARAFATUR RAHMAN

Position : SENIOR LECTURER

Date : JULY 2018

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : ALI MUHAMMAD HUSSEIN ABBAS

ID Number : MCC14003

Date : JULY 2018

AN EFFICIENT CSMA/CA PROTOCOL FOR IEEE 802.11

ALI MUHAMMAD HUSSEIN ABBAS

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Computer Science

Faculty of Computer Systems & Software Engineering

UNIVERSITI MALAYSIA PAHANG

JULY 2018

ACKNOWLEDGMENTS

Alhamdulillah, first of all, I wish to express my gratitude to Allah, for all the strengths and blessings to complete this thesis. I would like to thank my supervisor Dr. Md. Arafatur Rahman and co-supervisor Dr. Muamer N. Mohammed for their guidance and encouragement. It is a pleasure working with them. I would like to express my sincere gratitude to Universiti Malaysia Pahang (UMP) for providing consistent help and support. It is a wonderful place to work, and the staff is very dedicated and helpful. I have gained so much knowledge and experience from UMP. I would also like to thank the academic, management and technical staff of the Faculty of Computer Systems & Software Engineering (FSKKP) and the staff of Institute of Postgraduate Studies (IPS). Next, I would also like to express tremendous appreciation to my family, especially my mother, Saidyah Al-haj Abdrassul for their generous support in every way, which always been a source of energy and inspiration. Thanks to all my friends, colleagues, and all Malaysians for their openness, friendship, and hospitality. Finally, I would like to thank the Malaysia government for providing consistent services and security that helped to create a comfortable environment to study.

ABSTRAK

Sejak kewujudan mereka beberapa dekad yang lalu, WLAN telah disesuaikan untuk kemudahan mobiliti, dan ianya menjadi semakin popular di dunia. Piawaian yang paling penting dalam WLAN adalah IEEE 802.11. Piawaian ini memastikan yang tahap kesamaan peralatan yang digunakan, julat frekuensi yang lebih tinggi, teknik pengekodan cekap, dan kos rendah. Oleh itu, banyak kerja-kerja penyelidikan untuk penambahbaikan WLAN umumnya, berdasarkan ciri-ciri piawaian IEEE 802.11. Walau bagaimanapun, ia masih memberikan cabaran yang berkaitan dengan metrik prestasi seperti kadar perlanggaran, dan pemprosesan. Piawaian IEEE 802.11 adalah suatu set protokol bagi MAC dan spesifikasi lapisan fizikal untuk melaksanakan komunikasi komputer WLAN. CSMA / CA (protocol MAC) memainkan peranan yang penting dalam menyediakan medium penghantaran dan penghantaran data bagi stesen tanpa wayar. Oleh itu, penambahbaikan protokol CSMA / CA telah menjadi sangat penting untuk meningkatkan prestasi rangkaian IEEE 802.11, terutamanya apabila bilangan pengguna adalah tinggi. Oleh sebab itu, kerja penyelidikan ini adalah dikhususkan untuk menilai dan meningkatkan prestasi 802.11 dengan mencadangkan protokol MAC (CSMA / CA) yang cekap dimana kedua-dua ketepatan ‘contention window’ (julat ‘backoff’) dan keadaan rangkaian diambilkira. Bagi mempertimbangkan ketepatan ‘contention window’, protokol yang dicadangkan menggunakan tiga parameter kawalan untuk menentukan kadar perubahan yang diperlukan. Di samping itu, protokol yang dicadangkan menggunakan titik rujukan untuk kadar perlanggaran untuk menentukan tahap rangkaian pengisian. Oleh itu, ‘contention window’ diselaraskan berdasarkan kadar perubahan yang diperlukan untuk menunjukkan bilangan stesen aktif dalam rangkaian. Protokol yang dicadangkan dan senario yang diandaikan telah dilaksanakan pada OPNET simulator menggunakan perpustakaan tanpa wayar termaju (modul WLAN). Simulator itu juga digunakan untuk menilai metrik prestasi protokol yang dicadangkan, iaitu, kadar perlanggaran, pemprosesan dan data kejatuhan. Keputusan prestasi menekankan kepentingan mempertimbangkan ketepatan ‘contention window’. Keputusan keseluruhan eksperimen simulasi menggambarkan bahawa protokol yang dicadangkan mencapai prestasi yang lebih baik berbanding dengan protokol yang lain. Ia menunjukkan pengurangan 6% dalam kadar perlanggaran dan 4% kenaikan dalam kendalian menggunakan protokol yang dicadangkan berbanding dengan kerja-kerja berkaitan.

ABSTRACT

Since their emergence within the past decade, wireless networks have been adapted to enable mobility, and become increasingly popular in the world. Then, WLANs were introduced and mainly used to enhance mobility. Undoubtedly, its popularity has been increasing worldwide. The most important standard in WLANs is IEEE 802.11. This standard involves the concurrent use of equipment, thus permitting higher frequency range. Its coding technique is efficient, and its implementation cost is relatively low. As a result, most of the research works related to the enhancement of WLANs are designed based on the IEEE 802.11 standard. However, there are unresolved issues related to the performance metrics such as collision rate and throughput. IEEE 802.11 standard is a set of MAC protocols and physical layer specifications for implementing WLAN computer communication. MAC protocol plays an important role in accessing the transmission medium and the data transmission of wireless stations. Thus, the MAC protocol should be enhanced in order to increase the IEEE 802.11 network performance when the number of users increases. In the current work, the main aim was to enhance the performance of the 802.11 standard using an efficient CSMA/CA MAC protocol. The transmission mechanism of CSMA/CA protocol is based on the contention window (backoff range). According to the literature, the current CSMA/CA protocols do not consider the accuracy of contention window by researchers so far. In other words, the practical network operation has not been taken into account. The possibility of contention window change rate becoming larger/smaller than that required has been neglected. In either case, the channel is not efficiently used, thus degrading the system performance. In this study, both the accuracy of the contention window and the network condition were taken into account. In order to consider the accuracy of the contention window, a proposed protocol was introduced using three control parameters in order to determine the required change rate of the contention window. In addition, the proposed protocol employs a reference point for the collision rate in order to determine the network contention level. Thus, the contention window was adjusted based on the required change rate in order to reflect the number of active stations in the network. The proposed protocol and the assumed scenarios were implemented in the OPNET simulator by using the advanced wireless library (WLAN module). The simulator was used to evaluate the performance metrics of the proposed protocol, i.e. collision rate, throughput, and data drop. The performance results have highlighted the importance of taking into account the accuracy of the contention window. In fact, the performance of the proposed protocol was better than other protocols. The collision rate decreased by 6% and throughput underwent 4% increment upon using the proposed protocol.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACK	Acknowledgment
AP	Access Point
BEB	Binary Exponential Backoff
BSS	Basic Service Set
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTS	Clear-To-Send
CW	Contention Window
DCBTA	Dynamic Control Backoff Time Algorithm
DCF	Distributed Coordination Function
DIDD	Double Increase Double Decrease Algorithm
DIFS	DCF Interframe Space
DLC	Data Link Control
DMSN	Dynamic MAC for Scalable Network
DS	Distribution System
FDMA	Frequency Division Multiple Access
FIFO	First in First Out
FTP	File Transport Protocol
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IFS	Interframe Space
ISM	Industrial, Scientific and Medical Radio Bands
ISO	International Standards Organization
LILD	Linear Increase Linear Decrease Algorithm
LLC	Logical Link Control
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Medium Access Control
MILD	Multiple Increase Linear Decrease
MIMO	Multiple Input and Multiple Output
NAC	Number of Attempt Count
OFDM	Orthogonal Frequency Division Multiplexing

OSI	Open Systems Interconnection
PDA	Personal Data Assistant
PHY	Physical Layer
QoS	Quality of Service
RTS	Request-To-Send
STA	Station
TDMA	Time Division Multiple Access
U-NII	Unlicensed National Information Infrastructure
WLAN	Wireless Local Area Network

CHAPTER 1

INTRODUCTION

This chapter introduces the backgrounds of this research including wireless local area networks (WLANs) and IEEE 802.11 standard and highlights the research problem and motivation. In addition, this chapter presents the research objectives, the scopes of the research, the research direction, the research methodology and the research contributions. Finally, this chapter presents the organization of this thesis.

1.1 Background

Wireless communication is the fastest growing segment within the communication industry. As such, the number of users has experienced an exponential growth over the last decade; currently, there are ~ 3 billion users worldwide. Indeed, mobile device with wireless communication has become very popular within most of the developed countries and been replacing antiquated wire line systems in many developing countries (Kherani and Shorey, 2004). The developments of wireless laptop and palmtop computers have brightened the future of wireless networks such as those stand-alone systems and larger networking infrastructure. However, there are many technical challenges encountered while designing robust wireless networks for supporting emerging applications (W. Chen et al., 2002).

WLANs have started to replace wired networks in many homes, businesses, and campuses. Many new applications such as wireless sensor networks, automated highways and factories, smart homes and appliances, and remote telemedicine have been developed commercially. WLANs provide high-speed data within a small region, e.g. campus or small building, as users move from place to another (Ju et al., 2003). Wireless devices that access these LANs are typically stationary or moving at pedestrian speeds. All

WLANs standards operate in unlicensed frequency bands. The primary unlicensed bands are the ISM bands at 900 MHz, 2.4 GHz, and 5.8 GHz, and the Unlicensed National Information Infrastructure (U-NII) band at 5 GHz. For ISM bands, unlicensed users are secondary users. Thus, they must compete with those active primary users. There are no primary users in the U-NII band. The FCC license is not required in either ISM or U-NII bands. However, this advantage is a double-edged sword, since other unlicensed systems operating within these bands would generate significant interference as well. The interference problem can be mitigated by setting a limit on the power per unit bandwidth for unlicensed systems (Weinmiller et al., 1996). WLANs can have either a star architecture (with wireless access points or hubs placed throughout the coverage region), or a peer-to-peer architecture, where the wireless terminals self-configure into a network.

One of the most important WLANs standards is IEEE 802.11. The challenges in this standard are associated with the definition of contention to Quality of Service provisioning, energy conservation, privacy and security issues. The main difference with respect to solutions proposed for wired networking and cellular is that in the IEEE 802.11, adding a new node to the network is a matter of configuring (Conti et al., 2004). Due to these fundamental challenges, an efficient software that is able to cope with these challenges is needed.

1.2 Problem Statement

Due to the fact that IEEE 802.11 WLANs is using a shared media, the overwhelming traffic due to the increasing number of contending devices would affect the system performance (O'Hara and Petrick, 2005). The number of WLANs is growing as the number of populations increases (Geier, 2015). In 2014, the number of users was ~ 39% of the world population. By 2019, according to (Lee et al., 2016), the number would hit 51% of the world population. Therefore, the network should be redesigned in order to cater for the increasing demand which would otherwise fail to maintain the system efficiency (Nguyen and Ostermann, 2007). IEEE 802.11 WLAN is a set of MAC and physical layer specifications during implementation (Labiod and Afifi, 2007). Thus, MAC is a vital part of 802.11 because it controls contention over the shared media via IEEE 802.11(Holt and Huang, 2010).

The transmission mechanism of IEEE 802.11 is based on the CSMA/CA protocol (O'Hara and Petrick, 2005). Firstly, the MAC protocol of the transmitter station senses the transmission medium. If the transmission medium is idle for DIFS duration, the MAC protocol of the transmitter station would set the backoff timer. The backoff range of this timer is also known as Contention Window (CW), which is the number of choices available for random backoff. After that, the backoff timer is activated (i.e. countdown is started) and then the packet is transmitted from the MAC protocol of the transmitter station. If the transmission medium becomes busy while the backoff timer is decrementing, then the backoff timer would be frozen until the channel becomes idle again. If the MAC protocol does not receive the ACK frame, it is assumed that the data has been lost or collided. In this case, the MAC protocol of the transmitter station retransmits the packet by setting a new backoff timer such as doubling the CW and incrementing the backoff stage in the MAC protocol (Marsic, 2010).

Thus, CW plays a major role in 801.11 MAC protocol. However, there is a major problem related to CW (Nithya et al., 2012). For small CW, the collision probability is increased since the same time interval may be chosen by another station that attempts to transmit at the same time. For large CW, if there are only a few stations accessing the medium, then the time interval might be long which would degrade the network performance (Abbas et al., 2016). According to the literature, the current MAC protocols do not consider the accuracy of CW (backoff range) (Alkadeki et al., 2016; Balador and Movaghar, 2010; Balador et al., 2012). In addition, there is no explicit technique to guarantee the performance efficiency over the traditional MAC protocol (Xiao and Pan, 2009). Therefore, a MAC protocol that is able to produce a proper CW (by considering the accuracy of the CW) may enhance the performance metrics such as collision rate, data drop and throughput of IEEE 802.11.

1.3 Research Motivation

Wireless Local Area Networks (WLANs) are very popular nowadays. The most important standard in WLANs is IEEE 802.11 which is a set of MAC and physical layer specifications for implementing WLAN computer communication. They are created and maintained by the Institute of Electrical and Electronics Engineers (IEEE). The standards and amendments provide the basis for wireless network products using the Wi-Fi brand.

An efficient MAC protocol should be able to handle the situation such as increasing number of devices and/or users, and meanwhile to maximize the total throughput of the network as well as to minimize the collision rate of transmission. The existing protocol should be improved by incorporating those characteristics. Although the IEEE 802.11 standard adopts the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA Protocol) at the MAC layer in order to avoid collisions, its efficiency drops when the number of devices increases. Those works that simulated the MAC protocol by using a limited number of devices/environments were not convincing enough to characterize the behaviour of such a protocol. Thus, the contention level should be considered while characterizing the behavior of MAC protocol. Exploiting MAC protocol with the contented network is a better way to obtain a more reliable evaluation.

1.4 Research Objectives

- To analyse the behaviour of the traditional IEEE 802.11 MAC protocol.
- To compare the performance of the existing CSMA/CA solutions.
- To enhance the IEEE 802.11system performance in terms of collision rate, throughput and data drop.

1.5 Research Scope

There were several limitations associated with the current work. Firstly, due to the time constraint, only the infrastructure-less wireless network was considered, where devices communicated with each other directly without using router or access point. To generalize the results, the research should be performed on more networks with different communication types. Secondly, this research has investigated the behaviors of MAC in terms of system collision rate, data drop and throughput only. Finally, due to the complexity of performing a hardware experiment, only the software experiment was executed in the current work.

1.6 Research Direction

Figure 2.1 shows the research direction, whereby the boxes with dark color represent the research zones.

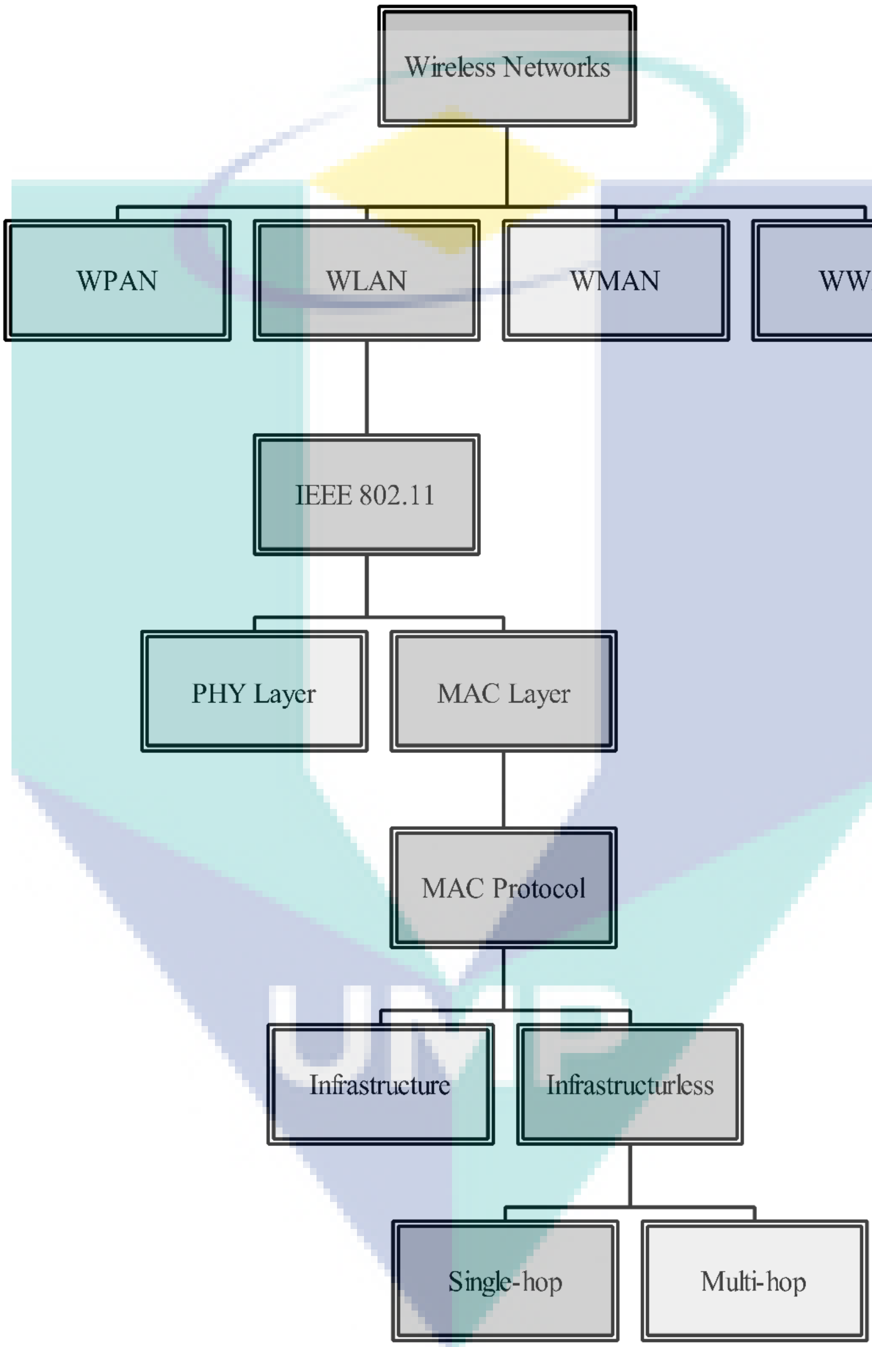

Figure 2.1 Research Direction

1.7 Brief of Methodology

CSMA/CA contains inter-frame spacing for different frame types and a contention window (CW) for introducing randomness into radio transmitters. The contention window is also known as the backoff range, which is the number of choices available for random backoff. If a collision occurs, then the transmitting stations would double the CW to reduce the probability of the subsequent collision (known as backoff mechanism). In this research, an efficient MAC protocol has been proposed to tune the CW accurately based on the network conditions. It is envisaged that the adapted protocol inherits its advantage of IEEE 802.11. By using network simulator tool, it is possible to compare the current results with those of other related works.

1.8 Research Contributions

There are two main contributions associated with the current research work. Firstly, the limitations and the behaviours of the existing IEEE 802.11 MAC protocol have been studied in detail. Secondly, a MAC protocol (CSMA/CA) has been improvised based on the traditional IEEE 802.11 MAC protocol, thus leading to reductions of collision rate, data drop and enhancement of throughput.

1.9 Organization of Thesis

This thesis contains five chapters. Chapter 1 presents the importance of WLANs and highlights the problem statement, the main objectives, and the scope of work. Chapter 2 reviews the relevant literature of network algorithms in order to identify the knowledge gaps. Chapter 3 details the current research methodology. Here, the proposed MAC model and the experimental parameters have been discussed. Also, the flowchart detailing the sequence of the works conducted has been presented as well. Chapter 4 discusses the experimental setups. The results have been compared with those of other studies. Chapter 5 presents the conclusions and offers some recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will provide a brief description of MAC layer protocols and highlights the transmission over IEEE 802.11 standard, then evaluate the information found in the literature related to the IEEE 802.11 standard. It will also clarify the literature and give a theoretical base for the research to help determine the nature of research. Works which are irrelevant will be discarded and those which are peripheral will be looked at critically. Some of the previous studies will be introduced, followed by critical analysis.

2.2 Background

Many mechanisms are used to maintain a network performance; some of this mechanisms are used at lower layers, others in different layers. Since there are many computers on the network, every layer needs a particular mechanism. Protocol layering is the key structuring mechanism used to support change by dividing the overall problem (Tanenbaum and Wetherall, 2011). To design an efficient network system, it is necessary to enhance the wireless communication layers. The best way to understand the communication layers is through the OSI model as shown in Figure 2.1. This model is based on a proposal developed by the International Standards Organization (ISO) as the first step toward international standardization of the protocols used in the various layers.

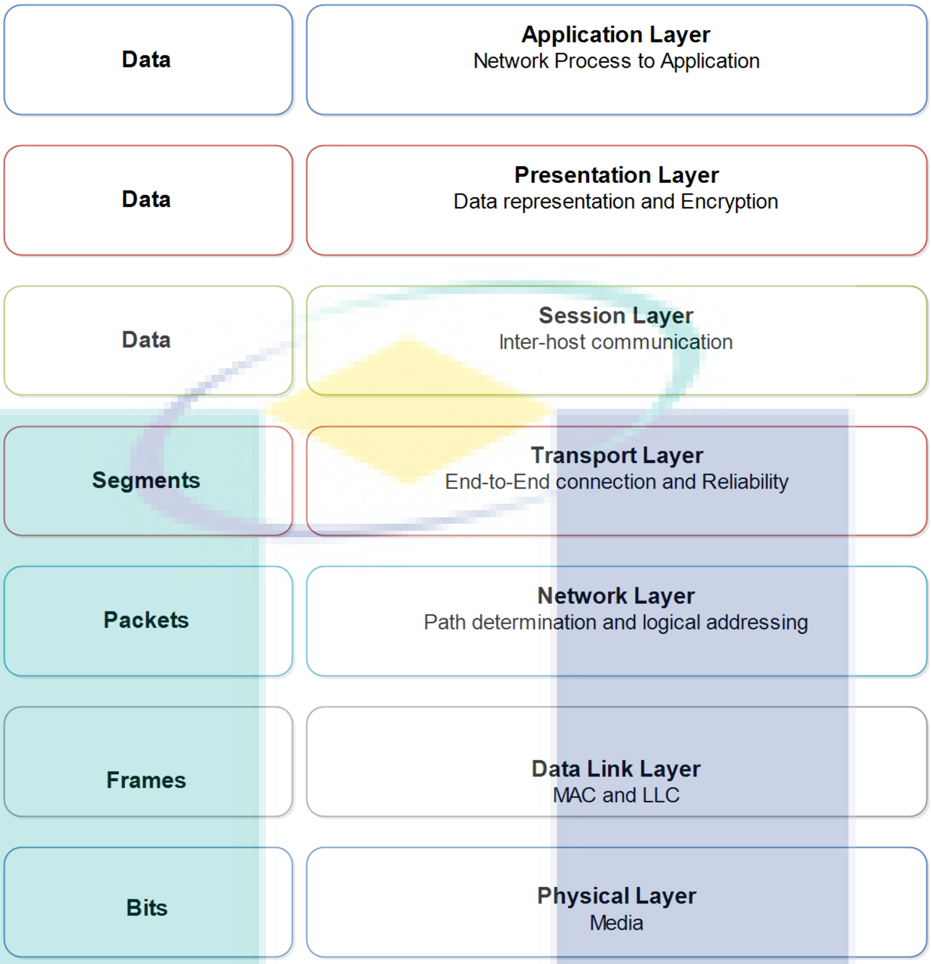

Figure 2.1 OSI Model

This section presents a general review for wireless transmissions, IEEE 802.11 standard, and MAC protocol. The OSI model has seven layers which can be briefly summarized as follows. The physical layer which deals with transmission bits across a connection channel. It is designed to ascertain that after one side sends a bit to the other side, the latter will receive the same bit. The issue associated with the physical layer is the type of power signal that should be used to represent a bit. Other issues are related to the remaining time of delivery, the configuration of initial connection, the connection stability, the number of pins of a network connector and the specific functions of each pin. These design problems are mostly related to mechanical, power and time interfaces, physical transmitting channel and physical layer (Peterson and Davie, 2007).

Data link layer is another layer used to convert a transmission facility into a link that is free of transmission errors. The actual errors are masked so that the network layer is unable to discover them. This is achievable by separating the entered information into data frames and sending the frames in a pattern via the transmitter. If the service is reliable, the receiver would confirm the right receipt of each frame by transmitting back an acknowledgment frame. Another issue emerging in the data link layer is about maintaining a speedy sender from drowning a slower receiver in data transmission. Many traffic control mechanisms are activated by letting the sender discover if the receiver allows more data (Gupta et al., 2002). Broadcasting network has a different concern in this layer, i.e. how to manage access to the shared medium. A specific sub-layer (medium access control) has been applied to address this issue.

The network layer drives the inter-networking process. The most important design issue is to determine how packets are routed from the sender to the receiver. Routes that are often dependent on static tables are wired into the network. In general, these routes can be modified automatically to avoid failure. In addition, they are established at the beginning of each transmission. As such, they can be highly dynamic in the sense that it determines a new route for every packet to reflect the actual network load. The problem occurs when several packets are introduced in the subnet at the same time. Managing congestion is also a responsibility of the network layer. This layer works harmoniously with the above layers to adjust the load placed on the network. In addition, the Quality of Service (QoS) is also a concern of network layer (Joshi, 2011).

The problem arises when a packet moves from one network to another. The addressing mechanism adopted by the network may be varied. The last network may not obtain the packet at all because the packet may be too large. The protocols can be varied as well. Therefore, the duty of a network layer is to coordinate different networks. In broadcast networks, the routing issue is not critical; therefore, the network layer is usually thin (Penttinen, 2015).

Transport layer receives data from the upper layer, separates it into shorter units whenever necessary, moves these units to the network layer, and ensures that the units arrive effectively. This process must be performed correctly in order to separate the upper layers from the electronics part. The transport layer decides the service type that can be provided to the upper layers and to the network individuals. The most well-established transport link is a clean point-to-point channel that delivers data sequentially. Nonetheless, there is another type of transport service that transports, and broadcasts separated messages to receivers with no restriction on the delivery sequence. This form of service is ascertained when the connection is required. Furthermore, it is practically difficult to establish an error-free channel. Moreover, this layer is a real end-to-end layer which brings data from the sender right to the receiver. In other words, the transport layer ensures that the system on the sender machine is connected to a similar system on the receiver machine during the conversation. Both machines are aided by the message headers and control messages. In the network layers, every protocol is lying between an end node and its immediate node, and not between all senders and receivers that are potentially divided to several routers (Alkhatib and Baicher, 2012).

The session layer enables end-users to set up sessions among them on different nodes. This layer delivers several services such as dialog management and synchronization. Basically, the primary duty of the session layer is to support the interconnections between users, thus enabling data transfer between different presentation entities. To accomplish that, the session layer may require resources offered by the transport layer. Session layer deals with transferring bits. This layer is all about the syntax and semantics of the data carried. In order to equip the computers with different internal data representations necessary for communication, it is necessary to develop some abstract data structures for the purpose of mutual exchange. This layer administers all abstract information architectures and enables upper layer data architectures for further definition and exchange (Wookey, 2017).

The last layer is the application layer which has a wide range of protocols normally required by end-users. Hypertext Transfer Protocol (HTTP) is a common application protocol in a global information medium. When a browser is looking for a website, it transfers the name of the website to the web server having the page using HTTP. The web server then returns the website. Different protocols are chosen for various purposes including file exchange, email, and media (Lachmann, 2014).

2.2.1 Features and Characteristics of WLANs

WLANs are very popular nowadays. Its main advantage is mobility, whereby users are able to roam freely. Mobile telephony is initially expensive as it is mainly used by highly mobile professionals (Gast, 2005). In this modern era, however, mobile telephony has been gaining immense popularity. Since WLANs do not require an Ethernet cable, users can stay connected as long as they are within the range of the base device. It offers great flexibility, where several base devices can be employed to connect one or more users to an existing network by using the same infrastructure. Once the base devices and antennas are in place, adding a user to WLANs is only a matter of authorization. Adding a user to WLANs does not involve running cables, punching down terminals, and patching in a new jack (DengLiang et al., 2004).

Nowadays, the WLANs have been commonly deployed in places such as coffeehouses, airports and train stations to allow customers to access the Internet. The WLANs is a natural upgrade of the conventional wired network, which is to get rid of the problematic running cables. With WLANs, it is not necessary to construct or make educated (or wild) guesses about the network demand. Also, WLANs can accommodate as many users, if not more, as that of a wired network (Fitzek et al., 2003).

Flexibility may be particularly important in older buildings because it reduces the need for constructions of infrastructures (Wesel and Khayata, 1997). Therefore, WLANs can be deployed rapidly in these buildings as it involves only a small amount of cabling works. Flexibility has also led to the development of community networks. As wireless equipment is getting more affordable, shared WLANs (which are open to visitors) have been set up by volunteers. Community networks have been commonly used in places that are too rugged for the traditional wired network (Pahlavan, 2011).

WLANs transmit data in a form of electromagnetic radiation, e.g. infrared light and radio waves. Nowadays, most portable PCs have infrared ports for establishing quick connections to printers and other peripherals (Sheng et al., 2008). However, infrared light is easily blocked by obstacles. On the other hand, radio waves can penetrate most office obstructions and offer a wider coverage range. Therefore, modern WLANs employs the radio wave physical layer.

Because of the unique fractures, WLANs have undergone an exponential growth which is expected to continue in the near future. Therefore, a communication device and protocol must offer similar efficiency number of users increase by maintaining system performance. One of the main issues in building an efficient network is that the setback of minor inefficiency of a small network can be amplified in contented networks (Jelenkovic et al., 2007). Maintaining system performance affects networks in numerous ways such as reliability, load, administration, and security. These effects are felt by all parts of the system.

Maintaining system performance can improve the reliability of a system and allows a network to be used even if it experienced significant change. It also affects system load; as the number of users increases, the amount of data that must be managed by the network system. Distribution is used to reduce the number of requests that must be handled by the network system (Radosavac et al., 2007). The administrative dimension of maintaining performance adds its own problems. As the number of devices in a system increase, it becomes impractical to maintain information about the system and its users on each device. As a system continues to grow, information about the system changes more frequently. This makes it less practical for a single individual to keep it up-to-date.

Security becomes increasingly important and increasingly difficult to implement when the number of users increases. The bigger the system, the more vulnerable it is to attack. There are more points from which an intruder can enter the network; the system has a greater number of legitimate users, and it is more likely that the users will have conflicting goals. The security mechanisms employed in different parts of a system will have different strengths. It is important that the effects of a security breach can be contained in the part of the system that is broken (Chhaya and Gupta, 1995).

Limitation of available resources such as channel bandwidth availability and energy is also affected by a number of users (Nesargi and Prakash, 2002). Networks must be able to optimize the usage of a channel for transmitting maximum data size and maintaining the source of energy. Therefore, an efficient network should offer maximum performance with limited bandwidth and energy (Tseng and Hsieh, 2002).

2.2.2 Overview of IEEE 802.11 Standard

The IEEE 802.11 MAC layer provides reliable data service to the higher layer protocol and controls fair access to the shared wireless medium (Chung and Piechota, 2003). It is a member of the IEEE 802 family, which is a series of specifications for local area network (LAN) technologies. Figure 2.2 shows the relationship between the various components of the 802 families and their place in the OSI model. 802 specifications are focused on the two lowest layers of the OSI model because they incorporate both physical and data link components. All 802 networks have both a MAC and a Physical (PHY) component. The MAC is a set of rules to determine how to access the medium and send data, but the details of transmission and reception are left to the PHY. Individual specifications in the 802 series are identified by a second number.

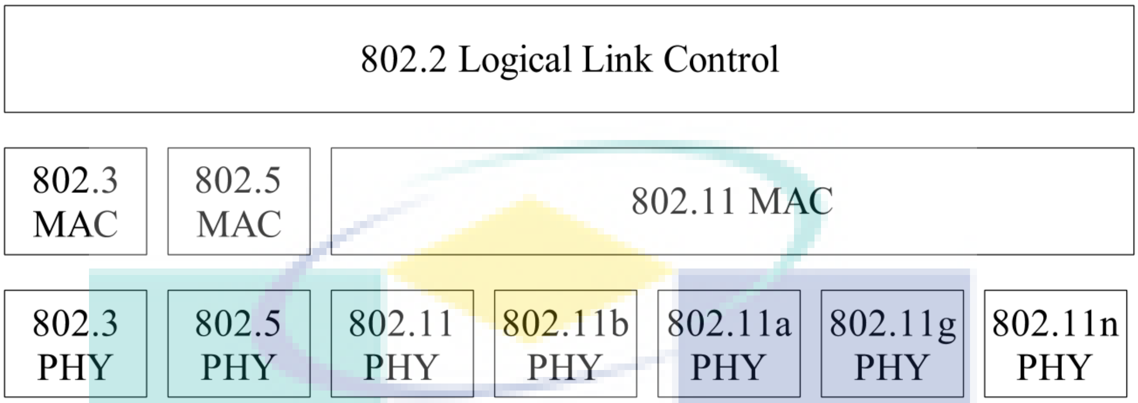

Figure 2.2 802.11 Family Tree

For example, 802.3 is the specification for a Carrier Sense Multiple Access with Collision Detection (CSMA/CD), which is related to (and often mistakenly called) Ethernet, and 802.5 is the Token Ring specification. Other specifications describe other parts of the 802 protocol stack. 802.2 specifies a common link layer, the Logical Link Control (LLC), which can be used by any lower layer LAN technology. Management features for 802 networks are specified in 802.1 (Khurana et al., 1998).

IEEE 802.11 is mainly used to hide the unreliable nature of wireless medium. Moreover, the node appears stationary to the higher layer protocol (above the MAC). There are two operation modes in the 802.11 standards, i.e. Ad-Hoc mode and infrastructure mode. The Ad-Hoc mode is a decentralized method whereby node communication is realized via the peer-to-peer method. For the infrastructure mode, a centralized method is used where node communication is coordinated through an Access Point (AP). The Basic Service Set (BSS) is typically a basic building block of the 802.11 wireless LAN (Bobbie and Yussiff, 2004). The incorporation of WLAN topology will be discussed next.

2.2.2.1 Topology

The IEEE 802.11 topology includes many components interacting to provide a wireless LAN that enables node mobility transparent to higher protocol layers, such as the LLC. A node is any device that contains the functionality of the 802.11 protocol (in other words, the MAC layer, the PHY layer, and an interface to a wireless medium). The functions of the 802.11 standards reside physically in a radio card, the software interface that drives the radio card, and the access point (AP). The 802.11 standard supports the following two topologies:

The first type of topology is independent basic service set This topology is also called Ad-Hoc network and is used for a particular purpose as necessary. It consists of a number of wireless nodes which directly communicate with each other (Bobbie and Yussiff, 2004). However, a node must reside within the reception range of the other node in order to initiate communication. Figure 2.3 shows the independent basic service set topology network.

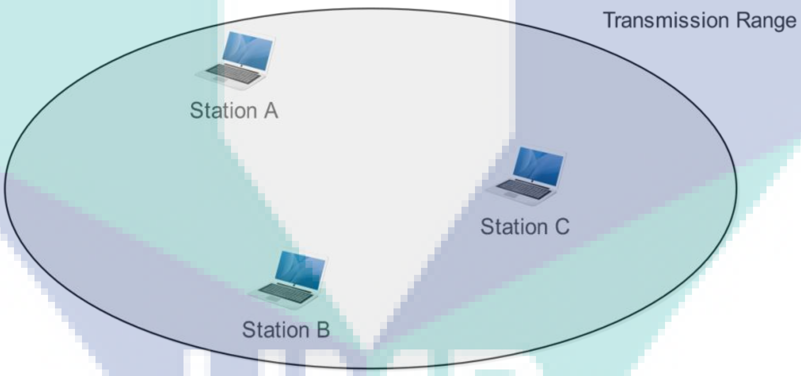

Figure 2.3 Independent Basic Service Set

The second type of topology is an infrastructure basic service set. This topology consists of several wireless nodes and an AP that functions as a relay for Basic Service Set (BSS). The sending node first transmits a frame to the AP. Then, the AP transfers the frame to the receiving node. In contrast to Infrastructure Basic Service Set (IBSS), all communications are relayed through AP in order to double the reception range of IBSS (Bobbie and Yussiff, 2004). Therefore, the wireless node must be residing within the reach of AP. Also, when the node is in power-saving mode, AP may buffer frames for that particular node for later transmission. However, the transmission capacity is lower than that of the case where the sender transmits frames directly to the receiver (Gast, 2005). In general, an AP is connected to a Distribution System (DS). Figure 2.4 shows the Infrastructure Basic Service Set topology.

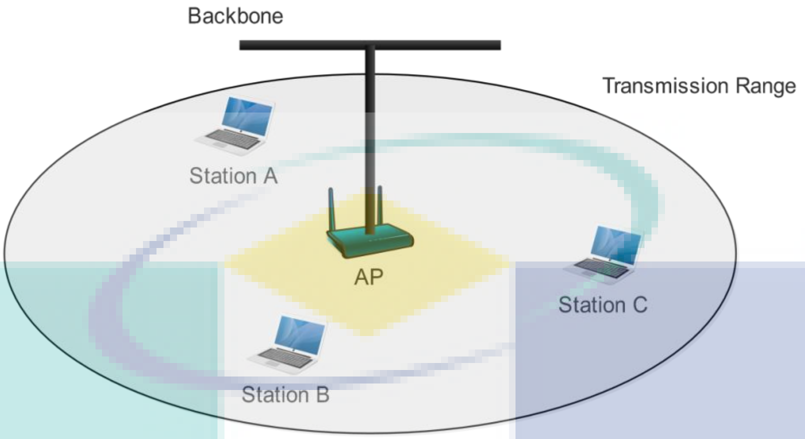

Figure 2.4 Infrastructure Basic Service Set

In general, DS could be a wired network or a special box that interconnects APs in another BSS. DS serves as the backbone of wireless LAN for communication with another wired/wireless network. DS checks if the traffic is relayed to a destination in the same BSS or forwarded to another AP through DS. It can also determine if it can be forwarded to a wired network with destinations. Extended Service Set (ESS). is a set of BSS infrastructure interconnected by a wired network to arbitrarily increase the range of mobility. For example, two IBSSs may be connected through a DS to form an ESS. Figure 2.5 shows the ESS topology.

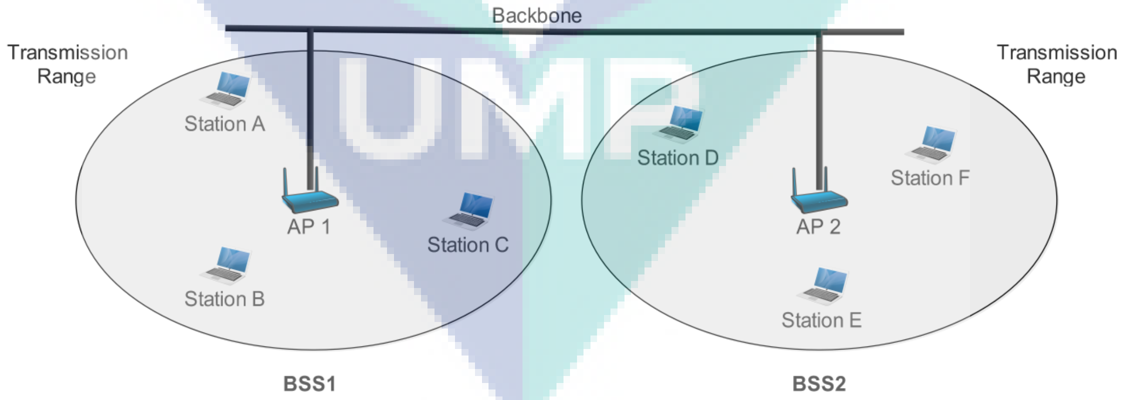

Figure 2.5 Extended Service Set

2.2.2.2 Interframe Spacing

IEEE 802.11 relies on the concept of Interframe Space (IFS), which is measured in a time unit, to give different priorities on channel access. A frame has to undergo a waiting duration of its respective IFS before accessing the channel. Smaller IFS signify higher channel access priority. Several IFS types are available in IEEE 802.11 standard. Short Interframe Space (SIFS) has the shortest IFS. An acknowledgment frame is an example that uses SIFS. Point Coordinate Function Interframe Space (PIFS) is the IFS used in Point Coordinate Function (PCF) mode. Nodes in PCF mode can transmit frames during the contention free period after PIFS has elapsed. DCF Interframe Space (DIFS) is used in Distributed Coordinate Function (DCF) mode. Nodes operating in this mode are contention-based and they are able to access the wireless channel after a period longer than DIFS. Extend Interframe Spacing (EIFS) is applied only when a node attempts to retransmit a failed packet. The actual value of IFS is dependent on the employed physical mechanism (e.g. DSSS or FHSS). The 802.11 standard implements two channel access mechanisms, i.e. Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The characteristics of these mechanisms are discussed below. In conclusion, the Interframe spacing plays a large role in coordinating access to the transmission medium. 802.11 uses these Interframe spacing to determine medium access (Gast, 2005); the relationship between them is shown in Figure 2.6.

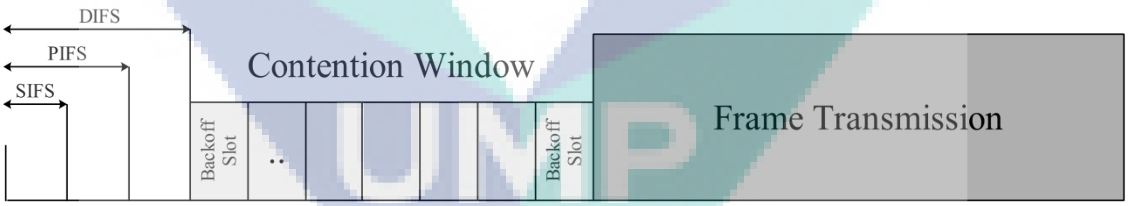

Figure 2.6 Relationship Between Interframe Spacing

2.2.2.3 IEEE 802.11 Access Modes

Access to the wireless medium is controlled by coordination functions. Basic access is provided by the distributed coordination function (DCF) with contention service. If contention-free service is required, it can be provided by the point coordination function (PCF), which is built on top of the DCF. Contention-free services are provided only in infrastructure networks. The coordination functions are illustrated in Figure 2.7

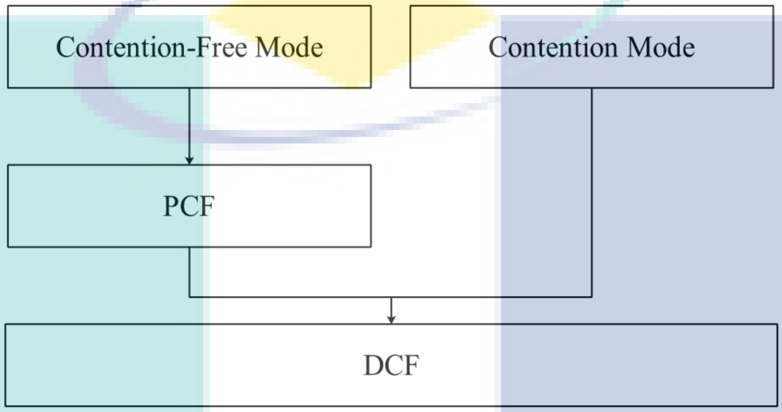

Figure 2.7 IEEE 802.11 Access Modes

Distributed Coordination Function (DCF) is the fundamental access mode of 802.11 MAC layer. It works based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, which is very similar to CSMA/CD employed in 802.3. For the latter, collision detection in wireless communication is not possible. A transmitting node cannot reliably detect collision because the transmitted signal is much stronger than the received signal. To detect a collision, the cost of building the associated hardware transceiver is high (Das et al., 2007).

Also, it consumes a lot of power which is not practical for mobile nodes. Hence, the 802.11 standard employs collision avoidance instead. Carrier Sense Multiple Access employs both physical and virtual mechanisms. The first mechanism depends on the medium and modulation used, and the latter uses Network Allocation Vector (NAV). NAV is a timer that gives the reserved time period of a medium. The node sets its NAV to reserve the time period. The countdown process is then executed in other nodes whereby the initial NAV value is decreased to zero. The medium is busy if the NAV is non-zero. Otherwise, the medium is idle and the node may access the medium. A node has to sense the medium before data transmission. The frame is transmitted after the channel is idle for at least a certain time frame denoted as DCF Interframe Space (DIPS) time. If the medium is busy, access to the channel is deferred for a random backoff time measured in terms of time slots. The random time slot is chosen from a range of 0 to CWsize-1, where CW is denoted as CW and CWsize is the size of the CW. The minimum and maximum values of CWsize are denoted as CWmin and CWmax, respectively. The default values for CWmin and CWmax are 16 and 1024 slots, respectively. If the wireless medium is busy during backoff, the countdown is paused and restarted until the medium is idle for a period of DIFS. Here, the backoff timer decreases by one slot time and continues as long as the medium remains idle. The frame is sent after the backoff value reaches zero. After a successful transmission, CWsize is set as CWmin and the backoff process is initiated. If the backoff value reaches zero and a collision is detected, a new backoff slot is selected and the backoff process starts again. When a collision is detected (ACK is not received), the CW is doubled. CWsize is treated as the next greatest power of two whenever there is a retransmission. For instance, first retransmission increases the CW from 32 to 64, second retransmission shifts the CW to 128 and so on. It is important to note that CW is bounded by CWmax which is 1024 for Direct-Sequence Spread Spectrum (DSSS) physical layer. Thus, backoff algorithm is useful in avoiding a collision, and doubling the CW could reduce the likelihood of a consecutive collision (A. Mishra et al., 2003).

Even though DCF is a simple and effective mechanism, DCF can neither support scalability nor guarantee to meet the multimedia applications requirements. That is to say, DCF does not guarantee bandwidth, packet delay, packet loss rate and jitter bounds for high scale networks or multimedia flows. Also, there is no way to guarantee the QoS requirements for high-priority traffic in DCF. Legacy DCF MAC does not support the concept of differentiating frames with different user priorities. The DCF is supposed to provide a medium access with equal probabilities to all nodes contending for the channel access in a distributed manner. Nevertheless, equal access probabilities are not desirable among nodes with different QoS requirements. The QoS depends on MAC to treat packets with different QoS requirements differently (Zhai and Fang, 2003).

However, Point Coordination Function (PCF) is another access mode operates only in infrastructure mode and it is optional in the 802.11 standards. However, PCF is important in QoS as it provides time-bound services. PCF mode is controlled by a Point Coordinator (PC) located within an AP. In addition to having the DCF contention period, PCF introduces a Contention-Free Period (CFP), in which the PC polls each node in turn for frame transmission. AP initiates the counting of CFP period by sending Delivery Traffic Indication Message (DTIM) beacon frames. The beacon frame contains synchronization and BSS information such as SSID and supported rates (Aad et al., 2005).

However, the sending of beacon frames can be delayed when the wireless medium is busy. At the beginning of CFP, AP gains control of the medium after sensing that the medium is idle for PCF Interframe Space (PIFS) time and the Target Beacon Transmission Time (TBTT). TBTT is the time where AP should schedule a beacon as the next frame for transmission. Time zero is a TBTT where DTIM is carried in the beacon at the start of CFP.

Since there is no contention in CFP, the AP schedules two-way transmission for each node via polling. Each CFP-enabled node is polled by the AP that sends the CF-Poll frame to one of the polled nodes. If it is necessary for the AP to send the data frame to this node, the frame is then attached to the CF-Poll (DATA+CF-Poll frame). Upon receiving a poll, the node transmits its data with ACK (DATA+CF-ACK frame) or response with an ACK (CF-ACK) in order to show that nothing will be sent. SIFS interval is used throughout the frame exchange. When one node completes its frame exchange sequence, the AP sends another CF-Poll to the next node on its poll list. A poll list is maintained in order to poll the nodes. The actual CFP duration is announced in the beacon, and the NAV values of all nodes are updated accordingly. The polling continues until the AP has completed the polling of all nodes in the poll list or the CFP period has expired. Then, the AP broadcasts the CF-End frame to indicate the end of CFP and the NAV values of all nodes are reset to zero. Once the CFP is finished, CP is followed and accesses using DCF are granted to the nodes upon reaching the next DTIM beacon. The sum of CFP and CP is called superframe (P. Chatzimisios et al., 2005).

There are several issues leading PCF to exhibit a performance drawback (Manshaei et al., 2005). First, nodes with PCF cannot separate from central network administration. Second, self-configuring and self-healing are not allowed. Third, the setup is less flexible than DCF. Fourth, more costs are involved due to decentralized administration. Fifth, nodes with PCF network need to rely on hardware and software. Sixth, there may be different types of traffic with different QoS requirements, but all these are not good enough to handle the various QoS requirements in large-scale conditions. Seventh, the transmission activity during the contention period interval has an impact on the time instant at which it can be started and consequently on the delay experienced by the nodes to be polled during the contention period. This may severely affect the performance of the networks. Finally, this mode of access has a lot of overheads because of the use of the superframe.

2.2.3 Overview of Channel Access Mechanisms

The data link layer has sub-layer calls Media Access Control (MAC) protocol. This MAC offers handling and channel access schedule that enable many nodes to connect to multiple access networks in order to form a shared channel. This sub-layer functions as a platform for the Logical Link Control (LLC) sublayer and the upper layer. Therefore, MAC is similar to a full duplex medium in a broadcast network. This communication channel in a multi-access network has the capacity to provide unicast, multicast or broadcast communication service (Nefzi and Song, 2012). A channel access mechanism is the part of the protocol that details how the node uses the medium and how it joins the other nodes that belong to the same network. In the next subsections, some major MAC protocols will be discussed according to Forouzan categorization (Forouzan and Fegan, 2007) as shown in Figure 2.8.

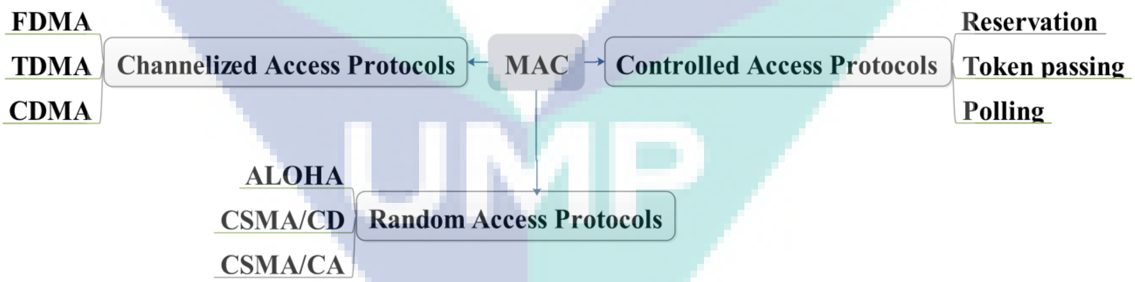

Figure 2.8 MAC Access Protocols

2.2.3.1 Channelized Access Protocols

Channelization is a shared protocol in which the current bandwidth of a connection is split into a few aspects such as code, frequency, or time between various nodes. Via the Frequency Division Multiple Access (FDMA), the current bandwidth is separated into frequencies. Every node is given a specific frequency to transmit its data. It also has a filtration system to restrict the sender frequencies. Moreover, the specific frequencies are separated from others by mini guard frequencies (Srikanth et al., 2012). FDMA specifies an established frequency for the whole duration of the communication, signifying that the flow data can be simply applied with FDMA. FDMA and Frequency-Division Multiplexing (FDM) are equivalent conceptually. FDM is identified as a physical technique that combines the loads from low-frequency and high-frequency channels. Signals modulated by the multiplexer produce a bandpass signal. The frequency of each channel is repositioned by the multiplexer. FDMA, on the contrary, uses the data link layer to inform its physical layer to generate a signal from the data handed to it. The signal has to be set up in the allocated frequency. There is certainly no physical multiplexer at the physical layer. The signal is filtered automatically by the node. They are combined after they are delivered to the common channel.

For the Time Division Multiple Accesses (TDMA), the frequency is shared in time. Every node is allocated a time slot for data transmission (Diamant and Lampe, 2011). This method requires synchronization between different nodes. Each node must recognize the starting and the ending positions of the slot. This process is hassling (causing delay) when the nodes are extended through a big area. To handle this delay, some guards have been introduced. Code Division Multiple Access (CDMA) was developed a few years ago. The current improvement in technology has eventually made the implementation practical. CDMA differs from FDMA in terms of the connection frequency. It is not identical to TDMA because most nodes can transmit information simultaneously. In CDMA, one channel holds all transmissions at the same time (Fouad and Leonard, 1976).

2.2.3.2 Controlled Access Protocols

In controlled access, a node is able to transmit data upon obtaining approval from other nodes. There are three types of protocols in this method, e.g. reservation, polling and token passing. The reservation protocol enforces that booking must be performed before a node is able to transmit information. Duration is split into intervals. In every interval, a booking frame comes before the information frames are transferred in that interval. If there are N nodes in the network, N booking slots will exist in the booking frame. Each slot is connected to a node. If a node is required to transmit information frame, booking is done in its individual slot. Nodes, where bookings have been established, can transmit their information frames and display the booking frame (Klimesch, 2012).

Polling protocol runs with topologies that one node is specified at the main node and the other nodes are treated as secondary nodes. Information interchanges must be done with the main node regardless of the destinations of the secondary nodes. The main node manages the connection. The main node authorizes a particular node to be used as a medium at a specific time. The main node requests the secondary nodes for information (polling) and informs the secondary nodes to accept any information transmitted by it (selection).

In the token passing protocol, the node in a system is fixed in a ring topology (K. Xu et al., 2002). The previous node refers to the node which is logically located before the successor (i.e. node in the ring). The present node is the single node that is accessing the medium. This connection is granted permission by the predecessor of the present node. The permission will be moved to other if the present node does not have any other information to transmit.

The big concern in token passing is: exactly how is the permission to contact with the channel approved from one node to an additional node? In the token passing protocol, a special frame known as the token is passed within the ring. Token offers the node permission to connect to the channel and transmit its information. If a node has some information to transmit, it waits until it gets the token from its predecessor. It then keeps the token and transmits its information. If the node has no more information to transmit, it discharges the token to the next logical node in the ring. The node is unable to transmit information until it gets the token again in the next round (Ciuffoletti, 2010).

In the token passing protocol, the token manager is released to connect with the administration for collision avoidance purpose. Since the number of the token is limited, a token must be kept properly. Also, the token manager manages priorities of the nodes and types of information transmitted. Moreover, the token manager discharges the tokens of low priority nodes to higher priority ones. This protocol has been proven successful. However, the token loss is an underlying problem of this protocol.

2.2.3.3 Random Access Protocols

In random access method, all nodes have the same priority, and none is getting the control on the other. In this arrangement, since there is no master node, no node authorizes others to send or receive data at any given time. In all cases, when data transmission is required, a technique identified by the medium protocol is employed. The decision is governed by the status of the channel. Therefore, any node must wait for its turn to transmit data.

Two primary features can be found in this model (Choi et al., 2006). Firstly, there is no fixed time for a node to send data. The nodes send the data randomly (random access). Secondly, all nodes are autonomous to the extent that they can send or receive data anytime subjected to the governing medium. In this method, any node can access the channel. Nonetheless, a collision occurs when many nodes attempt to send data. When it happens, the data will be destructed or altered. The performance of the random access method is assessed via system efficiency and effectiveness. Due to the fact that each node can deploy resources at its own convenience, this leads to rival nodes competing for the same resource at certain times, thus leading to signal collision. This is the reason why this method is sometimes called the contention method.

The random access protocol is expanded from a remarkable protocol called ALOHA which implements a straightforward process called multiple accesses. The protocol is improved by a process called Carrier Sense Multiple Access (CSMA) that enables a node to identify the channel before sending is done. Collision Detection (CSMA/CD) and Collision Avoidance (CSMA/CA) is the improved versions of CSMA. CSMA/CD gives instructions to the node when a collision occurs. CSMA minimizes the possibility of collision and enhances the efficiency of a communication system. The possibility of collision can be decreased if a node detects the channel before it is used. CSMA ensures that each node senses the channel before the sending process. In other words, CSMA is depending on sensing before transmitting (S. Xu and Saadawi, 2001).

CSMA system is effective in decreasing the possibility of collision. However, it is difficult to achieve zero collision as nodes are hooked up to a shared channel. Due to delay, there is a possibility of collision, which must be addressed in future studies CSMA/CD adjusts the protocol to deal with the collision. In CSMA/CD, a node detects the channel once it sends information to examine if the transmission is successful. The information is retransmitted if a collision occurs. In other words, CSMA/CD is able to determine the likelihood of collision but it is unable to avoid a collision (Tsai and Chen, 2005).

Another access protocol is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In CSMA/CD, when there is no collision, the node receives its own signal. Otherwise, the node takes two signals, i.e. its own signal and the signal transmitted by the second node. To differentiate these cases, the received signals in these cases must be significantly different. This means that it is necessary for the signal from the second node to add a significant amount of energy to the one created by the first node (Dinh and Kim, 2012). CSMA/CA is thereby developed to prevent collision via Interframe space, backoff, and acknowledgments.

CSMA/CA avoids the collision by delaying transmission even when the channel is unused. If an unused channel is discovered, the node does not transmit signal immediately. Delay occurs for a duration denoted as the Interframe Space (IFS). Even though the channel may appear unused when it is sensed, a distant node may have begun sending a signal (it may not arrive at this node yet). IFS allows signal transmission from the distant node. If IFS is over and the channel is still unused, the node can transmit, regardless of the truth that it continues to want to hold off a time match to the contention time. The IFS diverse can also be used to take top priority of the nodes or frame types. For instance, a node of smaller IFS has a greater priority (Rashwand and Jelena, 2012).

The Contention Window (CW) is described time separated into slots. A prepared node will choose a number randomly from the slots. The slots in the window adjust the binary exponential backoff approach, meaning that it is fixed to one slot at the starting time and then is multiplied by two each time the node cannot find an unused channel just after the IFS time. This is actually much the same as the protocol but that a random result defines the number of slots used by the delaying node. A node must detect the channel immediately after all slots. However, if the node discovers an occupied channel, the procedure will not be repeated. The timekeeper will stop, and it will be restarted when an unused channel is discovered, and its difference of nodes leads to much delay time. Figure 2.9 shows the state diagram describes CSMA/CA.

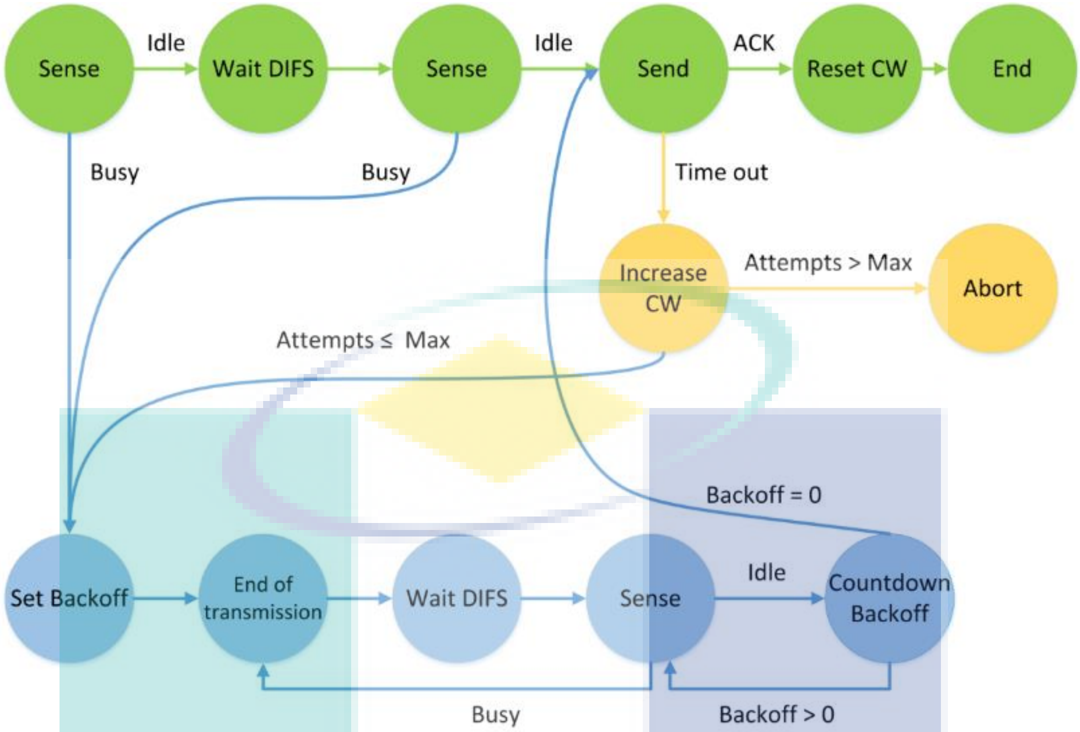

Figure 2.9 CSMA/CA State Diagram

As described above, CSMA/CA seems to be quite effective. It is important to note that in a wired network, the accepted signal has nearly the same power as the delivered signal because both signals are transmitted by the same cable. Therefore, the recognized power is much higher in a collision. Likewise, in a wireless network, the delivered power vanishes in transmission (Chatzimisios et al., 2003b). Therefore, a collision may add only a small percentage of additional power, which is made worthless for collision discovery. In this case, the ability of CSMA/CA in preventing a collision on wireless networks could be degraded. Due to the fact that collision may still exist; the information may be damaged during transmission. This problem can be partly circumvented by acknowledgment and timeout.

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) specifies two access methods. The basic access method and the optional access method are working based on two-way and four-way handshake mechanisms (Roshan and Leary, 2004). The first mechanism plays a major role in avoiding the collision by using ACK. Here, the transmitter node sends the data and waits for a duration known as the Short Inter-Frame Space (SIFS).

If the transmitter node does not receive the ACK within the duration of SIFS, it will assume that there is a collision or data loss (Chatzimisios et al., 2005). Thus, the two-way handshake mechanism (DATA/ACK) is suitable for small data packets because it works based on short interval time. However, the hidden node problem cannot be detected by using DATA/ACK. Meanwhile, the large data packet may promote the risk of collision. Therefore, the CSMA/CA mechanism specifies the four-way handshake as an optional mechanism. In this scenario, the transmitter node can reduce the risk of collision using Request to Send/Clear to Send (RTS/CTS) packets. This way, the transmitter node can reserve the transmission medium by sending the RTS packet to the receiver side. If the transmission medium is free, the receiver will confirm the reservation by replying the CTS packet to the sender node. As a result, the four-way handshake mechanism can reduce the risk of collision during the transmission of long packets. Moreover, this optional mechanism can deal with hidden node problems because it allows the transmitter node to reserve the transmission medium before transmitting.

2.2.3.4 Backoff Scheme

In the basic access scheme of random access technique, a sender node monitors the channel activity. If the channel is idle for a period of Distributed Interframe Space (DIFS), the sender node will send the packet. Then, a destination node sends the ACK message to the sender node after a period of Short Interframe Space (SIFS). Upon the reception of the ACK message by the sender node, it is confirmed that successful transmission has taken place. The channel is sensed as ‘busy’ by all other sender nodes from the start of DIFS to the end of ACK (Garg et al., 2003a). Figure 2.10 is illustrated the basic access scheme of random access technique.

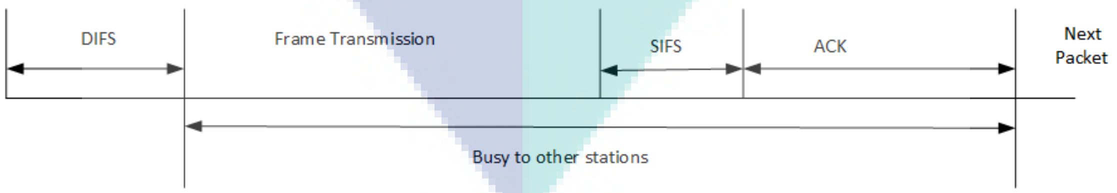

Figure 2.10 Basic Access Scheme of Random Access Technique

However, if the sender node finds that the channel is ‘busy’ during DIFS, it waits until the channel is idle for a period of DIFS. Then the backoff scheme is triggered before transmitting the packet. Note that the backoff scheme is also used between two consecutive packets by a node (e.g. if the same node sends the next packet) even if the channel is not busy for DIFS. The backoff scheme helps to minimize the collision with the packets sent by other nodes and to minimize the channel captured by the same node.

The backoff scheme works in the following manner (Penttinen, 2015). The time is slotted immediately after DIFS. Transmission is permitted at the beginning of a time slot. For each packet, a backoff time counter (c) is chosen with CW∈ [0, w − 1], where CW ∈ [CWmin, CWmax], respectively. Initially, the CW is taken as CWmin. For each failed packet, the CW is doubled or linearly increased. The backoff counter reduces by 1 after each time slot as long as the channel is idle. If the channel is found busy, the time counter remains unchanged until the channel becomes idle for a period of more than DIFS. When the value of the time counter is zero, the packet is transmitted. The backoff scheme is illustrated in Figure 2.11.

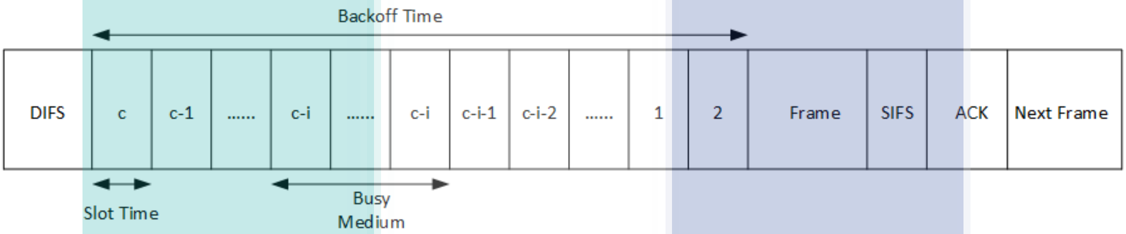

Figure 2.11 Backoff Scheme

The optional four-way handshaking (RTS/CTS) is another random access scheme incorporates into the basic access scheme before the actual packet is transmitted. In this scheme, the sender node waits until the channel is idle for a period of DIFS which is followed by backoff scheme as explained in the basic scheme. Instead of sending the packet directly, the sender node (A) sends the RTS message to the destination node (B). After a period of SIFS, B returns a CTS message upon receiving the RTS message. Next, the channel is reserved from A to send its packet to B. Finally, A sends the packet to node B followed by an ACK.

The information of packet length is stored in RTS and CTS messages. Hence, this information updates the Network Allocation Vector (NAV) that can notify the other nodes on the time for which the channel will be occupied. Thus, problems arising from a hidden node is mitigated since the hidden node can avoid the collision by observing the channel status using RTS/CTS frames.

In RTS/CTS scheme, with the perfect channel sensing by all nodes, a collision may occur only in the RTS frame when two or more nodes transmit signal at the same time slot (which is detected by the lack of CTS message). On the other hand, for basic access scheme, a collision may occur in data frame due to signal transmission in more than one node at the same time slot. However, RTS frame is smaller than a data frame. Therefore, RTS/CTS scheme is much better than the basic scheme especially when the packets are large (Roshan and Leary, 2004). The RTS/CTS scheme is illustrated in Figure 2.12.

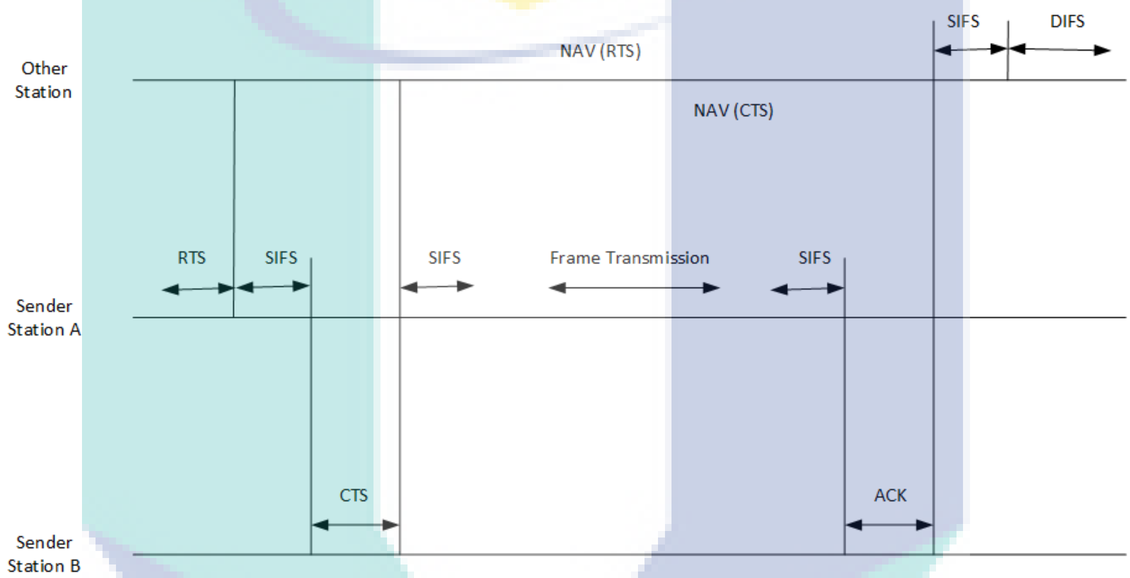

Figure 2.12 RTS/CTS Scheme

2.3 Related Work

It is apparent that the number of WLANs equipment and users is growing in both the consumer and enterprise worlds. This trend is expected to continue further. Therefore, both the communication device and protocol must maintain their efficiencies in order to cope with the growing demand. It is commonly known that a minor setback in regular networks could be amplified in contented networks (Jelenkovic et al., 2007). WLANs is recognized as one of the most popular wireless networks due to the abundance of portable mobile handheld devices and the handiness of untethered communications. Due to the increasing number of devices, increasing content size on WLANs (e.g. digital video, voice, video conferencing, and networked games) and huge demand for time-sensitive critical applications, an efficient network system must be developed. IEEE 802.11 is a set of MAC and physical layer (PHY) specifications used for implementing WLAN computer communication. Although this standard provides a simple, adaptive and fault-resilient network, it fails to satisfy the growing number of users. This problem can be resolved by over-provisioning, and most researchers have focused on designing a network with lower capacity (lower cost) while meeting the application requirements. Due to the frequent interference in WLANs (fading and multipath effects), it is challenging to conduct performance provisioning (Gast, 2005). This section focuses on the previous works performed to enhance the IEEE 802.11 standard.

2.3.1 Related work on IEEE 802.11

Maintaining performance by adopting the traditional standards is very challenging since there is no explicit guarantee for efficiency. In order to measure the performance of these networks, the parameters used in evaluating the general traffic layout can be used. For example, goodput is used to measure the packet arrival rate within a prescribed period; load level is employed to indicate the rate of usage of a medium; and available bandwidth is introduced to measure the new rate in sending traffic without interrupting the current flows in the network (Dujovne et al., 2010). Existing standards contain the simple Distributed Coordination Function (DCF) and the optional Point Coordination Function (PCF). Although PCF is contention-free, the scalability issue remains a risk during periods involving heavy network loads.

The IEEE 802.11 has been improved consistently to cope with different applications (Raniwala and Chiueh, 2005). For example, the IEEE 802.11a standard is a variant of the IEEE 802.11 standard. This standard operates in the 5 GHz range (data rate of 54 Mbps) and it supports both Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). However, DSSS is suffering from problems such as short transmission range and interference due to the use of high-frequency spectrum (Zhou et al., 2006). To alleviate this problem, IEEE 802.11b has been introduced. Still, it is designed based on the DSSS technology. Meanwhile, it operates in the 2.4 GHz spectrum (data rate of 11 Mbps). Nevertheless, it is not backward compatible with the previous (IEEE 802.11a) standard. Therefore, the IEEE 802.11g standard (2.4 GHz with a data rate of 54 Mbps) has been developed to support backward compatibility with the previous IEEE 802.11a standard. In order to support higher data rate, the IEEE 802.11n standard has been designed based on Multiple Input Multiple Output (MIMO) technology.

Although improvements have been made, the variants of IEEE 802.11 standards are still suffering from some problems. For example, in DCF schemes, it is highly competitive while accessing the medium which might create congestion problems when the loading is high. For example, in DCF schemes; the access to the medium is competitive and this may create congestion problems when a number of nodes exponentially increased, which can potentially result in unfair bandwidth share and affect network performance. Furthermore, there is no proper mechanism to maintain performance in the PCF environment.

2.3.2 Related work on IEEE 802.11 MAC

IEEE 802.11 MAC provides addressing and channel access control mechanisms that enable several terminals or network nodes to communicate in a network. It has been modified in order to improve the performance of the IEEE 802.11 standard. For example, the IEEE 802.11 MAC layer is able to address, frame and coordinate with the wireless medium (Li et al., 2007). Furthermore, the improvement of the MAC layer provides a network with a better QoS guarantee. Some of these improvements will be represented as follows:

2.3.2.1 QoS Scheduling

Another MAC improvement technique is the priority scheduler which selects packets from a queue with the highest priority. This approach is relatively simple; however, it can lead to starvation of lower priority packets whenever there exists a steady flow of high priority packets. There are two types of scheduling schemes, i.e. deadline-based and rate-based. Depending on the requirement of each flow, the process scheduler in the IEEE 802.11 standard distributes the packets from various flows to specific links within a small-time interval. The distribution should be performed in a hardware-friendly manner as well. Scheduling is designed to provide a better throughput while decreasing the transmission time. For efficiency, the changes in resource adaptation must be closely monitored (Yu et al., 2013). The cross-layer design algorithm (Zhang et al., 2009) has been developed for scheduling QoS packet. This algorithm takes into account both delay and information shared at the PHY, MAC and network layers. It manages high-speed data transmission without unfairness and monitors the changes in the network.

An HCF-based packet scheduler (Ansel et al., 2004) has been implemented based on the IEEE 802.11e standard. Both constant bit rate and variable bit rate of the QoS sensitive traffic are supported. It provides bandwidth support and smaller delays to all network flows as well. Parameters such as bit rate, delay, and throughput are considered in the QoS scheduling. Strict priority improvements technique is one of the scheduling algorithms. Here, the buffer is partitioned into numerous queues, in which its quantity is equal to that of priority flows. The packets are stored in these queues (by the scheduler) according to the associated priority level. Subsequently, the flows in the same queue are sent using the FIFO scheme. The implementation of this algorithm is straightforward; however, it is accompanied by an inconsistent bit rate and possible data losses. Moreover, the lower priority flows may have zero throughputs. A network calculus method has been used by (Georges et al., 2005) to evaluate the performance of the switch. It serves as a good model of packet exchanges and it can be used to determine the end-to-end delay. Note that the strict priority scheduling algorithm is normally implemented in Ethernet switches. A modified version has been proposed by (Jiang et al., 2002), where different flows are assigned with different parameters.

In the Weighted Fair Queuing (WFQ) algorithm, the queues are not served on FIFO. Instead, each flow is given a specific weight in accordance with the QoS requirements (Parekh and Gallager, 1993). Hence, the bit rate varies from one flow to another. There is an upper bound of the buffer size so that all flows can have a share of the bandwidth. An interleaved WFQ scheme has been implemented by (Y. M. Chen et al., 2005). An interleaved table has been used to specify the queue sequence so that higher priority flows are visited more frequently. Undoubtedly, this scheme circumvents the latency and jitter problems in traffic queues. In (Banchs and Perez, 2002), the WFQ scheme that is backward compatible with the IEEE 802.11 standard has been reported. Results showed this scheme is able to provide appropriate bandwidth distribution even with high traffic condition.

Weighted Round Robin (WRR) is a frame-based version of WFQ. Again, the flows are separated into different queues (with a unique weight). In order to cope with different packet sizes, a scheduling algorithm called the dynamic WRR has been proposed by (Kwon et al., 1998), which is suitable for all traffics having variable and constant bit rates. In this method, a dynamic weight is assigned to each queue, which is helpful in providing multimedia services even in the presence of bursty traffic. (Kwak et al., 2002) have proposed a modified dynamic WRR scheme to avoid the delay in real-time traffic and provide efficient transmission of other traffics.

The Earliest Due Date (EDD) scheme implemented in wired networks works by assigning deadlines to different packets. Packets with smaller deadlines are served first. Since the characteristic of wireless networks is varying consistently, the deployment of EDD is challenging. Therefore, (Elsayed and Khattab, 2006) have proposed a Channel-Dependent EDD (CD-EDD). This algorithm works based on the channel state, and the packets are queued based on the earliest expiry time as well as other channel parameters. The highest transmission rate is then granted to the prioritized flow.

Traffic shaping is implemented to control the traffic flow via limiting the number of packets per node. A traffic controller is normally adopted to satisfy the QoS requirements of each flow. Depending on the flow requirement and variations in the channel, the resources are then allocated via traffic shaping. This process can be used to determine the system performance (Morris et al., 2008). Traffic shaping parameters such as aggregation level and bursting level have been used in the QoS model of the IEEE 802.11 standard. Here, aggregation level is the number of packets grouped into a single

IEEE 802.11 packet. Bursting level, on the other hand, is the number of packets transmitted at each Transmission Opportunity (D. Zhang and Ionescu, 2007).

2.3.2.2 Priority Queues

Priority queues are enforced at the MAC layer upon segregating the data packets. A packet with the highest priority is transmitted first. There are eight levels of priority (see Table 2.1). Normally, the most critical application contains the highest level (with the highest priority). The next two levels could be delay-sensitive video and audio applications. Regular data traffic and activity such as video streaming are assigned to level four or below (Sundareswaran et al., 2007).

Table 2.1 Priority Levels for Various Applications Types for Priority Queuing

Priority	Access Priority	Category
Lowest	1	Background Traffic
	2	Background Traffic
	0	Best Effort
	3	Best Effort
	4	Video
	5	Video
	6	Video
Highest	7	Voice, Management

2.3.2.3 DCF Improvements

DCF improvements are part of the MAC improvements as well (Ni and Turletti, 2004). One of the examples of DCF improvement is Distributed Fair Scheduling (DFS). In general, it is not advisable to restrict the service traffic, to provide better service and to assign more bandwidth during high traffic. In DFS, a weight is assigned to each flow. The value of weight is proportional to the flow's priority and bandwidth. A central AP is used to contain information of all traffic flows from different nodes. These flows are then assigned with a weight. All traffics must go through the AP (Lindgren et al., 2003). In order to determine the transmission order of each node, the DCF scheme adopts the backoff mechanism of IEEE 802.11. Each node selects a random backoff time (dependent on packet length and flow priority) upon starting the transmission. For example, those nodes with lower priority flows have longer backoff time interval. Using packet size in the backoff calculation ensures fairness among the nodes, resulting in smaller packets being sent more often. In the case of a node experiencing a collision, the new backoff interval is generated using the same algorithm.

Interframe Spacing (DIFS) is an alternative solution used to adjust the distributed duration among flows (Aad and Castelluccia, 2001). Similar to data frames, the priority of each flow is dependent on the DIFS duration. The use of backoff time is retained in order to prevent a collision. This strategy is practical as the effect of the delay is more significant than that of packet loss. Another approach called Differentiated Maximum Frame Length has been recommended as well. In order to achieve service differentiation, nodes are allowed to transmit frames with different maximum frame sizes. Nodes with high priority flows are allowed to transmit a larger frame. For stability purpose, strategies such as disposing or fragmenting those packets that exceed the maximum frame size and maintaining the upper bound of the packet size in each node can be implemented (Aad and Castelluccia, 2000) The fragmented segments are sent without any request to send in between, waiting just for the reception of corresponding acknowledgments. Upon implementing these mechanisms, the data rates are similar to those without fragmentation.

In blackburst method, every node can access a medium (thereby jams the medium) for a prescribed time interval only (Ni and Turletti, 2004). A node with higher priority is given more privilege to transmit the data packet through the channel. Once the node detects the channel that has been idling for a period of PIFS, a jamming (blackburst) signal is sent from the node to jam the channel. The duration of this blackburst signal is indeed proportional to the waiting time for a new node before accessing the medium. Upon transmitting its blackburst signal, the lengths of other blackburst signals are compared with that of its current signal. Subsequently, the node with the longest blackburst duration is given priority to access the channel. Some improvement techniques for the DCF scheme are reported in Table 2.2.

Table 2.2 Comparison for Improvements on DCF Scheme

Author (Year)	MAC scheme	Advantages	Disadvantages
(Aad and Castelluccia, 2000)	Differentiated Maximum Frame Length	Reduces contention overhead and achieves good differentiation	Better with noisy environments, longer packets are more likely to be more corrupted than the shorter ones, thus decreasing the service differentiation efficiency
(Aad and Castelluccia, 2001)	Varying DIFS	Provides benefits to real-time applications where the higher delay is more significant than lower packet loss	Low priority traffic suffers when high priority frames are queued
(Lindgren et al., 2003)	Distributed Fair Scheduling (DFS)	Provides fairness to all flows; the performance of high priority flow is increased	It has a high implementation complexity
(Ni and Turletti, 2004)	Blackburst	Minimizes delay of real-time flows; high priority flows get maximum benefit in the absence of low priority flows	It requires constant access intervals for high priority traffic

2.3.2.4 PCF Improvements

The MAC Improvements can be also performed in terms of PCF (Ni and Turletti, 2004) such as Distributed Time Division Multiplexing (TDM). Similar to the regular PCF, TDM uses a polling method. Apart from that, time slots are defined in TDM as well, and each time slot is assigned to a specific node. By using time slots, the frequency of using AP in controlling the packet transmission can be greatly minimized (Drabu, 1999). Hybrid Coordination Function (HCF) is implemented in the IEEE 802.11e standard in order to improve DCF and PCF. HCF employs two methods: (1) contention-based, or Enhanced Distributed Channel Access (EDCA); (2) contention-free, or HCF-Controlled Channel Access (HCCA). AP is adopted as a traffic manager, a Hybrid Coordinator (HC) (Chen et al., 2011) and a centralized coordinator. HC manages the frame exchange and the frame handling rules in HCF. HC is applicable for both contention-based and contention-free periods. The traffic consists of several wireless nodes (STAs), whereby each STA is associated with a set of QoS parameters managed by AP (Kowalski, 2013). AP uses a polling method to control the traffic via sending polling packets to the nodes. Upon polling a node, a frame that contains the response and the data to be transmitted are forwarded to the poll. Therefore, the polling is dependent on the priority while ensuring QoS (Garg et al., 2003b).

2.3.2.5 IEEE 802.11e Improvements

The IEEE 802.11e standard (extended version of the IEEE802.11 standard) is able to work on any PHY implementation (Mangold et al., 2002). QoS nodes (QSTAs) contain wireless nodes equipped with IEEE802.11e features. These nodes are associated with a QoS access point (QAP) to generate a QoS Basic Service Set (QBSS). The IEEE 802.11e standard improves the MAC layer by segregating the data packets based on priority requirements, negotiation of QoS parameters via AP and admission control. Also, this standard supports a contention-based MAC layer scheme called Enhanced DCF (EDCF) and a polling-based scheme called HCF Controlled Channel Access (HCCA), which are extremely useful for QoS provisioning to support delay-sensitive voice and video applications (Choi et al., 2003).

In DCF, a Contention Window (CW or contention time of a channel) is set after a frame is transmitted in order to avoid a collision. Due to the fact that each node is unable to seize the channel immediately, the MAC protocol employs a randomly chosen time period for each node upon transmission (Yang and Vaidya, 2006). This contention window is adopted in the Enhanced DCF (EDCF) method to differentiate between high priority and low priority services (Romdhani et al., 2003). The contention window of shorter length is then assigned (via AP) to the nodes of higher priority for subsequent transmission (Krithika and Pushpavalli, 2012). The Interframe Spacing (IFS) can be modified according to different traffic categories. Instead of using DIFS (for DCF traffic previously), a new inter-frame spacing called Arbitration Interframe Spacing (AIFS) can be employed. The duration of AIFS used for traffic is longer than that of DIFS. Therefore, a traffic of smaller AIFS has higher priority (Villalon et al., 2005).

The HCF Controlled Channel Access (HCCA) in the IEEE 802.11e standard makes use of Hybrid Coordinator (HC) to allocate the bandwidth of the wireless medium (Khan et al., 2013). Upon obtaining the Transmission Opportunity (TXOP), data deliveries can then be initiated to provide transmission opportunities to nodes with higher priority without any backoff. That is, HC is able to access the channels after a period of PIFS (instead of a period of DIFS required by other nodes (Mangold et al., 2003)). Due to the fact that PIFS is smaller than DIFS and AIFS, the priority level of HC is higher than DCF that use AIFS.

Access to the wireless medium is controlled within a specific period called the Control Access Period (CAP) in HCCA (Ni, 2005). Here, the HC (or AP) grants the permission of using the medium to a node. The AP can access a medium in advance and provide the TXOP to other nodes. As a result, the data transfer from a node can be executed regardless of the congestion level in the channel (Rashid et al., 2008). Also, AP can provide the parameters needed for QoS provisioning (Dujovne et al., 2010). For example, CAP in the contention period is employed to regulate access to the medium in order to monitor various QoS parameters (Reddy et al., 2006). Nevertheless, in this method, AP is not the controller as nodes having the DCF traffic or any EDCA traffic can interfere with the scheduling performed at the AP level, which would delay the pre-scheduled data transfer at a node (Yuan et al., 2016). Moreover, in CAP, RTS might be employed to prevent other nodes from contending the medium. This would undoubtedly cause a marginal increase in the overhead (Rashid et al., 2007).

Contention Free Period (CFP) is an efficient method as it allows AP to fully control the medium (Cervello and Choi, 2006) so that all nodes do not contend for accessing the medium (Jing and Chienhua, 2002). Here, AP handles the scheduling of the traffic and the QoS provisioning. AP can set numerous CAPs and it uses the smallest time interval to separate the CAPs (Rashid et al., 2007).

There are other important features associated with the IEEE 802.11e standard. The TXOP parameter is used to specify a time limit while utilizing the radio resources at the nodes (Mangold et al., 2003). Here, AP employs the Automatic Power Save Delivery (APSD) mechanism to send multiple frames within a time period. Note that AP may sleep to conserve energy (Perez and Mur, 2010). The APSD mechanism supports both scheduled APSD and unscheduled APSD for the power-saving purpose (a legacy of IEEE 802.11). The IEEE 802.11e standard supports block ACKs as well in order to acknowledge numerous MAC Protocol Data Units (MPDUs) in a single block acknowledgment frame. This could reduce the overhead undoubtedly (Tinnirello and Choi, 2005). NoAck is another improved version that is able to show packet loss so that retransmission can be performed quickly in order to reduce delay (Politis et al., 2011). It supports direct link setup to allow direct node-to-node transfer within a service set.

2.3.3 Related work on MAC based on Backoff Mechanism

Many solutions have been proposed to improve MAC protocol. The backoff mechanism is most popular in IEEE 802.11 MAC, which is based on the contention window size (CW). If the CW is too small, then the collision probability will be increased. The system performance will be affected and if the CW is too large, the system will take a long time (delay) to access the medium. Thus, the CW adjustment is the most important part of the backoff Mechanism to improve a network congestion control (Cho and Jiang, 2015). The goal of “collision and delay problems resolution algorithm” is to set a CW following the network congestion condition.

Many algorithms have been proposed by taking into account important aspects such as system throughput, delay, and QoS requirements. BEB is the most common algorithm where the CW is increased rapidly after unsuccessful transmission. The CW is decreased promptly to the minimum value if the transmission is successful (Bianchi, 2000). This algorithm allows a node with successful transmission to access the medium again, thus leading to unfairness and wild oscillation (probability of collision increases). To prevent such wild oscillation and unfairness, MILD is proposed by gradually adjusting the CW (Bharghavan et al., 1994).

In the DIDD algorithm, the CW is increased/decreased exponentially (Chatzimisios et al., 2005). The rapid increase would reduce the probability of continuous collision in the case of heavy networks (a large number of active nodes in the system). Meanwhile, the exponential decrease would reduce the probability of collision in the same system as well. In contrast, LILD is applicable for heavy networks (where the CW is reduced) for reducing the probability of collision (Soni and Chockalingam, 2003) Nevertheless, LILD is not applicable for heavy networks (where the CW is increased) because space is inadequate to avoid a collision.

The above algorithms do not support scalability because the contention level condition is not considered. Dynamic approaches can be adapted to adjust the contention window size depending on the network congestion condition. For example, in AEDCF, PCB, and DDCWC algorithms, each node senses the medium and estimates the contention level condition. The CW is then calculated to improve the system performance (Balador et al., 2012; Liang et al., 2008; Romdhani et al., 2003). The accuracy of the estimated system congestion status determines the appropriateness of the calculated CW.

The system congestion status can be determined as well by using the control parameter approach (threshold). When the current CW is less than or equal to the threshold, the network is in a low congestion condition and vice-versa. For example, MIMLD is proposed by introducing a control parameter called CWbasic with three possible stages: multiplicative increase, multiplicative decrease, and linear decrease. CWbasic identifies the contention level in the wireless medium (Pang et al., 2004). MIMLD has improved the system performance easily without involving measurement and computation. However, MIMLD is not applicable for heavy network due to the rapid shrink of the CW in the case of high congestion.

In contrast, ELBA is applicable for light and heavy networks because its contention window size is tuned linearly when there are more competitive wireless nodes (Lin et al., 2008). In another research, DCBTA algorithm is proposed (Alkadeki et al., 2016), the CW in this algorithm is increased rapidly in the case of unsuccessful transmission in order to have fewer collision during the waiting period. DCBTA performs better than other algorithms in the case of heavy networks due to the improvement of system throughput and the reduction of collision probability. However, since this algorithm does not consider the accuracy of the CW change rate. Thus, it does not take into account the practical network operation and the channel will not use efficiently. The most related backoff algorithms improvements are summarized in Table 2.3.

Table 2.3 Comparison for Enhancements on Backoff Mechanism

Author (Year)	**Algorithm**	**Modification**	**Performance**
Bharghavan (1994)	Multiplicative Increase and Linear Decrease (MILD)	Modified version of Binary Exponential Backoff (BEB)	Performed better than BEB
Soni (2003)	Linear Increase and Linear Decrease (LILD)	Modified version of Multiplicative Increase and Linear Decrease (MILD)	Performed better than BEB and MILD
Pang (2004)	Multiplicative Increase Multiplicative Linear Decrease (MIMLD)	Modified version of Multiplicative Increase and Linear Decrease (MILD)	Performed better than BEB
Deng (2004)	Linear/Multiplicative Increase and Linear Decrease (LMILD)	Modified version of Multiplicative Increase and Linear Decrease (MILD)	Performed better than BEB and MILD
Chatzimisios (2005)	Doubles Increased Doubles Decreased (DIDD)	Modified version of Binary Exponential Backoff (BEB)	Performed better than BEB
Lin (2008)	Exponential Linear Backoff Algorithm (ELBA)	Modified version of Linear Increase and Linear Decrease (LILD)	Performed better then LILD with low traffic networks

Table 2.3 Continued

Author (Year)	Algorithm	Modification	Performance
Balador (2012)	Dynamic Deterministic Contention Window Control (DDCWC)	Modified version of the IEEE 802.11 DCF	Provided better throughput
Alkadeki (2016)	Dynamic Control Backoff Time (DCBTA)	Modified version of Binary Exponential Backoff (BEB)	Had a better performance and provide better throughput compared to BEB and ELBA

2.3.4 Critical Analysis for the Related Work

This section discusses the previous studies on the IEEE 802.11MAC. The model presented by Bianchi in 2000 is the most famous analytical performance model for IEEE 802.11 DCF under heavy traffic conditions. The model showed the behavior of a single node that is using a 2D Markov chain analysis model, and this is the proper way of representing a series of changes/transitions between different states, like the behavior of IEEE 802.11 DCF. Several works have consequently been based on this model. Meanwhile, (Bianchi, 2000) analyzed the saturation throughput performance on the basis of the conditional collision probability, effectively neglecting the idle period. The model presumed that the collision and busy probabilities are the same. (Chendeb Taher et al., 2011) then argued that it is not justifiable to assume that the busy channel probability and collision probability as the same because the collision probability and busy probability are two different events.

Alternative approaches towards extending 802.11 analytical models are available. For instance, (J. Wang et al., 2015) used the Equilibrium Point Analysis (EPA) to propose a novel performance analytical model under more flexible network sources. This method can be used to propose the performance of IEEE 802.11 DCF analytical model based on various network conditions. It is an appropriate method for the evaluation of the system throughput under different parameter setup. However, this model only presented the mechanism of transmission under idle, transmission, and collision states. The authors, in this case, did not consider the mechanism of transmission under the busy state.

(Dong and Varaiya, 2005) used virtual slot time under saturated traffic conditions to propose a performance analytical model for IEEE 802.11 DCF. The authors represented the activities in the transmission medium using virtual slot activity, and this can present transmission error. However, this is a similar mechanism to the principle of the 2D Markov chain analysis models. This method is based on the collision and error transmission probabilities but did not consider the busy state probability. Besides, the Bianchi's model has been extended by many researchers to enhance the performance of the IEEE 802.11 DCF model. However, there are some limitations of Bianchi's model that must be investigated. Some of the limitations include the assumption of an idle channel such as no error or hidden node exists, infinite packet retransmissions, the saturated contention levels, and the dependence on only collision probability for analytical performance. To address some of these issues, (Vishnevsky and Lyakhov, 2002) had modified the Bianchi's model to incorporate the channel noise and also extended the model from a single-hop model to a multi-hop model. The authors considered the problem of the hidden nodes by assuming that an average number of hidden nodes exist in each node.

(Ergen and Varaiya, 2005) suggested a new analytical performance model for IEEE 802.11a under non-saturated network conditions. The model also assumed the busy probability and collision probability to be the same. Similarly, (Malone et al., 2007) extended the Bianchi's model to non-saturated network conditions by the addition of a new state to represent the post backoff which was not considered in the Bianchi's model. However, Malone's model was based on the idle and collision probabilities. The Malone's model, however, did not consider the busy probability because it extended the Bianchi's model based on the condition of the traffic only.

On the contrary, many researchers have concentrated much on the IEEE 802.11 standard improvements. In this regard, (Lin et al., 2008) focused on the Enhancement Distributed Channel Access (EDCA) under saturated network conditions. They depended on the mean value analysis (MVA) to propose a novel analytical model for IEEE 802.11e performance. With this method, there is less computation overhead compared to the multi-dimensional Markov Model.

(Hui and Devetsikiotis, 2004) suggested a unified analytical model for the performance of the IEEE802.11e-EDCA using the Markov Model analysis on the

Bianchis' model (Bianchi, 2000) and the Tay's model (Tay and Chua, 2001), where both models are combined into one model. The authors suggested a common performance analytical model to reduce the ambiguity during the application of the model. It can be observed that most of the models discussed were based on the extension of the Bianchi's model and did not consider the busy probability in the analytical model. Some of the models merely assumed the busy and collision probabilities as the same, which is yet to be justified (Alkadeki et al., 2013).

As earlier stated, most of the works on the behavior of single hop cases and wireless network performances have been based on the Markov chain analysis model. With this, (Bianchi, 2000) proposed a better evaluation model for the performance of the IEEE 802.11 DCF under saturated network loads. However, the standard of the network is based on several layers, and therefore, there may be delays in the different layers of a network such as the MAC layer and upper layer. (Wu et al., 2002) considered the maximum entry limit while extending the Bianchi model. In the model, the DCF scheme was modified to a new scheme known as DCF+ which can enhance the transmission control protocol (TCP) performance. This suggested that the authors focused on the MAC layer for the improvement of the performance analysis model, as well as on the transport layer to support packets transmission over WLANs (Alkadeki et al., 2013). (M. Mishra and Sahoo, 2006) focused on the improvement of QoS by investigating the delay control problem over the upper layer. The work demonstrated that the upper layer could not efficiently provide delay support alone without involving the MAC layer. On the contrary, several studies have focused on the delay in the MAC layer rather than delay in the transport layer. For instance, (Chatzimisios et al., 2003a) had based their model on the Markov chain analysis model to work on the MAC layer for the development of Wu's performance analysis model (Wu et al., 2002) by considering the limits of the packet retry limits under saturated network conditions. The work proved that the model would offer better results considering the packets retry limits compared to the models that do not consider packets retry limits.

(Vukovic and Smavatkul, 2004) similarly enhanced the performance of the Bianchi's model from a 2D Markov chain to a one-dimensional Markov chain. The authors of this model calculated the average packet delay by reducing the performance of the Wu analytical model (Wu et al., 2002) from the two dimensional Markov chain to a one dimensional Markov chain. Meanwhile, the one dimensional Markov chain is good for simple calculations but not ideal for larger networks (Alkadeki et al., 2013). Similarly, (P Raptis and Vitsas, 2005) proposed a novel analytical model for the estimation of the average packet delay of IEEE 802.11 DCF. The model, according to the authors, provided a better accuracy compared to the Vukovic's model (Vukovic and Smavatkul, 2004).

(Paschalis Raptis et al., 2009) developed an IEEE 802.11 DCF delay model under saturated network conditions by considering the most likely delay events, like average packet drop time, packet delay jitter, average packet delay, and packet delay distribution. However, the author had based his model on Wu's model and therefore, the delay model did not consider the difference between busy and collision probabilities. Some researchers similarly focused on the prediction of the real time. For instance, (Qi et al., 2009) employed multiplayer games for the estimation of the performance of IEEE 802.11. They derived the jitter, throughput, and delay as clients. (Ivanov et al., 2011) suggested an estimation method for the distribution of packet service time under saturated network conditions. The model portrayed the behavior of the delay in the MAC layer as a terminal renewal process which is based on successful transmissions. The author of the model did not consider the busy probability. Most of the existing models concentrated on the estimation of the average packet delay in the MAC layer while leaving the distribution of the delay unsolved (Ivanov et al., 2011). Additionally, most models do not consider the difference between collision and busy probabilities and this is why most studies do not consider the busy probability.

As earlier mentioned, the IEEE 802.11 backoff mechanism is important for the control of the channel access to maximize fairness and throughput (Cho and Jiang, 2015). Several methods exist for the extension or proposing of backoff mechanisms, of which most are based on the modification of the backoff parameters such as the size of the contention window (CW) and the backoff stage. This is why many studies have focused on the modification of the size of the CW during the development of the backoff mechanism for the improvement of IEEE 802.11 DCF performance. Therefore, there could be an improvement in the system throughput and collision probability reduction through the use of an appropriate CW. However, most methods do not consider the dynamic contention levels. (Bharghavan et al., 1994) for instance, proposed a novel backoff mechanism known as Multiplicative Increase and Linear Decrease (MILD) algorithm by focusing on the modification of the CW to CW×1.5 instead of doubling it after each unsuccessful packet transmission. Moreover, the CW is reduced by one after each successful packet transmission instead of resetting back to zero. However, the decrease in the CW helped to avoid any performance degradation. The MILD algorithm is, therefore, better with larger networks compared to BEB algorithm.

(DengVarshney et al., 2004) created a new algorithm known as Linear Increase Linear Decrease (LILD) algorithm by extending the MILD algorithm. They applied the CW+ CWmin as the CW instead of multiplying by 1.5 to avoid slow linear changes. The LILD algorithm provided a better performance compared to the MILD over larger networks. Similarly, (Song et al., 2003) proposed a new backoff mechanism known as Exponential Increase Exponential Decrease (EIED) algorithm by exponentially increasing and decreasing the size of the CW. (Chatzimisios et al., 2005) proposed the Double Increment Double Decrement (DIDD) algorithm by doubling the size of the CW after each unsuccessful packet transmission in a similar manner to the BEB algorithm but dividing the CW by two after every successful packet transmission. The DIDD algorithm performed better than the other algorithms earlier mentioned. Additionally, the improvement of the BEB algorithm is still attracting much researcher’s interest. (Cheng et al., 2014)) recently reported the performance of the BEB algorithm as poor due to the restoration of collisions and the CW after each successful packet transmission. This research is focused on the improvement of collision avoidance under saturated contention levels.

However, all the algorithms discussed in this review did not consider dynamic contention levels as there are other fascinating steps that can still be taken. For instance, (Lin et al., 2008) in his work, had focused on the channel contention levels to propose the Exponential Linear Backoff Algorithm (ELBA) which combined both linear and exponential algorithms based on the network condition and provides a better system throughput compared to the conventional BEB, EIED, and LILD algorithms. (Liang et al., 2008) monitored the channel contention levels using pause count backoff, with the aim of setting an appropriate CW based on estimation results.

(Cui and Wei, 2009) developed an adaptive backoff mechanism that is based on the difference between fairness and efficiency in Ad-Hoc networks. The algorithm is based on a fair schedule for the control of the increment and decrement in the size of the

CW considering the status of the channel. (Fu et al., 2009) considered the dynamic contention levels to propose an algorithm that is based on the monitoring of the channel prior to the transmission of data. Each node in the algorithm can record the number of busy slots via an observation window. The packet sender can estimate a CW and dynamic priority based on the number of successful packet transmissions. (Balador and Movaghar, 2010; Balador et al., 2012) had monitored the network loads using a Channel State vector (CS) by proposing the Dynamic Deterministic Contention Window Control Algorithm (DDCWC) which is based on the monitoring of the conditions of the network by checking the CS. However, it is hard to select an optimum CW using CS based on different network conditions. DCBTA is another algorithm has been proposed, in this algorithm, the CW is increased more rapidly in the case of unsuccessful transmission in order to have fewer collision during the waiting period (Alkadeki et al., 2016). DCBTA performs better than other algorithms in the case of heavy networks due to the improvement of system throughput and the reduction of collision probability.

2.3.5 Limitations of the Latest Related Work

As discussed before, when the MAC protocol employs the backoff mechanism, a single station would transmit at channel capacity and the other stations would be completely backed off. Thus, after every collision, it is very likely that the station of lesser time interval would retransmit first, and its time counter is then reset to CWmin. This phenomenon keeps recurring after every collision, with the time interval becomes so small to avoid collisions. To rectify this problem, the MAC protocol mechanism must consider accuracy to producing a proper CW.

CSMA/CA with DCBTA backoff is the latest related protocol that performs better than other MAC protocols in the event of heavy networks due to the reduction of collision probability (Alkadeki et al., 2016). However, while this work did not consider the accuracy of CW, it neglected the possibility that the CW change rate could be smaller than that required (CW increment), thus providing large CWs that would lead to excessive idle period. Likewise, when the CW change rate is larger than that required (CW decrement), it provides small CWs that would lead to an excessive number of collisions. In either case, the channel is not used efficiently.

Therefore, a MAC protocol mechanism considers the accuracy of CW by tuning the CW change rate to reflect the network condition may lead to enhancing the system performance. Thus, by considering the accuracy of CW, situations such as improper interval time that increases the collision probability and excessive idle time that degrades the network performance can be avoided.

2.4 Summary

This chapter was divided into two parts. The first part has reviewed the basic components of IEEE 802.11 standard. It described the component functions and protocols of IEEE 802.11 such as topology, access modes, CSMA/CA, two-way and four-way handshakes. The procedure for transmission such as standard backoff was also explained. The second part reviewed those research works detailing on the performance and enhancement of IEEE 802.11. The knowledge gap was then identified.

From the literature, the use of CSMA/CA backoff is crucial for controlling collision rates and system throughput for CW-based wireless networks. In fact, there is a difference between avoiding a collision and producing a proper CW. However, most of the previous works did not take CW accuracy into account. Some research works considered both busy probability and collision probability, while others ignored the busy probability and considered the collision probability only. These assumptions are not justified. Thus, a proper CW must be considered in the enhanced IEEE 802.11.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methods involved in designing and developing the MAC protocol (CSMA/CA). The chapter starts by highlighting the research and design strategies of the proposed work, followed by the introduction of MAC protocol. Next, the chapter presents the development and implementation of the proposed MAC. This chapter concludes with the validation of the network model.

3.2 Research Strategy

In order to achieve the stated objectives, the research strategy is very important, supplemented by a clear workflow on how the proposed work should be designed and implemented. The research strategy includes several stages, i.e. data collection, data analysis, data interpretation, and data reporting (Creswell, 2014). In order to design the research strategy in the current work, the waterfall model was used to define the research process.

The proposed work was executed in the following order. Firstly, the literature related to the IEEE 802.11 standard and the MAC layer was reviewed. The second stage involved the design of the proposed work. The third stage revolved around the modelling of the proposed work. The fourth stage concerned on code implementation and software execution, followed by benchmarking the results with others. The fifth stage involved the validation of the outputs and the final stage highlighted on the result evaluations and the associated conclusions. Figure 3.1 shows the waterfall model which is beneficial in research management (Creswell, 2014).

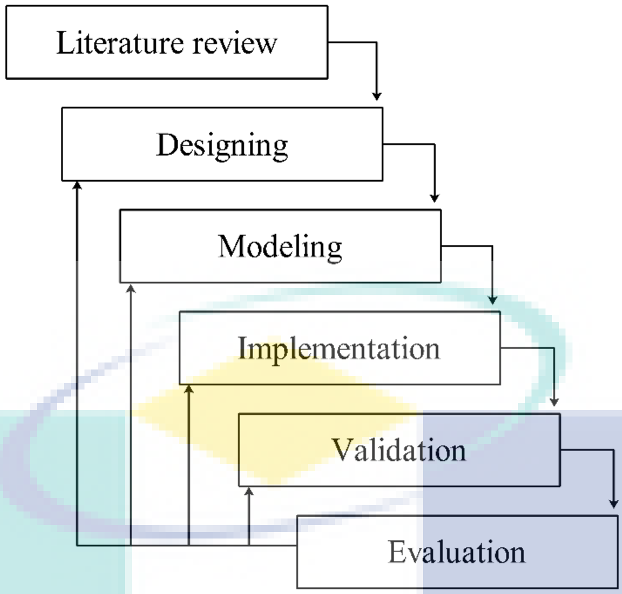

Figure 3.1 Research Strategy Model

Based on the research strategy model, the quantitative approach was selected since the mathematical/numerical models have been developed based on the existing literature. Therefore, the quantitative approach is a suitable approach in this case for data collection and summarizing the research information. The MAC layer is the most important layer for enhancing the system performance. This work has been initiated by studying the effect of altering the behavior of the existing MAC solutions, their drawbacks, and the parameters that affect network performance. Based on this information, the MAC protocol can then be improved.

3.3 The Proposed MAC Protocol

Although the IEEE 802.11 standard adopts the CSMA/CA MAC protocol to avoid collisions, it is not able to prevent the loss in efficiency as the number of users (contented nodes) increases in the network. CSMA/CA has been implemented in IEEE 802.11 WLANs through a Distributed Coordination Function (infrastructure-less). It works based on deferring the transmission of each node for a random number of empty slots that are produced from the Contention Window (CW).

As mentioned in Chapter 2, the accuracy of CW was not considered by researchers so far. In other words, the practical network operation has not been taken into account. The possibility of CW change rate becoming larger/smaller than that required has been neglected. In either case, the channel is not efficiently used, thus degrading the system performance.

In this study, a MAC protocol has been proposed based on the traditional IEEE 802.11 with backoffs. This new model considers the CW accuracy and the contention level. The proposed protocol has been implemented at various contention levels. Various control parameters have been introduced to tune the required CW in order to avoid a collision and unnecessary delays. In addition, the proposed protocol uses a reference point for the collision rate in order to determine the network contention level. In the proposed protocol, CW has been adjusted to reflect the number of active stations in the network. The proposed protocol consists of seven basic stages.

The first stage is the *Initialization Stage*. In this stage, when a node transmits a data packet, both CWmin and CWmax are set; this procedure is similar to the traditional MAC protocol. Meanwhile, in the proposed protocol, a control parameter reference point for the collision rate (Threshold) is set to determine the network contention level.

After initializing the protocol parameters, the communication channel must be available to transmit the data packet. Therefore, the node performs a sensing operation on the channel (*Sensing Channel Stage*). If the channel is available for the first data transmission, the node will perform another sense after a short period of time denoted as DIFS to avoid data collision. If the channel is still idle, then the node would proceed to the *Packet Transmission Stage*. Otherwise, the *Countdown Backoff Stage* is performed.

Before a node attempts to send a data packet, it uniformly selects a backoff value from a window [0, CW - 1]. The backoff value is decremented by one for each time slot while the channel is idling (*Countdown Backoff Stage*). During the busy time, the backoff counter is frozen in order to ensure the evenness among other nodes. When the backoff value is zero, the node proceeds to the *Packet Transmission Stage*. Figure 3.2 shows the proposed protocol stages.

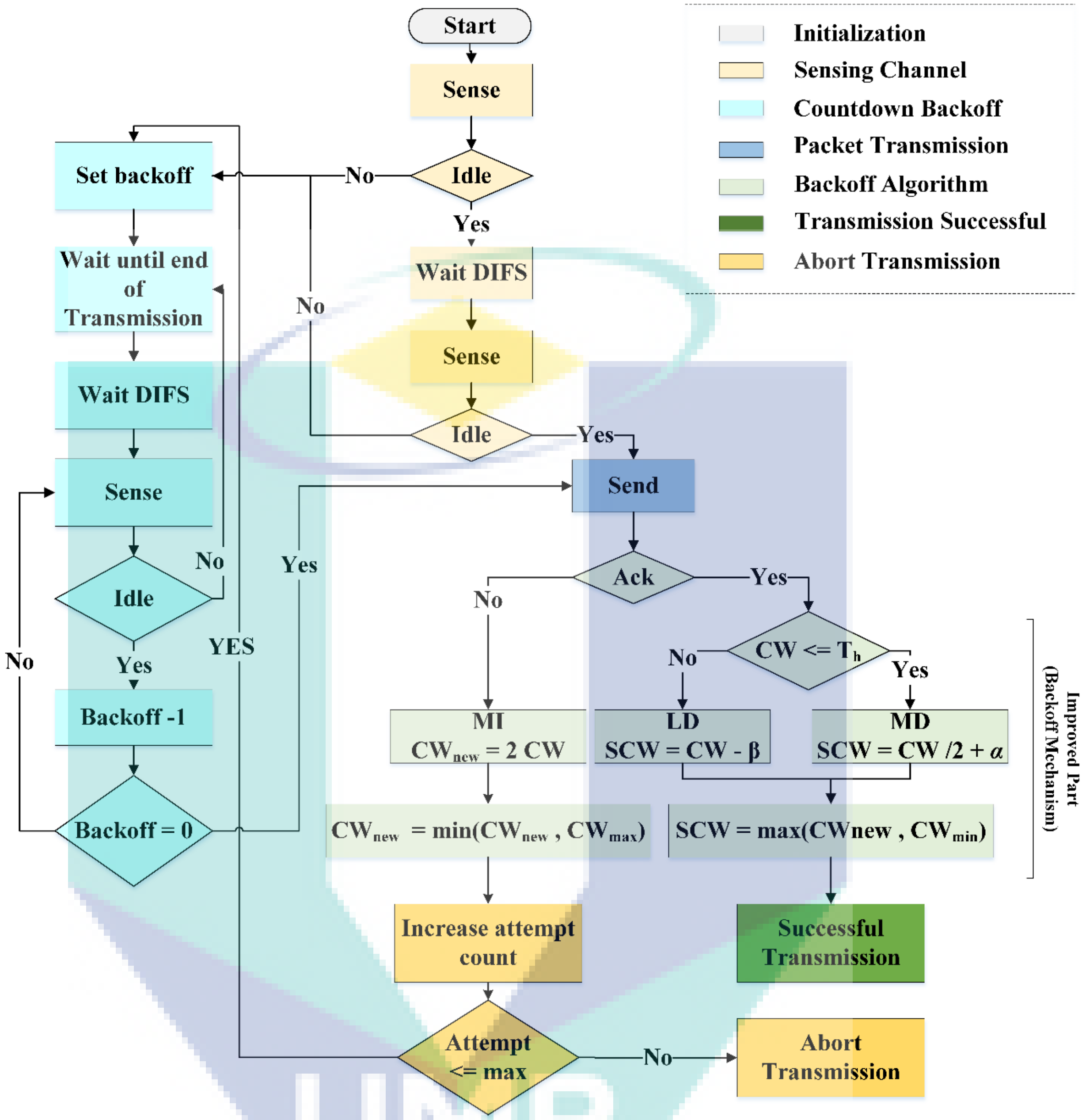

Figure 3.2 The Proposed Protocol Stages

After the *Channel Sensing Stage* or the *Countdown Backoff Stage*, the packet is sent (*Packet Transmission Stage*). Upon sending the packet, the node waits for the acknowledgment (ACK) message of the receiving node. Based on the received ACK, the node updates its CW for further communication. Next, the *Backoff Stage*, which is the essential part of the proposed protocol, is executed. In this stage, the CW is adjusted to reflect the number of active stations in the network. The proposed protocol backoff is applied and the node undergoes one of the three possible phases in order to calculate the CW (CWnew) for transmitting data packets. If the node does not receive the ACK from the receiving node within a certain time interval (or collision), it will undergo to increase phase. Otherwise, the transmission is successful and the node resets CW to CWmin as performed in the traditional MAC protocol. In the proposed protocol, however, the node may undergo any of the two phases (decrease phase) depending on the threshold value (T_h). If CW ≤ T_h, the new CW is adjusted by Alpha (α) where it is a control parameter that determines the required change rate of CW in order to avoid a collision and unnecessary delays on low-level contention network. Otherwise, the CW is adjusted by Beta (β), the control parameter that determines the required change rate of CW in order to avoid a collision and unnecessary delays on high-level contention network. Figure 3.3 shows the backoff of the proposed protocol.

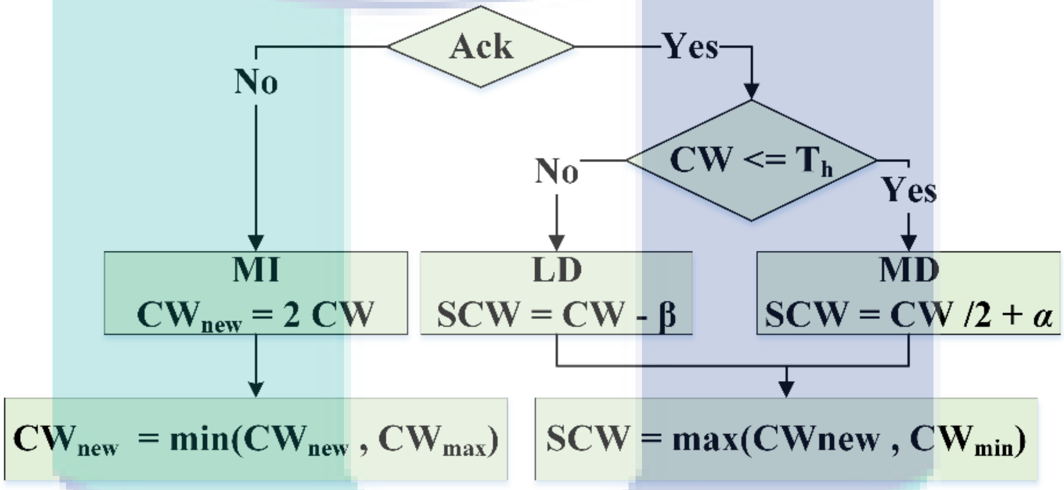

Figure 3.3 The Backoff of the Proposed Protocol

The above procedure is continued until successful transmission. However, if the Number of Attempts Counts (NAC) exceeds the limit of a number of attempts, the node would abort the transmission. When the node receives the ACK within a specific time interval, the packet transmission is considered successful. The proposed protocol output is the backoff mechanism which inherits the attributes to the proposed protocol. The aspects of the backoff mechanism have been addressed concurrently in the IEEE 802.11 environment. Figure 3.4 shows the algorithm on how to assign backoff value to each station in the network.

```
BEGIN
Initialize CWmin ← 32
Initialize CWmin ← 1024
If first-time data transmission then
  Initialize SCW ← CWmin
  Initialize CW ← CWmin
Else
  Initialize CW ← SCW
end if
Initialize Threshold ← 512
If Successful Case then
  If CW <= Threshold then
    SCW ← (CW /2) + α
  else
    SCW ← CW – β
  end if
  If CWnew < CWmin then
    SCW ← CWmin
  end if
Else
  CWnew ← CW * 2
  If CWnew > CWmax then
    CWnew ← CWmax
  end if
end if
END
```

Figure 3.4 The Proposed Protocol Backoff Algorithm

3.4 Network Modeling

IEEE 802.11 uses the CSMA/CA protocol to provide a contention-based service (Ethernet-like). CSMA/CA is provided by the distributed coordination function (DCF). Thus, the DCF mode has been considered in the current work in order to permit interactions between multiple independent stations without central control. Therefore, this strategy could be used in either IBSS network or infrastructure network. Before transmission, each station checks whether the medium is idle. If the medium is not idle, the transmission is deferred and an orderly exponential backoff mechanism is activated to avoid collisions.

In the current work, upon performing the simulation using OPNET Modular, performance parameters such as collision rate and throughput were then analyzed. OPNET is a numerical computing environment that simulates the behavior of a network and emulates it in discrete time. In order to create a design for the proposed work, the following assumptions were made: (1) the signal of a node can cover all nodes; (2) non-conflicting nodes can communicate concurrently; (3) the buffer in each node follows the first in first out (FIFO) manner for sending data from the node queue; (4) a node can transmit one packet in each time slot and (5) the topology does not change during the running period because this system is a fixed network. Figure 3.5 gives an example of the DCF Network topology.

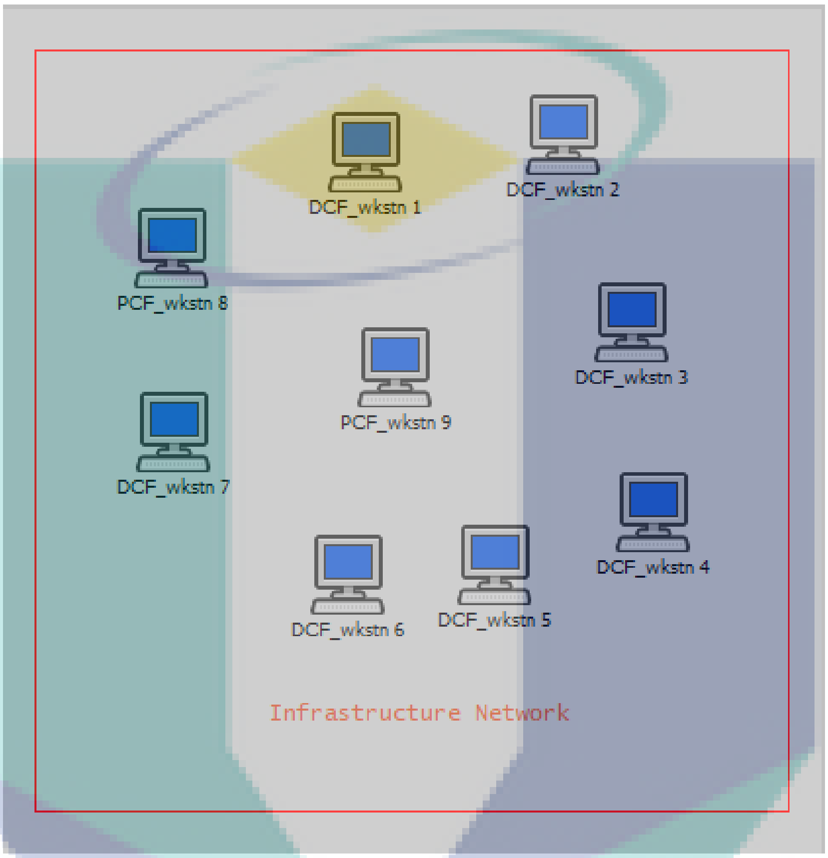

Figure 3.5 Network Topology

3.5 Implementation

The section describes the tools used in the implementation stage. Typically, the choices of tools for research implementation depend on their availabilities (hardware and/or software implementations). The current work focused on software (network simulator) implementation as hardware is costly. Network simulators are widely recognized and used in engineering research as no physical testing is involved. In this research, the network performance indicators such as collision rate, throughput, and data loss were evaluated without using hardware tools. The OPNET simulator has been used as a tool for developing, implementing and validating the proposed protocol for IEEE 802.11 standard. This simulator can also be used to compare the performance of the proposed protocol to those of the other related protocols. OPNET supports the C programming language which has been used to write the source codes in this study.

3.6 Validation

There are several network simulators, e.g. NS2, OmNet++, JSIM, NetSim, and OPNET (Siraj et al., 2012). The OPNET simulator has built-in modes such as built-in communication models, rich library application protocols and graphical user interface. In addition, the OPNET simulator has proven to be very reliable (Pan, 2008). OPNET simulator has enjoyed wide acceptability due to its robustness. It has been successfully applied to simulate network instances in node manufacturing, internet service provision, military communication, educational institutions, etc. Many representations of the OPNET simulator form small to large networks have been presented. In this work, all the nodes were considered stationary and operated based on the IEEE 802.11 MAC-based CSMA/CA protocol. Each node could communicate with others and thus, there were no hidden terminals in the simulation experiments. The topology of the network is considered as a single-hop wireless network, where nodes communicate with others directly without using a router or access point. The outputs of the experiments were then validated using the network simulator (OPNET) by repeating each experiment (14x) until the results converged.

3.7 Evaluation

The main goal of the proposed protocol was to enhance the system performance by reducing the collision rate and increasing the system throughput. The performance metrics such as collision rate, throughput, and data drop were evaluated using the numerical simulator (OPNET).

3.7.1 Collison Rate

Packet collision rate is the number of data packet collisions occurring in a network over a specified period of time. It indicates the rate at which data packets collide or are lost upon collisions. Packet collision rate is measured as the percentage of data packets that have been successfully sent out. If the number of nodes increases, the collision rate would decrease gradually. The higher mobility of nodes would decrease the collision rate. A collision occurs when two or more network nodes attempt to send data simultaneously, thereby causing a collision and damaging the transmitted data. Therefore, the nodes have to resend the data, and thus degrading the system efficiency (Lammle and Swartz, 2013).

3.7.2 Throughput

Throughput is the average rate of successful message delivery over a communication channel. The throughput decreases as the number of nodes increases. It indicates the amount of works completed within a time frame. It can be expressed as individual station throughput or system throughput. System throughput is the throughput of all stations that share a common communication medium. Throughput is conceptualized to evaluate the productivity of the computer network. It is calculated in terms of bit per second (Sakthivel and Chandrasekaran, 2012).

3.7.3 Data Drop

Network congestion is the main cause of data drop that can affect all types of networks. When an excessively large amount of data arrives, the sending is not possible and hence these data would be dropped. Data drop can reduce the throughput for a given sender, whether unintentionally due to network malfunction, or intentionally as a means to balance the available bandwidth between multiple senders when a given router or network link approaches its maximum capacity. Data drop is measured as the number of data packets dropped during communication (Kurose and Ross, 2010).

3.8 Summary

This chapter has presented the research strategy, which is one of the sequences in the design process. Each stage has been designed based on the outcome of the previous stage. Based on the nature of the research work, the quantitative approach has been selected. An efficient CSMA/CA protocol for IEEE 802.11 has been proposed in order to enhance the performance of the IEEE 802.11 standard. The implementation tools, network modeling, validation and evaluation methods have been discussed in this chapter.

CHAPTER 4

RESULTS AND IMPLEMENTATION

4.1 Introduction

This chapter discusses the experiments performed in this study and the numerical results. Firstly, the experimental design in the current work was presented. Secondly, the behaviour of the traditional CSMA/CA was presented and analysed. Thirdly, the performance of the CSMA/CA solution was presented and analysed. Next, the accuracies of the parameters used in the proposed protocol were examined. Finally, the proposed protocol was evaluated. Figure 4.1 shows the research experimental design.

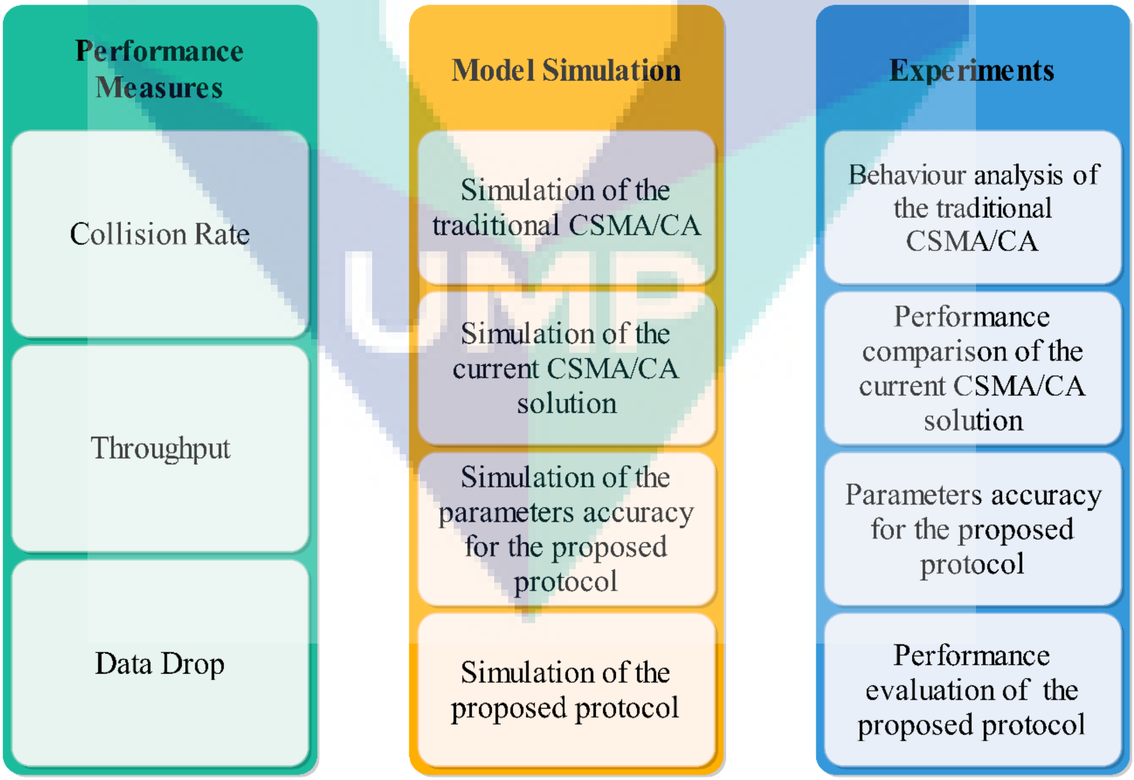

Figure 4.1 Research Experimental Design

4.2 Behaviour Analysis of the Traditional IEEE 802.11 CSMA/CA

Based on this experiment, the behaviours of the traditional MAC protocol (CSMA/CA) based on BEB backoff in terms of collision rate, total throughput, and data drop can be analysed. the results are obtained used to show the impact of the contending devices and the traffic rates (packet inter-arrival time) over the traditional CSMA/CA. The aim of this experiment was to assess the ability and the effectiveness of CSMA/CA.

4.2.1 Simulation Model

In order to simulate this experiment, a distinct simulation environment was developed. To develop this environment, the simulation software OPNET was used. This software was used to assess the performances and a series of scenarios. The size of this simulation environment was 500x500 m. For this experiment, the wireless node was considered as sender and receiver. The number of wireless nodes set in this experiment ranged from 10 to 150 with 10 intervals. Figure 4.2 shows the simulation environment for the traditional CSMA/CA.

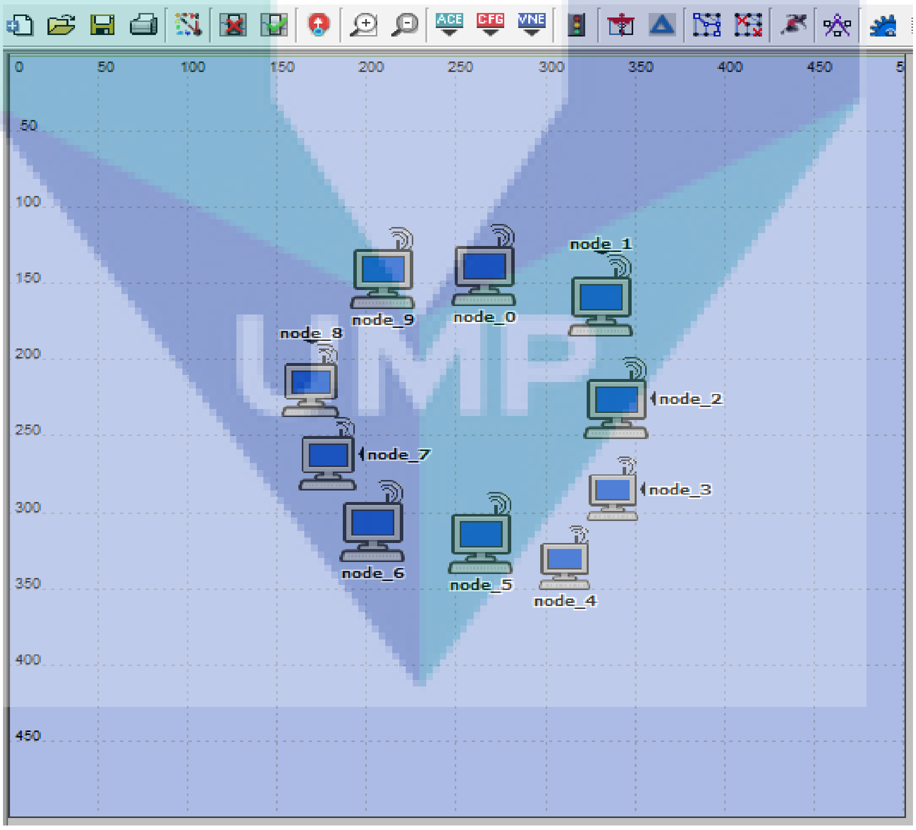

Figure 4.2 Simulation Environment for the traditional CSMA/CA

Meanwhile, the packet inter-arrival time (traffic rate) in this experiment ranged from 0 to 7 seconds in order to avoid buffer overflow. It was assumed that each wireless node sent packets without any error/hidden problem. The IEEE 802.11 MAC is an efficient method used to evaluate the system performance under various parameter settings (X. Wang et al., 2009). The simulation parameters have been shown in Table 4.1.

Table 4.1 Simulation Parameters

Parameter Name	**Value**
Simulator	OPNET
Channel Type	Wireless
Physical Protocol	802.11n
Channel Rate	54 Mbps
Access Mode	DCF
Packet Payload	1000 byte
MAC Header	224 bits
PHY Header	48 bits
ACK	304 bits
Slot Time	20μsec
DIFS	50μsec
SIFS	10μsec
Propagation Delay	0
RTS/CTC	None
Hidden Problem	None
Traffic Rate	0.015-7sec
Transmission Mode	Single-hop
MAC Protocol	CSMA/CA
CWmin	31
CWmax	1023
Network Area	500x500m
Simulation Time	6000sec
Number of Runs	14x

4.2.2 Results & Discussion

The collision rate was plotted against the number of nodes as presented in Figure 4.3. As observed, the collision rate increased with respect to the number of nodes due to the nature of the backoff mechanism of the traditional CSMA/CA. For this mechanism, after each successful transmission, CW is reduced rapidly to its minimum regardless of the state of the network (contention level). Thus, the backoff mechanism in the traditional CSMA/CA does not take into account the practical network operation. The traditional CSMA/CA neglects the possibility that the number of actively contending stations (hence the network contention intensity) can change over time.

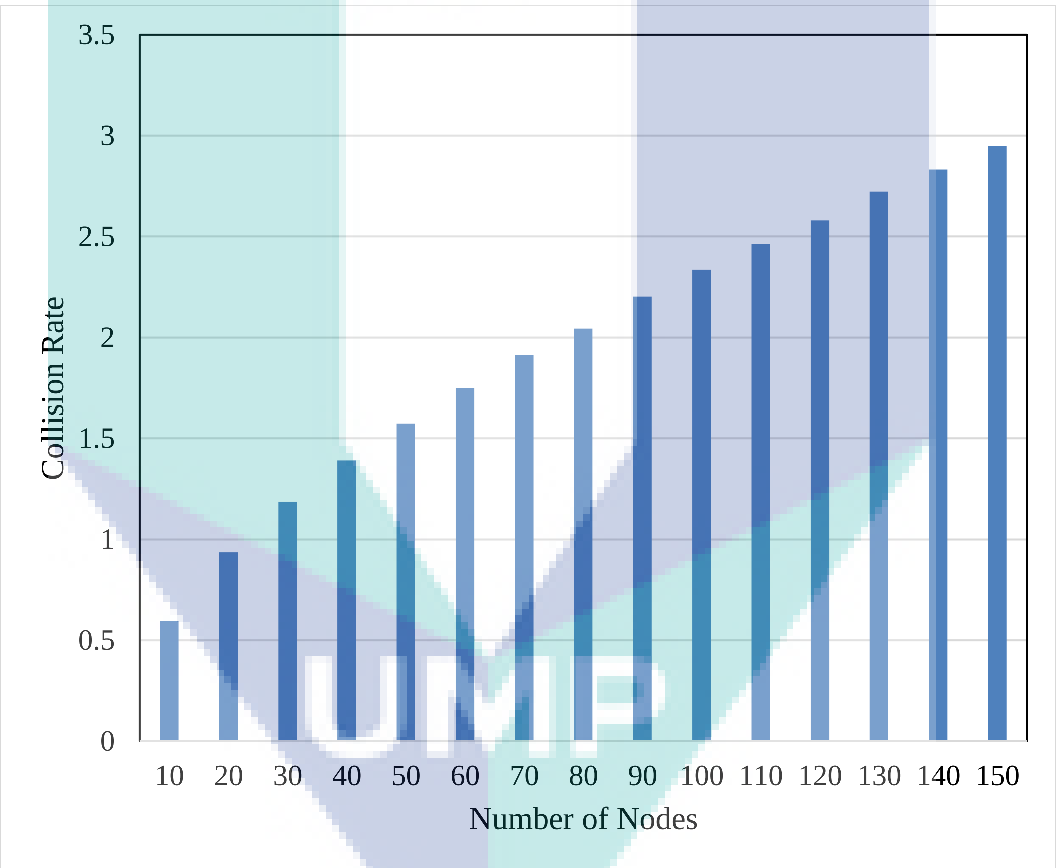

Figure 4.3 Network Collision Rate for the Traditional CSMA/CA

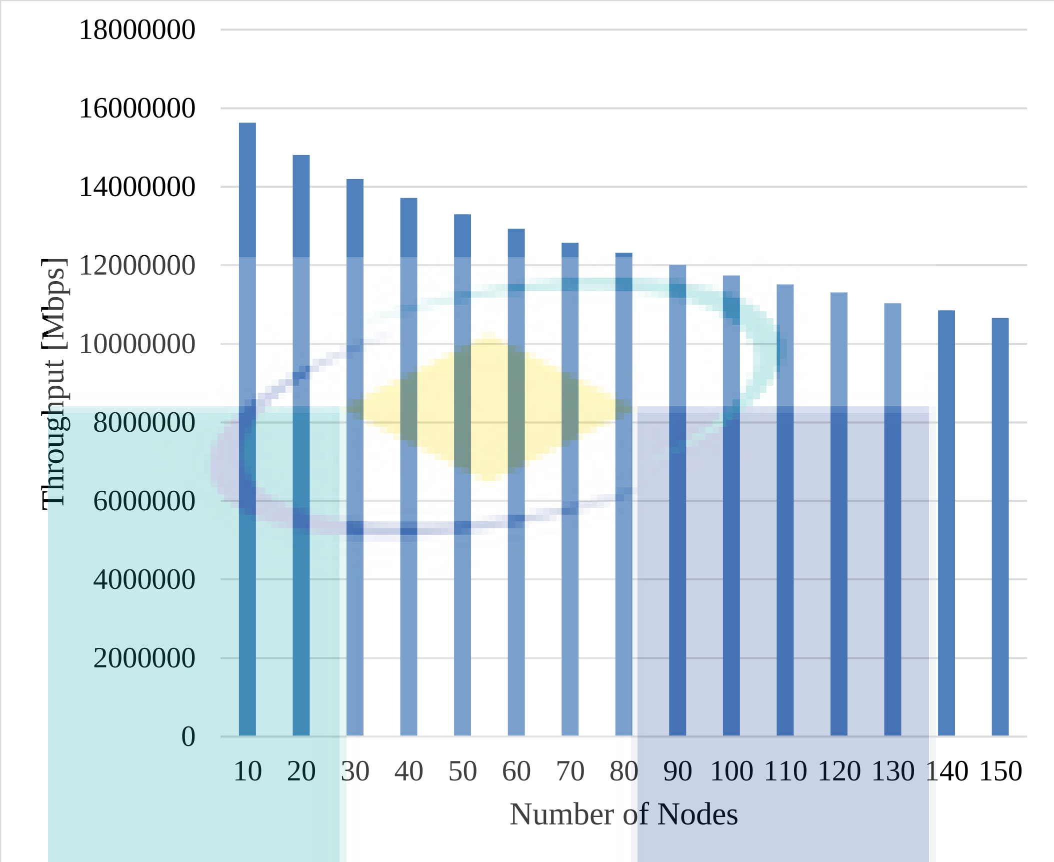

Figure 4.4 Network Throughput for the Traditional CSMA/CA

The total system throughput was reported in Figure 4.4. As expected, the throughput decreased when the number of nodes increased. Excessive backoffs due to an excessive number of active stations and very small CW would lead to inefficient usage of the channel bandwidth. The reason for this very small CW is that CW is reduced rapidly to its minimum regardless of the contention level.

Figure 4.5 shows the data drop against the number of nodes. The collision occurred in the network (due to the backoff mechanism) would increase the data drop in the system. The averaged collision rate was plotted against the inter-arrival time (traffic rate) as shown in Figure 4.6. It was noticed that the collision rate decreased when the inter-arrival time increased due to the reduction of the traffic speed in the network. Therefore, the level of contention over the transmission channel decreased (thus lower number of collisions). traffic speed, which would lead to an unsaturated traffic that causes lower network throughput.

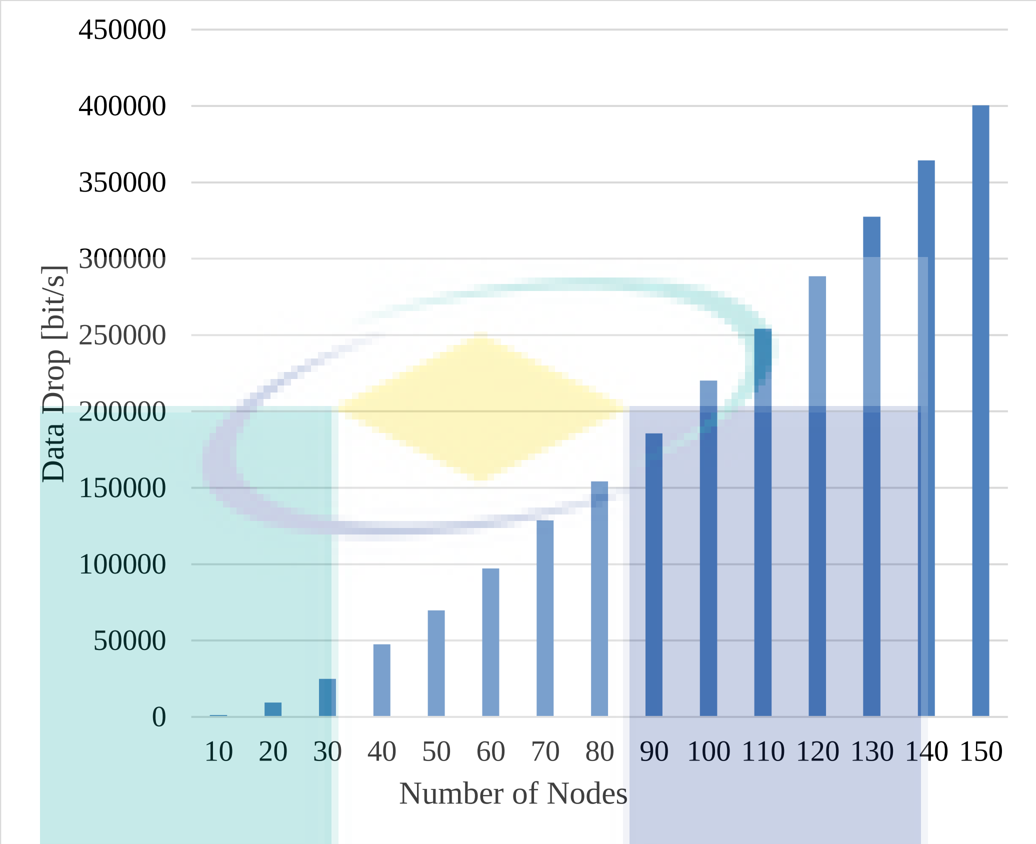

Figure 4.5 Network Data Drop for the Traditional CSMA/CA

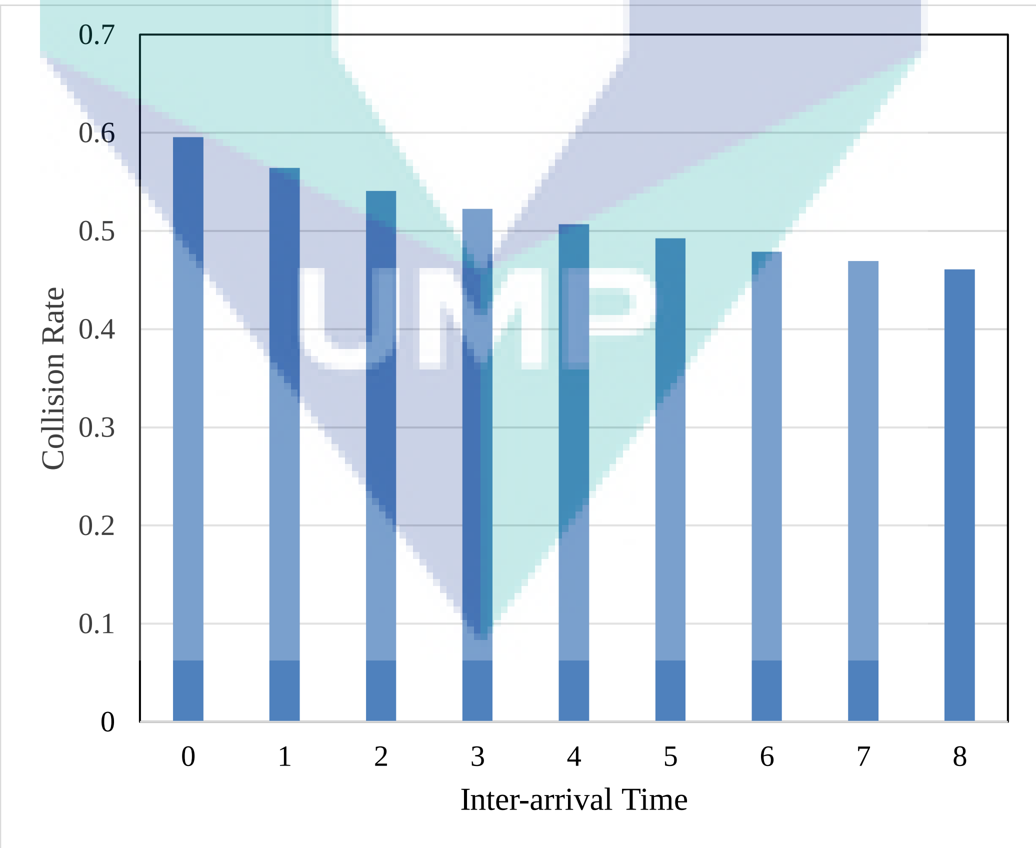

Figure 4.6 Network Collision Rate vs. Packet Inter-arrival Time

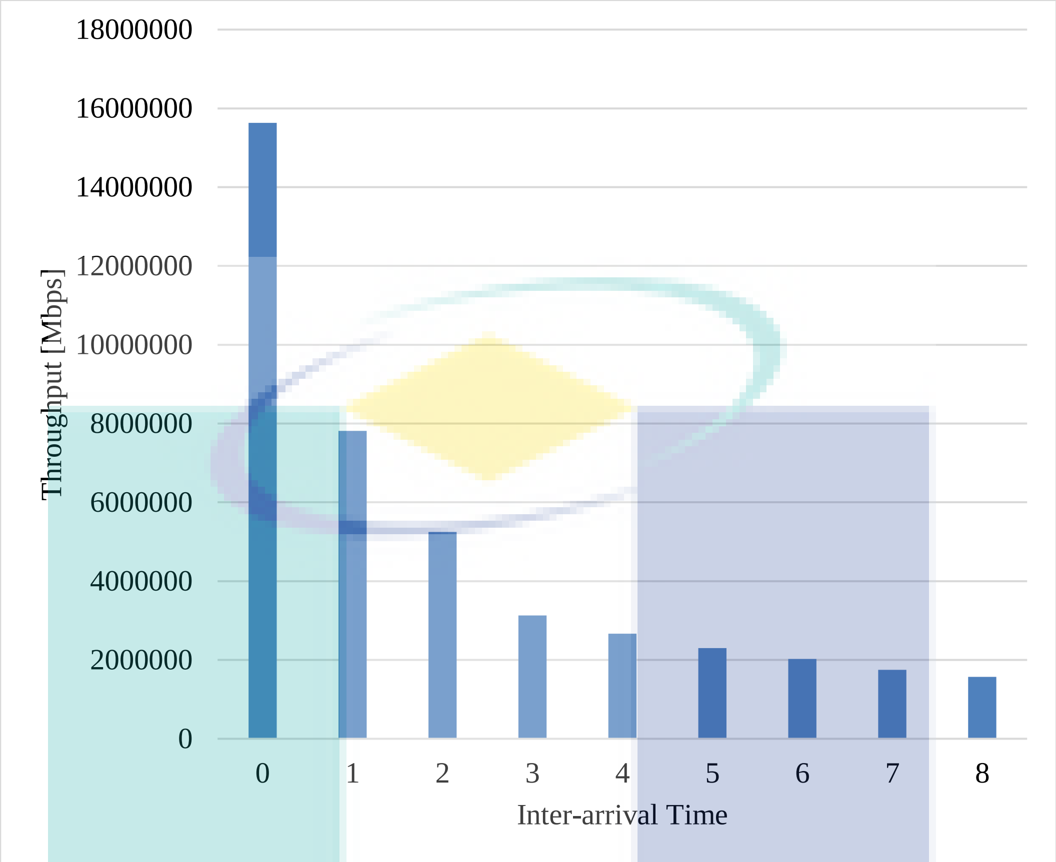

Figure 4.7 Network Throughput vs. Packet Inter-arrival Time

The total network throughput was plotted against the inter-arrival time (traffic rate) as presented in Figure 4.7. It was found that the network throughput decreased when the inter-arrival time increased. Again, it was due to the reduction of traffic speed, which would lead to an unsaturated traffic that causes lower network throughput.

4.3 Performance Comparison of the EEE 802.11 CSMA/CA Solution

This experiment presents a performance comparison of the CSMA/CA solution based on backoff mechanism in terms of collision rate, total throughput, and network data drop. The results are obtained used to show the impact of the contending devices on the CSMA/CA solution by exploiting the existing solution in comparatively contented networks. The aim of this experiment was to assess the ability and effectiveness of the CSMA/CA solution.

4.3.1 Simulation Model

In order to simulate this experiment, the distinct simulation environment was developed. A series of scenarios were then simulated. The main steps involved were: (1) design the node model; (2) create the elements of the network, and (3) define the behaviour of each object via "OPNET Node Editor". A network object consists of multiple modules that define that object. The number of wireless nodes set during the experiment ranged from 10 to 150 with 10 intervals. The size of the simulation environment was 500x500 m. For this experiment, the wireless node was considered as sender and receiver. The experiment assumed that each wireless node sent packets without any error/hidden problem. The simulation parameters used in this experiment were similar to that used in the previous experiment. Figure 4.8 shows the structure of the node model in the simulation environment.

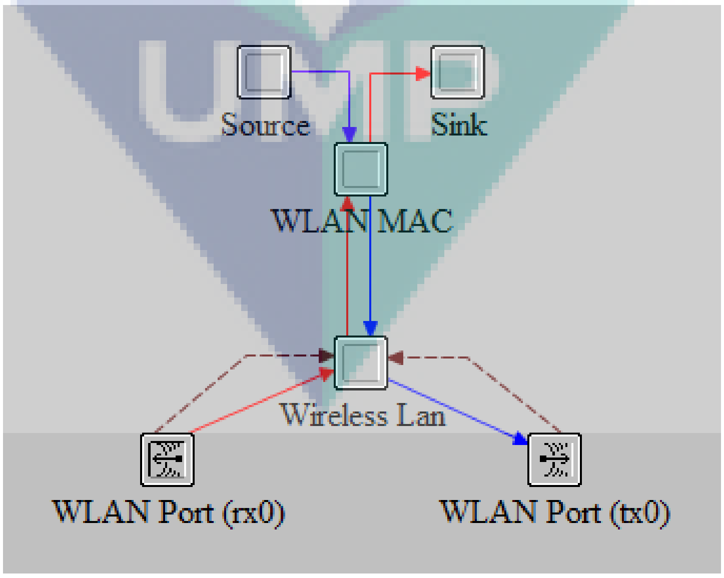

Figure 4.8 Structure of the Node Model in the Simulation Environment

4.3.2 Results & Discussion

The collision rate was shown in Figure 4.9. It was noticed that the collision rate increased when the number of nodes increased. The MAC protocol with DIDD (backoff) performed better than the protocol with LILD (backoff) when the number of competing nodes was less than 120. Conversely, when the number of nodes was more than 120, the collision rate decreased and became lower than that with DIDD. The collision rate of the protocol with BEB backoff mechanism was always larger than those with DIDD and LILD.

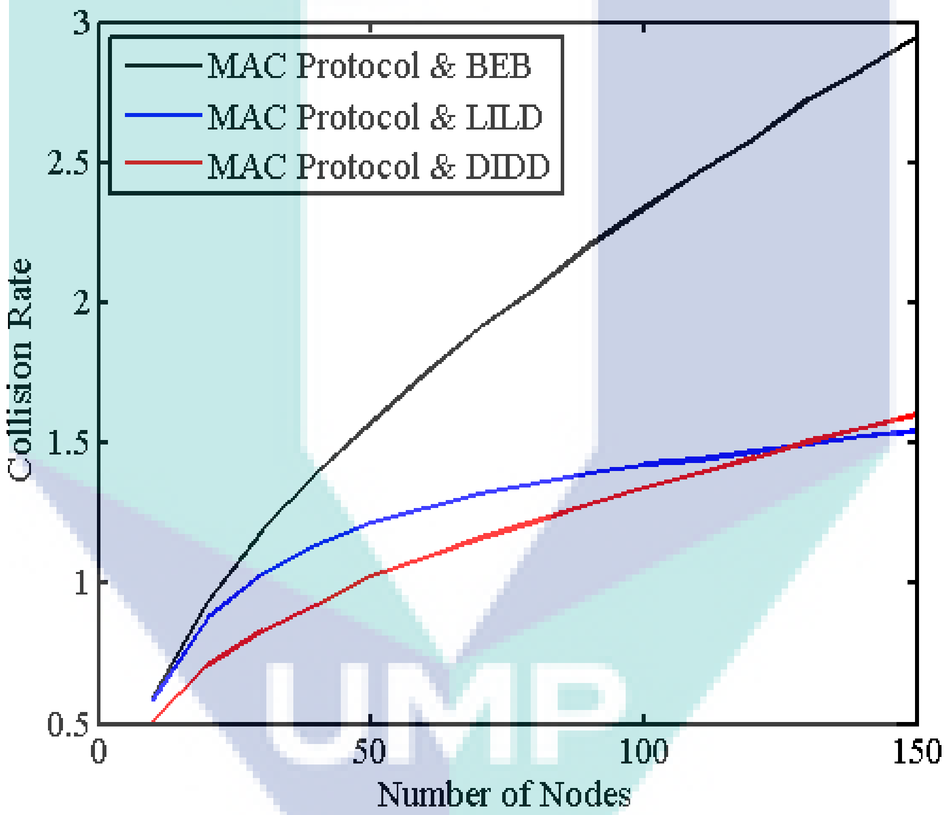

Figure 4.9 Network Collision Rate for 150 Nodes

The significant difference between the protocol with BEB and others is due to a specific reason. For this protocol, after each successful transmission, CW is reduced rapidly to the minimum level regardless of the state of the network. The network suffers from several collisions thereafter, which would, in turn, increase the CW in order to overcome the collision. MAC with LILD has better performance in the high-contention network because CW is gradually changed after a successful transmission. The current

CW which is suitable for the network status is then saved, thus reducing the probability of collision in the network.

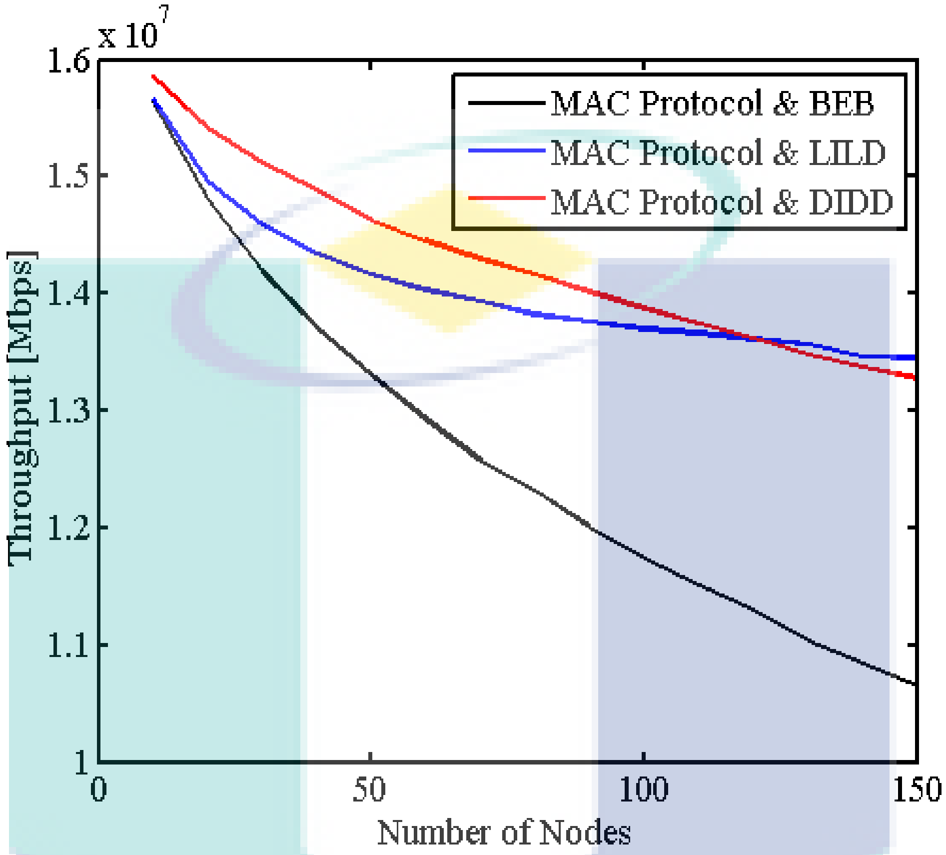

Figure 4.10 Network Throughput for 150 Nodes

Figure 4.10 shows the throughputs of different MAC protocols. As expected, the protocol with DIDD backoff provided higher throughput than those with BEB and LILD when the number of nodes was less than 120 due to the fact that it had the lowest collision rate in this status. However, the protocol with LILD outperformed both BEB and DIDD and gave higher throughput when the number of nodes was larger than 120 due to the reason mentioned above.

Figure 4.11 shows the number of data drops for different MAC protocols in this experiment. The protocol with DIDD provided the lowest data drop when the number of nodes was lower than 120 as it had the lowest collision rate in this status (low-contention). However, it was observed that the protocol with LILD had lower data drop than those of BEB and LILD and it gave better performance when the number of nodes was larger than 120 as it had the lowest collision rate in that status (high contention).

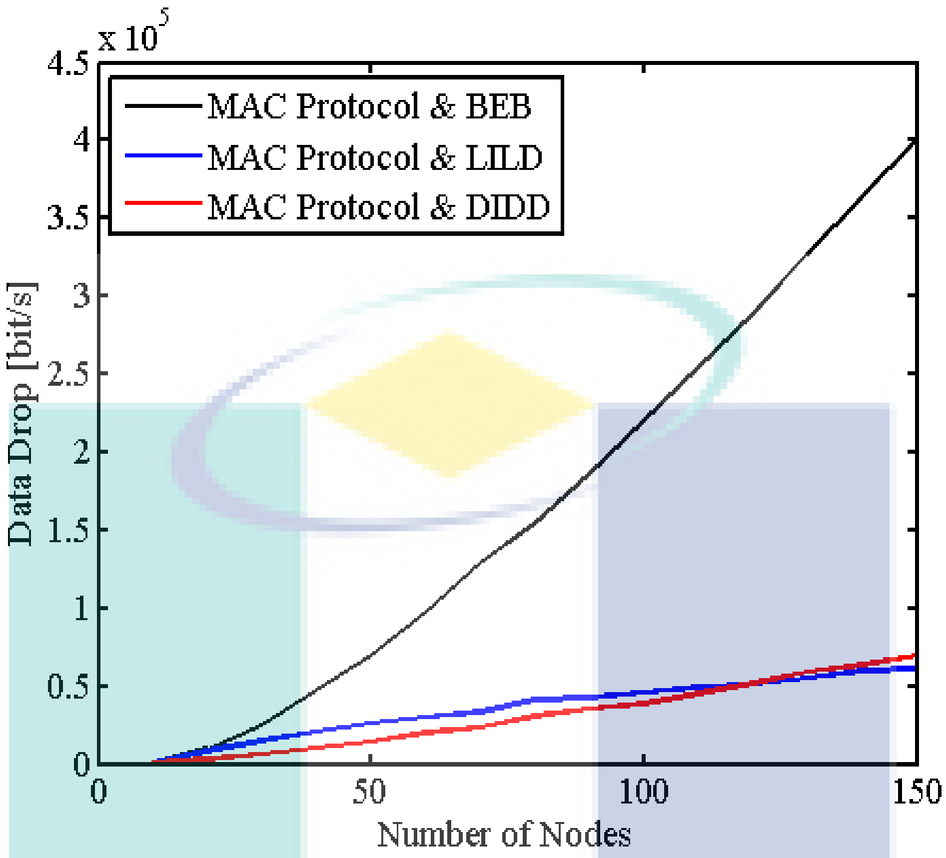

Figure 4.11 Network Data Drop for 150 Nodes

4.4 Parameters Accuracy for the Proposed Protocol

These experiments were carried out in order to investigate the accuracies of the parameters of the proposed protocol. In these experiments, three dependent parameters were measured: (1) the reference point for the collision rate that determines the network contention level (Threshold); (2) the required change rate of the contention to avoid collision and unnecessary delays on low contention network (Alpha); and (3) the required change rate of the contention to avoid collision and unnecessary delays in high contention network (Beta). The best combination of these parameters for the proposed protocol was then sought.

4.4.1 Simulation Model

In order to simulate this experiment, the distinct simulation environment was developed. A series of scenarios were then simulated. The main step to implement the parameters accuracy for the protocol parameters is to design a process model. The process models in these experiments were formed by creating states (Finite State Machines) and lines that represent transitions between states. The size of this simulation environment was 500x500 m. For the experiment, wireless nodes were considered as sender and receiver. In this simulation, each node was assumed to send packets without any error or hidden problem. The number of wireless nodes ranged from 10 - 100 and 100 - 200 with 10 intervals. Note, the network that consists of more than 100 nodes is considered as a comparatively contented network. The simulation parameters used in this experiment were similar to those used in the previous experiment. Figure 4.12 shows the node model for the simulation environment.

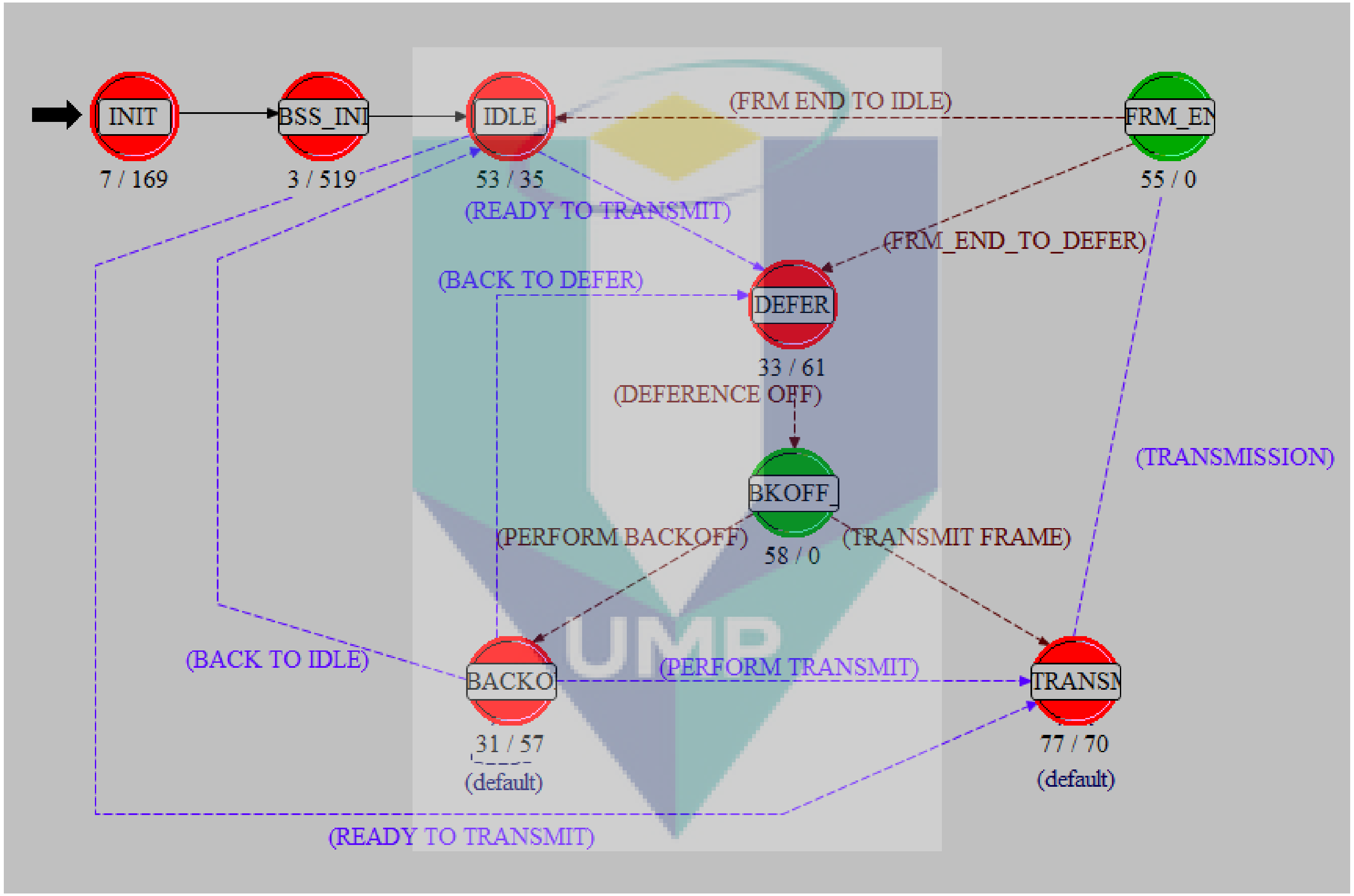

Figure 4.12 Node Model for the Simulation Environment

4.4.2 Results & Discussion

In this section, three control parameters were measured via numerical simulation and the most precise values of these parameters were then selected for the proposed protocol. The simulation was initiated by specifying Threshold (T_h), i.e. a reference point for the collision rate which determined the network contention in the proposed protocol. In order to set the value for T_h, several scenarios were simulated, and the nodes were set as 110, 130, and 150. Meanwhile, the CWs were set as 32, 64, 128, 256, 512, and 1024. As shown in Figure 4.13, when T_h was 512, the protocol performed better than others because 512 is the average value between the smallest and the largest values of the CW where the points determine the network contention. Therefore, T_h was selected as 512 in the proposed protocol.

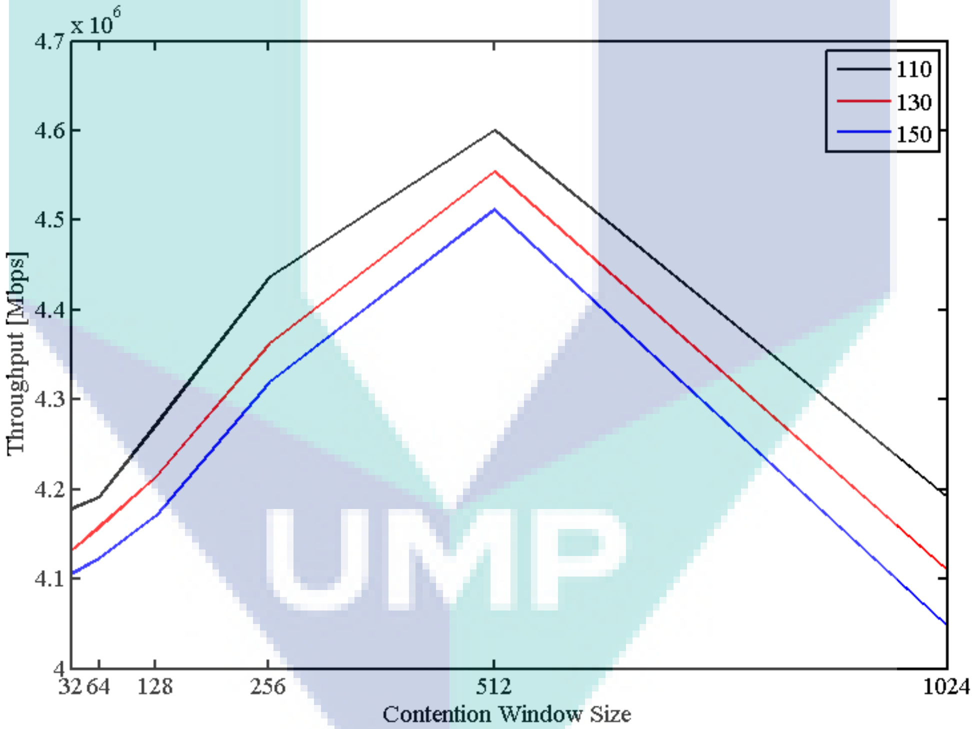

Figure 4.13 Network Throughput vs. Contention Window Size

Alpha (α) determines the required change rate of CW in order to avoid collision and unnecessary delays on low contention network. To set the values of α, several scenarios were simulated at low congestion level by varying the number of nodes (see Figure 4.14). It was observed that the performance of the protocol was better when α was 2. Beyond this value, the change rate of CW increased in the event of successful transmission and resulted in unnecessary delay. If $\alpha < 2$, the change rate of CW decreased in the event of successful transmission. A smaller CW was then generated which would be inefficient in avoiding collision. Therefore, α was set as 2 in this case.

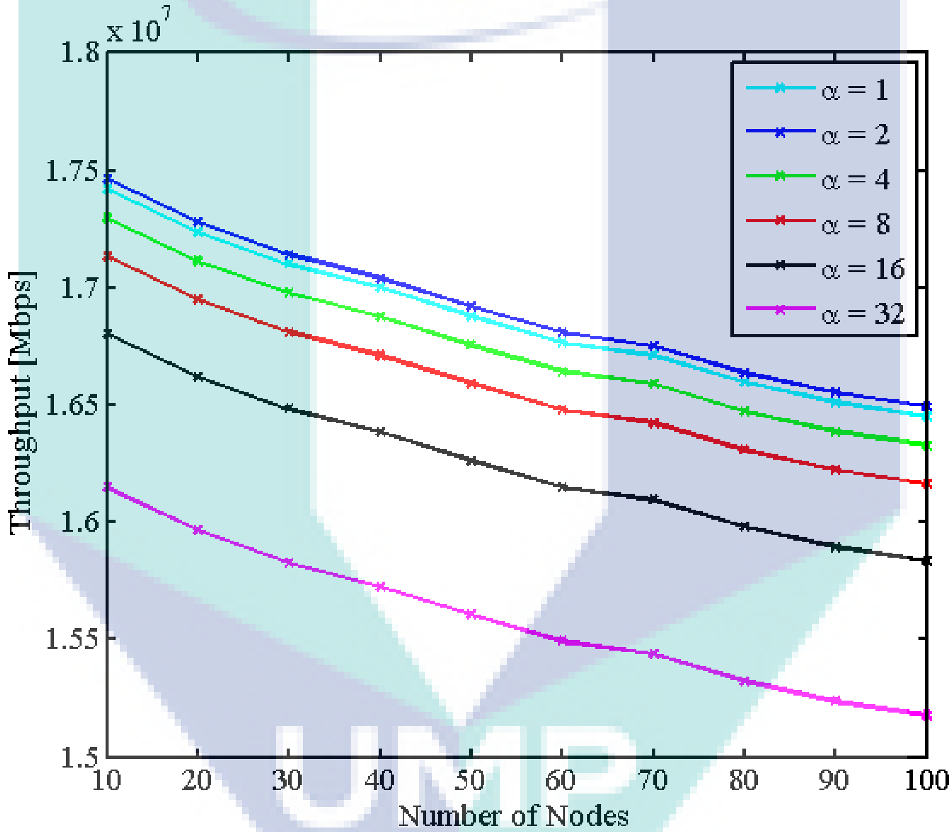

Figure 4.14 Network Throughput vs. α Value

The control parameter Beta (β) determines the required change rate of CW for avoiding a collision and unnecessary delays in high contention network. Several scenarios were simulated in order to find an optimal value of β at high congestion level, with a number of nodes ranged from 110 to 200 as shown in Figure 4.15. It was observed that the performance of the protocol was the best when $\beta = 1$. At higher β, smaller CW was produced, which was inappropriate for high contention network.

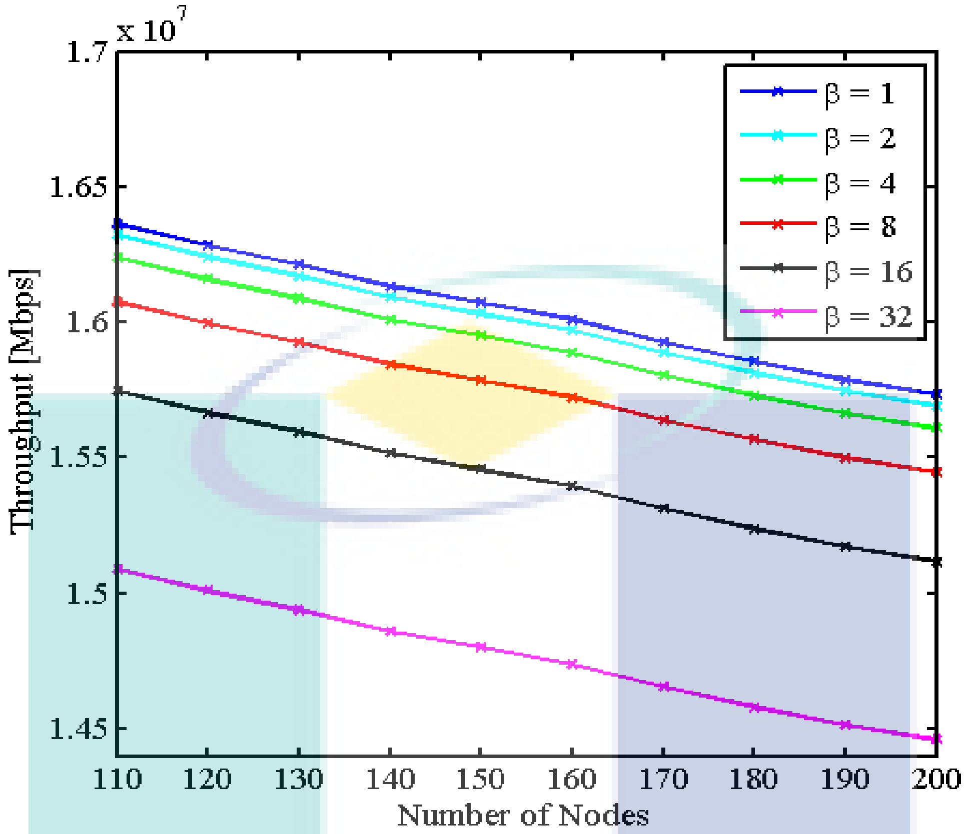

Figure 4.15 Network Throughput vs. β Value

4.5 Performance Evaluation of the Proposed Protocol

The performance metrics of the proposed protocol in terms of collision rate, total throughput, and data drop were evaluated. The results obtained clearly showed the impact of the proposed protocol on the wireless networks.

4.5.1 Simulation Model

In order to simulate this experiment, the distinct simulation environment was developed using OPNET. The performance was assessed upon simulating a series of scenarios. In order to implement different CSMA/CA backoff in the simulator, a source code (C and Proto-C) was written for each module by using OPNET development methodology that could process all module types. The size of this simulation environment was 500x500 m. For the experiment, wireless nodes were considered as sender and receiver. The experiment assumed that each wireless node sent packets without any error/hidden problem. The number of wireless nodes set for this experiment ranged from 10 to 400 with 10 intervals. The simulation parameters used in this experiment were similar to those used in the previous experiment.

4.5.2 Results & Discussion

In this experiment, several scenarios were simulated in order to evaluate the performance of the proposed protocol. Figure 4.16 shows the collision rate against the number of nodes. It was observed that the collision rate increased when the number of nodes increased. The MAC protocol with DIDD (backoff) performed better than the MAC protocol with LILD when the network was under low-contention condition due to the exponential increase of CW (Chatzimisios et al., 2005). On the other hand, when the network was under the high-contention condition, the collision rate decreased and became lower than that in the protocol with LILD. This was due to the fact that CW changed gradually after each successful transmission. The current CW value suitable for the network status was then saved, thus reducing the probability of collision.

The collision rate of the MAC protocol with BEB was always the biggest among all because, after each successful transmission, the value of CW was reduced rapidly to its minimum regardless of the state of the network. The network would suffer from several collisions before the CW reached the required level in overcoming the collision.

The collision rate of the MAC protocol with BEB was always the biggest of all because, after each successful transmission, the value of CW was reduced rapidly to its minimum regardless of the state of the network. The network would suffer from several collisions before the CW reached the required level in overcoming the collision.

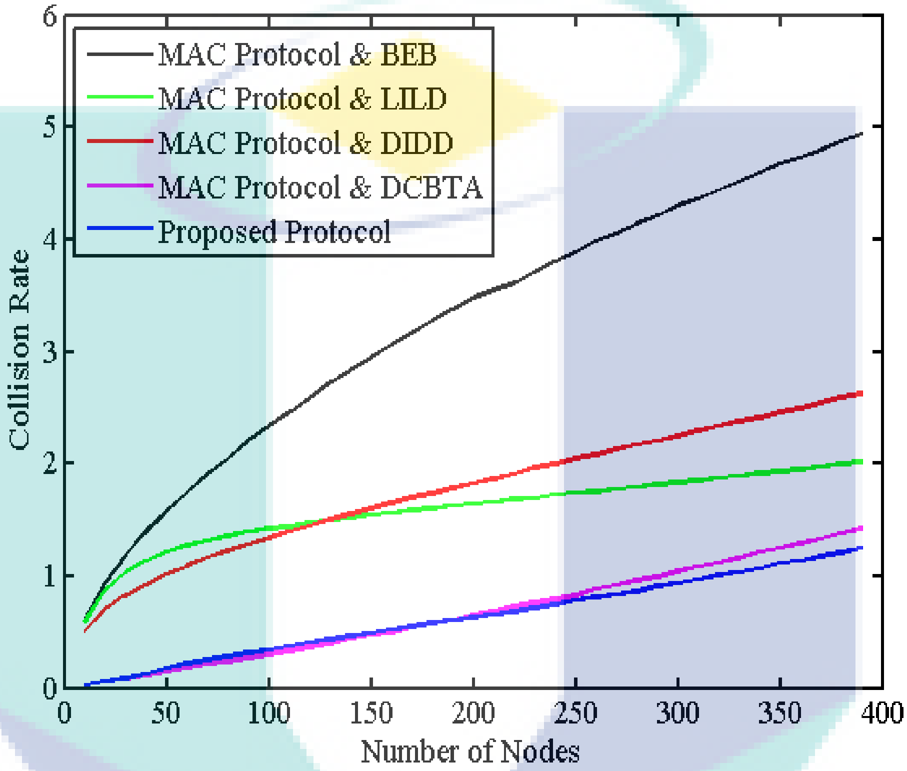

Figure 4.16 Network Collision Rate for 400 Nodes

The MAC protocol with DCBTA backoff performed better than those with LILD and DIDD in terms of collision rate because CW increased rapidly during collision in the MAC protocol with DCBTA. This would reduce the collision rate remarkably. However, delay occurs in the event of large CW because the MAC protocol with DCBTA does not consider the accuracy of the CW (Alkadeki et al., 2016). To resolve this issue, the proposed protocol considered the accuracy of the CW, and increased the decrement speed of CW in the event of successful transmission. CW was set based on the network behavior. Due to these methods, the proposed protocol outperformed the others.

Figure 4.17 plots the throughput against the number of nodes. As expected, the protocol with DCBTA provided a higher throughput than those with LILD and DIDD because CW increased at a faster rate in the protocol with DCBTA which would in turn, reduce the collision rate. However, it was observed that the MAC protocol with DCBTA gave lower throughput when the number of nodes was below 100 as the accuracy of the CW change rate was not taken into account (Alkadeki et al., 2016). To solve this issue, the proposed protocol has considered the accuracy of the CW change rate through the backoff mechanism and tuned the speed of CW based on network contention level. Due to this method, the proposed protocol outperformed the others in terms of throughput.

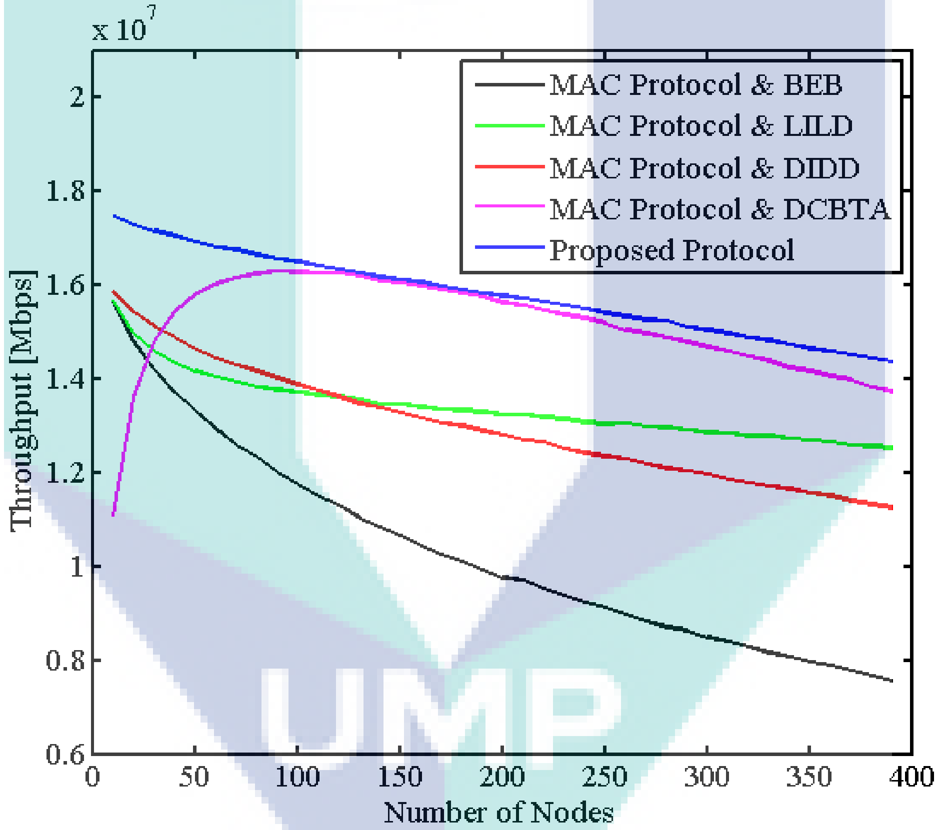

Figure 4.17 Network Throughput for 400 Nodes

Figure 4.18 shows the data drop for a different number of nodes. Similar to the previous experiment, the proposed protocol outperformed others in terms of numbers of data drop due to the consideration of the accuracy of the CW change rate through the backoff mechanism and tuned the speed of CW based on network contention level.

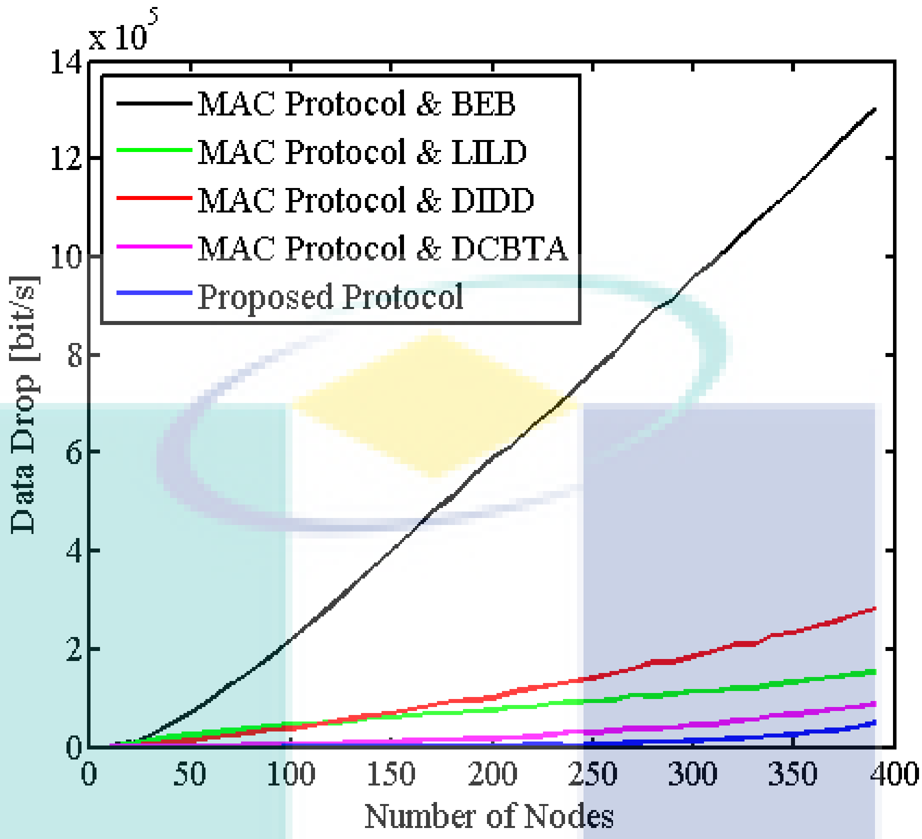

Figure 4.18 Network Data Drop for 400 Nodes

The collision rate against the inter-arrival times (traffic rates) was plotted in Figure 4.19. It was noticed that the collision rate decreased when the number of inter-arrival times increased. In fact, the traffic speed in the network decreased when the inter-arrival time increased. Thus, the reduction in the traffic speed would decrease the level of contention over the transmission channel (hence lower collisions).

The network throughput was plotted against the inter-arrival time as shown in Figure 4.20. It was noticed that the network throughput decreased when the number of inter-arrival times increased. As mentioned above, the traffic speed in the network decreased when the inter-arrival time increased. Thus, the reduction in the traffic speed would generate unsaturated traffic, thus leading to lower network throughput.

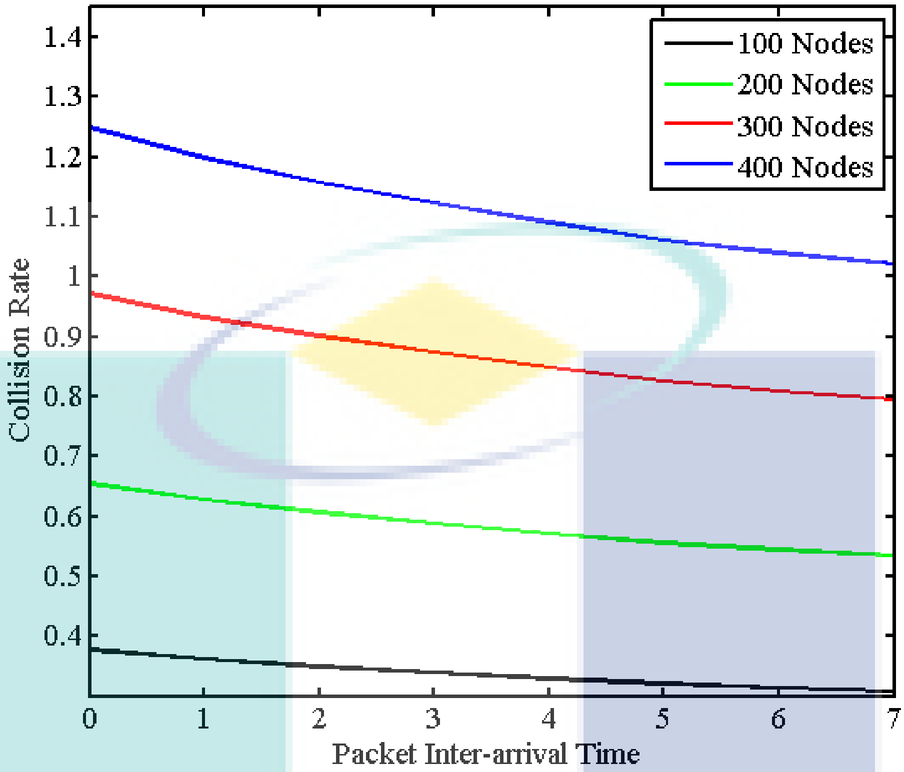

Figure 4.19 Network Collision Rate vs. Packet Inter-arrival Time

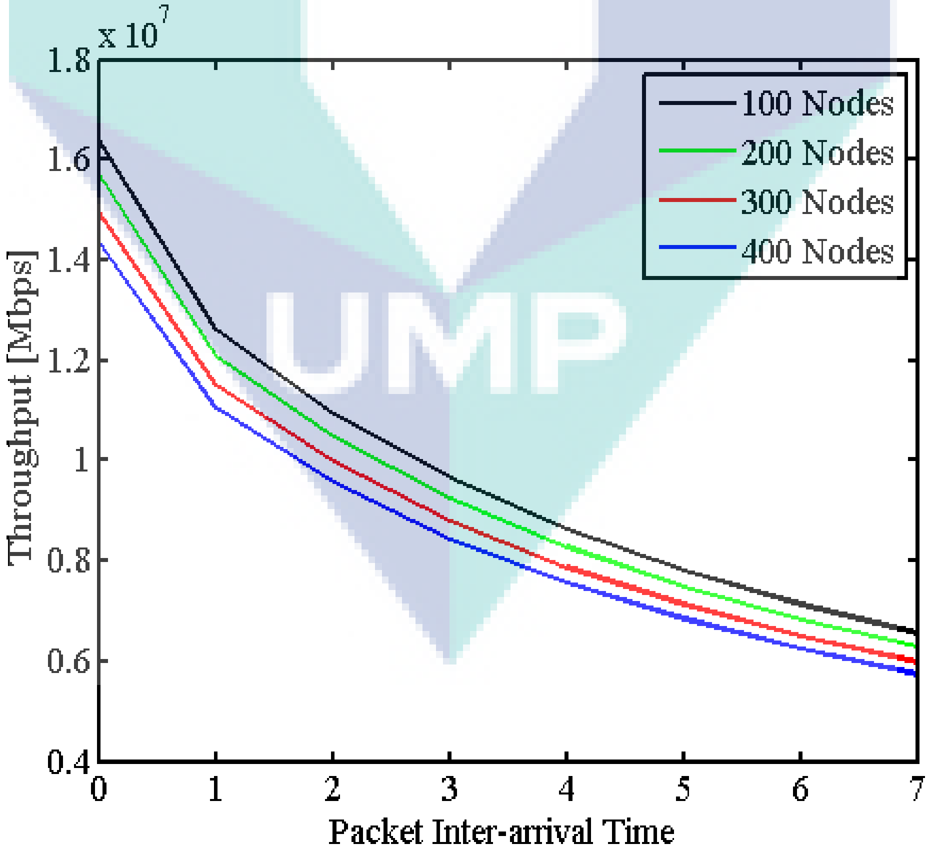

Figure 4.20 Network Throughput vs. Packet Inter-arrival Time

4.6 Summary

The numerical experiments and the associated results have been discussed in this chapter. The behaviour of the traditional CSMA/CA has been presented and analysed. This experiment concluded that both collision rate and data drop increased dramatically when the number of the nodes increased. On the other hand, throughput decreased with respect to the number of nodes. It was noticed that the collision rate decreased when the number of inter-arrival times increased because the speed of network traffic descended with respect to the inter-arrival time. It was noticed also that the network throughput shrank when the inter-arrival time increased due to the unsaturated traffic (hence lower network throughput). Therefore, the traditional IEEE 802.11 protocol is contention-sensitive when the number of active stations increases. Thus, by analysing the behaviour of the traditional IEEE 802.11 CSMA/CA, the first research objective has been accomplished.

The performance of CSMA/CA solution was then presented and analysed. This experiment concluded that the performance of the existing protocols dropped during high contention condition. The protocol with DIDD provided a rapid variation of CW, which was suitable for a variable load or a low number of stations. In contrast, the protocol with LILD was more suitable for constant loads or a large number of stations because CW was tuned linearly and slowly. There is a trade-off between wasting some backoff time and risking a collision followed by the retransmission. Also, the excessive idling time during congestion (to avoid collision) would degrade the network performance. Therefore, the effect of CW is prominent in the system performance. Upon comparing and evaluating the performance of the CSMA/CA solution, the second research objective has been accomplished.

Thirdly, the accuracies of the parameters of the proposed protocol were analysed via three experiments. When the control parameter Threshold (T_h) was 512, the protocol performed better than the others because 512 is the average value between the smallest and the largest values of the CW where the points determine the network contention. Furthermore, it was observed that the performance of the protocol was better when $\alpha = 2$ as $\alpha > 2$ would increase the value of CW and lead to unnecessary delay. Meanwhile, the performance of the protocol was better when $\beta = 1$. Increased β would translate into smaller CW which was inappropriate for high contention network.

Finally, the proposed protocol was introduced and evaluated. In this experiment, an efficient CSMA/CA (MAC protocol) was introduced to represent the actual network situations. It has been observed that the existing MAC protocol has lower system performance in terms of system collision rate, data drop and throughput, as the accuracy of the CW is not considered. Also, the existing MAC protocol neglects the possibility that the CW change rate could be larger than that required, providing small CWs lead to excessive collisions and backoffs; on the other hand, when the CW change rate can be smaller than required, providing large CWs lead to unnecessary idle time during which no station attempts to transmit. In either case, the channel is not used efficiently. On the other hand, the proposed protocol has considered both contention level and change rate in CW. The motivation of this work was to enhance the performance of IEEE 802.11 in terms of system collision rate, data drop and throughput. The simulation results showed that the proposed protocol could enhance the performances of those systems reported in the previous works. Thus, by enhancing the performance of IEEE 802.11, the last research objective has been accomplished.

CHAPTER 5

CONCLUSION AND FUTURE DIRECTION

5.1 Conclusion

WLANs is growing as the number of users increases. Hence, the efficiency of a MAC protocol must be maintained while coping with this demand. Therefore, this research was conducted in order to enhance the WLANs performance and reduce the failure rate. At the beginning of this research, the literature related to the IEEE 802.11 standard has been identified and investigated. Then, the literature related to the 802.11 MAC protocol has been reviewed. It has been concluded that the existing MAC protocol solutions do not consider the accuracy of CW which has a direct influence on the system performance. Thus, this assumption is not practical as the channel is not used efficiently.

In this research, several objectives have been set. The first objective was formulated to analyze the behaviour of the traditional IEEE 802.11 protocol (CSMA/CA). In order to achieve this objective, an experiment has been conducted to show the impacts of the contending devices and the traffic rate over the traditional CSMA/CA based on the backoff mechanism. This experiment showed that collision rate and data drop increased dramatically with respect to the number of nodes. Therefore, the traditional IEEE 802.11 protocol is contention-sensitive when the number of nodes increases.

The second objective was devised to compare the performances of the existing CSMA/CA solutions under a high-contention network. This objective has been achieved by exploiting the existing protocol solutions with high-contention network and identifying the performance challenges. It has been noticed that the performances of the existing protocols dropped under high contention condition. In addition, it has been noticed that an accuracy of CW can make a big difference on the system performance.

The last objective dealt with the development of an efficient MAC protocol that took the accuracy of CW into account. The proposed protocol was improved based on the traditional IEEE 802.11 MAC protocol. Three experiments were carried out to determine the values of the control parameters. The motivation of this work was to enhance the performance of IEEE 802.11 in terms of system collision rate and throughput. The simulation results showed that the proposed protocol could enhance the system performance.

5.2 Future Direction

This research has provided some useful guidelines for designing an efficient network system. The performance has been analyzed based on the number of nodes and the collision probability only. Therefore, other factors such as contention level and energy consumption could be considered in the future work. Moreover, this work has focused on the behaviour of the infrastructure-less network. In future, the performance of multi-hop wireless networks could be analyzed for more accurate estimation of the MAC layer of IEEE 802.11.

This research has been conducted on the single-hop wireless network only, where nodes communicate with each other directly without relying on the router or access point. Involving more participants for different communication types can be considered as well in the future work. In addition, this research has investigated the behaviors of MAC in terms of system collision rate, throughput, and data drop. A better understanding can be attained by considering other indicators.

Furthermore, inter-layering communication can be used to design an efficient network system. A cross-layer dynamic mechanism can overcome the limitations of the existing protocols more efficiently. Finally, this scalability issue can be explored in other networks such as *Cognitive Radio Networks* and *Wireless Sensor Networks* in order to achieve higher network performance.

REFERENCES

Aad, I., and Castelluccia, C. 2000. Introducing service differentiation into IEEE 802.11. *Presented at the Fifth IEEE Conference on Computers and Communications*, pp. 438-443.

Aad, I., and Castelluccia, C. 2001. Differentiation mechanisms for IEEE 802.11. *Presented at the Twentieth IEEE Annual Joint Conference of the Computer and Communications Societies*, pp. 209-218.

Aad, I., Ni, Q., Barakat, C., and Turletti, T. 2005. Enhancing IEEE 802.11 MAC in congested environments. *Computer Communications.* 28(14): 1605-1617.

Abbas, A. M., Ali, J., Rahman, M. A., and Azad, S. 2016. Comparative investigation on CSMA/CA based MAC protocols for scalable networks. *Presented at the International Conference on Computer and Communication Engineering (ICCCE)*, pp. 428-433.

Alkadeki, H., Wang, X., and Odetayo, M. 2013. A new analytical model to compute a packet transmission probability for IEEE 802.11. *Presented at the World Congress on Multimedia and Computer Science*.

Alkadeki, H., Wang, X., and Odetayo, M. 2016. Improving performance of IEEE 802.11 by a dynamic control backoff algorithm under unsaturated traffic loads. *International Journal of Wireless and Mobile Networks*.

Alkhatib, A., and Baicher, G. S. 2012. Wireless sensor network architecture. *Presented at the International Conference on Computer Networks and Communication Systems*.

Ansel, P., Ni, Q., and Turletti, T. 2004. An efficient scheduling scheme for IEEE 802.11e. *Presented at the Ad Hoc and Wireless Networks Conference*, pp. 24-26.

Balador, A., and Movaghar, A. 2010. The novel contention window control scheme for IEEE 802.11 MAC Protocol. *Presented at the Second IEEE International Conference on Networks Security Wireless Communications and Trusted Computing*, pp. 134-137.

Balador, A., Movaghar, A., Jabbehdari, S., and Kanellopoulos, D. 2012. A novel contention window control scheme for IEEE 802.11 WLANs. *Institution of Electronics and Telecommunication Engineers Technical Review.* 29(3): 202-212.

Banchs, A., and Perez, X. 2002. Distributed weighted fair queuing in 802.11 *Presented at the IEEE International Conference on Communications*, pp. 3121-3127.

Bharghavan, V., Demers, A., Shenker, S., and Zhang, L. 1994. MACAW: A media access protocol for wireless LAN's. *ACM SIGCOMM Computer Communication Review.* 24(4): 212-225.

Bianchi, G. 2000. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE Journal on Selected Areas in Communications.* 18(3): 535-547.

Bobbie, P., and Yussiff, A. 2004. Modeling and simulation of IEEE 802.11 WLAN and bluetooth piconet range interference. *Presented at the Communications, Internet, and Information Technology Conference,* pp. 44-49.

Cervello, G., and Choi, S. 2006. *Collision avoidance in IEEE 802.11 contention free period (CFP) with overlapping basic service sets (BSSs).* US Patent 7054329.

Chatzimisios, Boucouvalas, A., Vitsas, V., Vafiadis, A., Oikonomidis, A., and Huang, P. 2005. A simple and effective backoff scheme for the IEEE 802.11 MAC protocol. *Presented at the Second International Conference on Cybernetics and Information Technologies, Systems and Applications,* pp. 48-53.

Chatzimisios, P., Boucouvalas, A., and Vitsas, V. 2003a. IEEE 802.11 packet delay a finite retry limit analysis. *Presented at the IEEE Global Telecommunications Conference,* pp. 950-954.

Chatzimisios, P., Boucouvalas, A. C., and Vitsas, V. 2003b. IEEE 802.11 packet delay a finite retry limit analysis. *Presented at the IEEE Global Telecommunications Conference,* 2: pp. 954-959.

Chatzimisios, P., Boucouvalas, A. C., and Vitsas, V. 2005. Performance analysis of the IEEE 802.11 MAC protocol for wireless LANs. *International Journal of Communication Systems.* 18(6): 545-569.

Chen, Chuang, Tseng, F., and Ke. 2011. High performance distributed coordination function with QoS support in IEEE 802.11e networks. *Presented at the Telecommunication Networks and Applications Conference,* pp. 1-6.

Chen, W., Jian, B., and Lo, S. 2002. An adaptive retransmission scheme with QoS support for the IEEE 802.11 MAC enhancement. *Presented at the IEEE 55th Vehicular Technology Conference,* 1: pp. 70-74.

Chen, Y. M., Chung, H., Tong, Z., and Lee, E. 2005. *Interleaved weighted fair queuing mechanism and system.* US Patent 6975638.

Chendeb Taher, N., Ghamri, Y., El Hassan, B., and Agoulmine, N. 2011. An accurate analytical model for 802.11e EDCA under different traffic conditions with contention-free bursting. *Journal of Computer Networks and Communications*.

Cheng, H., Yan, X., Lian, H., Weng, L., Zhang, Q., and Feng, Z. 2014. A novel collision avoidance algorithm for IEEE 802.11 wireless LANs. *Presented at the IEEE Military Communications Conference*, pp. 879-884.

Chhaya, H. S., and Gupta, S. 1995. Throughput and fairness properties of asynchronous data transfer methods in the IEEE 802.11 MAC protocol. *Presented at the Sixth IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,* 2: pp. 613-617.

Cho, J. W., and Jiang, Y. 2015. Fundamentals of the backoff process in 802.11: Dichotomy of the aggregation. *IEEE Transactions on Information Theory*. 61(4): 1687-1701.

Choi, S., Choi, Y., and Lee, I. 2006. IEEE 802.11 MAC level FEC scheme with retransmission combining. *IEEE Transactions on Wireless Communications*. 5(1): 203-211.

Choi, S., Del Prado, J., and Mangold, S. 2003. IEEE 802.11e contention-based channel access (EDCF) performance evaluation. *Presented at the IEEE International Conference on Communications*, pp. 1151-1156.

Chung, S., and Piechota, K. 2003. Understanding the MAC impact of 802.11e. *Communication Systems Design*.

Ciuffoletti, A. 2010. Secure token passing at application level. *Future Generation Computer Systems*. 26(7): 1026-1031.

Conti, M., Maselli, G., Turi, G., and Giordano, S. 2004. Cross-layering in mobile Ad-Hoc network design. *Computer Networking*. 37(2): 48-51.

Creswell, J. 2014. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. California: SAGE.

Cui, H. X., and Wei, G. 2009. A novel backoff algorithm based on the tradeoff of efficiency and fairness for Ad Hoc networks. *Presented at the International Conference on Communications and Mobile Computing*, pp. 81-86.

Das, A., Mjeku, M., Nkansah, A., and Gomes, N. J. 2007. Effects on IEEE 802.11 MAC throughput in wireless LAN over fiber systems. *Journal of Lightwave Technology*. 25(11): 321-328.

Deng, J., Liang, B., and Varshney, P. K. 2004. Tuning the carrier sensing range of IEEE 802.11 MAC. *Presented at the IEEE Global Telecommunications Conference*, 5: pp. 2987-2991.

Deng, J., Varshney, P. K., and Haas, Z. J. 2004. A new backoff algorithm for the IEEE 802.11 distributed coordination function. *Journal of Computer Networks and Communications*.

Diamant, R., and Lampe, L. 2011. Spatial reuse time-division multiple access for broadcast Ad-Hoc underwater acoustic communication networks. *IEEE Journal of Oceanic Engineering*. 36(2): 172-185.

Dinh, N. Q., and Kim, D. 2012. Performance evaluation of priority CSMA/CA mechanism on a wireless network. *Computer Standards and Interfaces*. 34(1): 117-123.

Dong, X. J., and Varaiya, P. 2005. Saturation throughput analysis of IEEE 802.11 wireless LANs for a lossy channel. *IEEE Communications Letters*. 9(2): 100-102.

Drabu, Y. 1999. *A survey of QoS techniques in 802.11*. Working Paper. Kent State University.

Dujovne, D., Turletti, T., and Filali, F. 2010. A taxonomy of IEEE 802.11 wireless parameters and open source measurement tools. *IEEE Communications Surveys and Tutorials*. 12(2): 249-262.

Elsayed, K. M., and Khattab, A. K. 2006. Channel-aware earliest deadline due fair scheduling for wireless multimedia networks. *Wireless Personal Communications*. 38(2): 233-252.

Ergen, M., and Varaiya, P. 2005. Throughput analysis and admission control for IEEE 802.11a. *Mobile Networks and Applications*. 10(5): 705-716.

Fitzek, F. H., Angelini, D., Mazzini, G., and Zorzi, M. 2003. Design and performance of an enhanced IEEE 802.11 MAC protocol for multihop coverage extension. *IEEE Wireless Communications*. 10(6): 30-39.

Forouzan, B., and Fegan, S. 2007. *Data Communications and Networking*. New York: McGraw Hill.

Fouad, T., and Leonard, K. 1976. Packet switching in radio channels: Polling and dynamic split-channel reservation multiple access. *IEEE Transactions on Communications*. 24(8).

Fu, J., Zhang, Q., and Wang, H. 2009. A new backoff algorithm based on the dynamic modulating parameters of IEEE 802.11. *Presented at the 5th IEEE International Conference on Wireless Communications, Networking and Mobile Computing*, pp. 1-4.

Garg, P., Doshi, R., Greene, R., Baker, M., Malek, M., and Cheng, X. 2003a. IEEE 802.11e MAC for QoS over wireless. *Presented at the IEEE International Conference on Performance, Computing, and Communications*, pp. 537-542.

Garg, P., Doshi, R., Greene, R., Baker, M., Malek, M., and Cheng, X. 2003b. Using IEEE 802.11e MAC for QoS over Wireless. *Presented at the IEEE International Conference on Performance, Computing, and Communications*, pp. 537-542.

Gast, M. 2005. *802.11 Wireless Networks*. California: O'Reilly Media.

Geier, J. 2015. *Designing and Deploying 802.11 Wireless Networks*. England: Pearson Education.

Gupta, V., Krishnamurthy, S., and Faloutsos, M. 2002. Denial of service attacks at the MAC layer in wireless Ad-Hoc networks. *Presented at the MILCOM Conference*, 2: pp. 1118-1123.

Holt, A., and Huang, C. Y. 2010. *802.11 Wireless Networks: Security and Analysis*. London: Springer.

Hui, J., and Devetsikiotis, M. 2004. Performance analysis of IEEE 802.11e EDCA by a unified model. *Presented at the IEEE Global Telecommunications Conference,* pp. 754-759.

Ivanov, S., Botvich, D., and Balasubramaniam, S. 2011. On delay distribution in IEEE 802.11 wireless networks. *Presented at the IEEE Symposium on Computers and Communications,* pp. 254-256.

Jelenkovic, P. R., Momcilovic, P., and Squillante, M. S. 2007. Scalability of wireless networks. *IEEE/ACM Transactions on Networking.* 15(2): 295-308.

Jiang, Y., Tham, C., and Ko, C. 2002. A probabilistic priority scheduling discipline for multi-service networks. *Computer Communications.* 25(13): 1243-1254.

Jing, Y., and Chienhua, C. 2002. Support of multimedia services with the IEEE 802.11 MAC protocol. *Presented at the IEEE International Conference on Communications*, pp. 600-604.

Joshi, P. 2011. Security issues in routing protocols in MANETs at the network layer. *Procedia Computer Science.* 3(2011): 954-960.

Ju, H., Rubin, I., and Kuan, Y. 2003. An adaptive RTS/CTS control mechanism for IEEE 802.11 MAC protocol. *Presented at the 57th IEEE Semiannual Technology Conference,* 2: pp. 1469-1473.

Khan, M., Khan, T. A., and Beg, M. 2013. Optimization of wireless network MAC layer parameters. *International Journal of Innovative Technology and Exploring Engineering.* 2(6): 241-244.

Kherani, A. A., and Shorey, R. 2004. Throughput analysis of TCP in multi-hop wireless networks with IEEE 802.11 MAC. *Presented at the IEEE Wireless Communications and Networking Conference,* 1: pp. 237-242.

Khurana, S., Kahol, A., and Jayasumana, A. P. 1998. Effect of hidden terminals on the performance of IEEE 802.11 MAC protocol. *Presented at the 23rd Annual Conference on Local Computer Networks,* pp. 12-20.

Klimesch, W. 2012. Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences.* 16(12): 606-617.

Kowalski, J. 2013. *Hybrid coordination in an IEEE 802.11 network.* US Patent 8472416.

Krithika, P., and Pushpavalli, M. 2012. Quality of service optimization in IEEE 802.11e networks using enhanced distributed channel access techniques. *International Journal of Computer Networks and Wireless Communications.* 2(6): 680-684.

Kurose, J. F., and Ross, K. W. 2010. *Computer Networking*. England: Addison Wesley.

Kwak, J., Nam, J., and Kim, D. 2002. A modified dynamic weighted round robin cell scheduling algorithm. *Electronics and Telecommunications Research Institute Journal.* 24(5): 360-372.

Kwon, T., Lee, S., and Rho, J. 1998. Scheduling algorithm for real-time burst traffic using dynamic weighted round robin. *Presented at the IEEE International Symposium on Circuits and Systems*, pp. 506-509.

Labiod, H., and Afifi, H. 2007. *Wi-FiTM, BluetoothTM, ZigbeeTM and WiMaxTM*. Netherlands: Springer.

Lachmann, G. V. 2014. *Boundary Layer and Flow Control: Its Principles and Application*. Amsterdam: Elsevier.

Lammle, T., and Swartz, J. 2013. *CCNA Data Center-Introducing Cisco Data Center Networking Study Guide*. New York: John Wiley & Sons.

Lee, J., Lee, H., Yi, Y., Chong, S., Knightly, E. W., and Chiang, M. 2016. Making 802.11 DCF near-optimal: Design, implementation, and evaluation. *IEEE/ACM Transactions on Networking.* 24(3): 1745-1758.

Li, Y., Chen, C., Song, Y., and Wang, Z. 2007. Real-time QoS support in wireless sensor networks. *International Federation of Automatic Control.* 40(22): 373-380.

Liang, H., Zeadally, S., Chilamkurti, N., and Shieh, C. 2008. A novel pause count backoff algorithm for channel access in IEEE 802.11 based wireless LANs. *Presented at the International Symposium on Computer Science and Its Applications*, pp. 163-168.

Lin, C. H., Shieh, C. K., Hwang, W. S., and Ke, C. H. 2008. An exponential-linear backoff algorithm for contention based wireless networks. *Presented at the International Conference on Mobile Technology, Applications, and Systems*.

Lindgren, A., Almquist, A., and Schelen, O. 2003. Quality of service schemes for IEEE 802.11 wireless LANs. *Mobile Networks and Applications.* 8(3): 223-235.

Malone, D., Duffy, K., and Leith, D. 2007. Modeling the 802.11 distributed coordination function in nonsaturated heterogeneous conditions. *IEEE/ACM Transactions on Networking.* 15(1): 159-172.

Mangold, S., Choi, S., Hiertz, G. R., Klein, O., and Walke, B. 2003. Analysis of IEEE 802.11e for QoS support in wireless LANs. *IEEE Wireless Communications.* 10(6): 40-50.

Mangold, S., Choi, S., May, P., Klein, O., Hiertz, G., and Stibor, L. 2002. IEEE 802.11e wireless LAN for quality of service. *Presented at the European Wireless (EW) Conference*, 2: pp. 32-39.

Manshaei, M. H., Cantieni, G. R., Barakat, C., and Turletti, T. 2005. Performance analysis of the IEEE 802.11 MAC and physical layer protocol. *Presented at the Sixth IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks,* pp. 88-97.

Marsic, I. 2010. *Computer Networks: Performance and Quality of Service*. New Jersey: Rutgerss Press.

Mishra, A., Shin, M., and Arbaugh, W. 2003. An empirical analysis of the IEEE 802.11 MAC layer handoff process. *Computer Communications.* 33(2): 93-102.

Mishra, M., and Sahoo, A. 2006. A contention window based differentiation mechanism for providing QoS in wireless LANs. *Presented at the 9th International Conference on Information Technology,* pp. 72-76.

Morris, K., Hudson, D., and Goyal, A. 2008. *Automatic adaptive network traffic prioritization and shaping.* US Patent 7460476.

Nefzi, B., and Song, Y. 2012. QoS for wireless sensor networks: Enabling service differentiation at the MAC sub-layer using COSEN. *Ad Hoc Networks.* 10(4): 680-695.

Nesargi, S., and Prakash, R. 2002. MANET configuration of hosts in a mobile Ad hoc network. *Presented at the IEEE Twenty-First Annual Joint Conference on Computer and Communications Societies*, pp. 1059-1068.

Nguyen, D. T., and Ostermann, J. 2007. Congestion control for scalable video streaming using the scalability extension. *IEEE Journal of Selected Topics in Signal Processing.* 1(2): 246-253.

Ni, Q. 2005. Performance analysis and enhancements for IEEE 802.11e wireless networks. *IEEE Network.* 19(4): 21-27.

Ni, Q., and Turletti, T. 2004. A survey of QoS enhancements for IEEE 802.11 wireless LAN. *Wireless Communications and Mobile Computing.* 4(5): 547-566.

Nithya, B., Mala, C., and KumarB, V. 2012. Simulation and performance analysis of various IEEE 802.11 backoff algorithms. *Procedia Technology.* 6: 840-847.

O'Hara, B., and Petrick, A. 2005. *IEEE 802.11 Handbook: A Designer's Companion*. New York: Wiley.

Pahlavan, K. 2011. *Principles of Wireless Networks*. New York: Wiley.

Pan, J. 2008. *A survey of network simulation tools: Current status and future developments.* Report.

Pang, Q., Liew, S. C., Lee, J., and Chan, S. 2004. A TCP like adaptive contention window for WLAN. *Presented at the IEEE International Conference on Communications,* pp. 3723-3727.

Parekh, A. K., and Gallager, R. G. 1993. A generalized processor sharing approach to flow control in integrated services networks. *IEEE/ACM Transactions on Networking.* 1(3): 344-357.

Penttinen, J. 2015. *The Telecommunications Handbook.* New York: Wiley.

Perez, X., and Mur, D. 2010. IEEE 802.11e QoS and power saving features overview and analysis of combined performance. *IEEE Wireless Communications.* 17(4).

Peterson, L., and Davie, B. 2007. *Computer Networks: A systems Approach*. Amsterdam: Elsevier.

Politis, A., Mavridis, I., and Manitsaris, A. 2011. Exploiting multimedia frame semantics and MAC-layer enhancements for QoS provisioning in IEEE 802.11e congested networks. *International Journal on Advances in Networks and Services.* 4(1): 176-185.

Qi, H., Malone, D., and Botvich, D. 2009. 802.11 Wireless LAN multiplayer game capacity and optimization. *Presented at the 8th Annual Workshop on Network and Systems Support for Games*.

Radosavac, S., Cárdenas, A. A., Baras, J. S., and Moustakides, G. V. 2007. Detecting IEEE 802.11 MAC layer misbehavior in Ad Hoc networks: Robust strategies against individual and colluding attackers. *Journal of Computer Security*. 15(1): 103-128.

Raniwala, A., and Chiueh, T. 2005. Architecture and algorithms for an IEEE 802.11 based multi-channel wireless mesh network. *Presented at the 24th IEEE Annual Joint Conference of the IEEE Computer and Communications Societies*, pp. 2223-2234.

Raptis, P., and Vitsas, V. 2005. Packet delay modeling of IEEE 802.11 WLANs. *Presented at the International Conference on Cyber Information Technology and System Applications*.

Raptis, P., Vitsas, V., and Paparrizos, K. 2009. Packet delay metrics for IEEE 802.11 distributed coordination function. *Mobile Networks and Applications*. 14(6): 772–781.

Rashid, M. M., Hossain, E., and Bhargava, V. K. 2007. HCCA scheduler design for guaranteed QoS in IEEE 802.11e based WLANs. *Presented at the IEEE Conference on Wireless Communications and Networking*, pp. 1538-1543.

Rashid, M. M., Hossain, E., and Bhargava, V. K. 2008. Controlled channel access scheduling for guaranteed QoS in 802.11e based WLANs. *IEEE Transactions on Wireless Communications.* 7(4): 1287-1297.

Rashwand, S., and Jelena. 2012. Effects of access phases lengths on performance of IEEE 802.15 CSMA/CA. *Computer Networks.* 56(12): 2832-2846.

Reddy, T., Karthigeyan, I., Manoj, B., and Murthy, C. 2006. Quality of service provisioning in Ad Hoc wireless networks: A survey of issues and solutions. *Ad Hoc Networks.* 4(1): 83-124.

Romdhani, L., Ni, Q., and Turletti, T. 2003. Adaptive EDCF: Enhanced service differentiation for IEEE 802.11 wireless Ad Hoc networks. *Presented at the IEEE Wireless Communications and Networking Conference*, pp. 1373-1378.

Roshan, P., and Leary, J. 2004. *802.11 Wireless LAN Fundamentals*. Indiana: Cisco Press.

Sakthivel, T., and Chandrasekaran, R. 2012. Detection and prevention of wormhole attacks in MANETs using path tracing approach. *European Journal of Scientific Research.* 76(2): 240-252.

Sheng, Y., Tan, K., Chen, G., Kotz, D., and Campbell, A. 2008. Detecting 802.11 MAC layer spoofing using received signal strength. *Presented at the 27th INFOCOM Conference on Computer Communications*, pp. 1768-1776.

Siraj, S., Gupta, A., and Badgujar, R. 2012. Network simulation tools survey. *International Journal of Advanced Research in Computer and Communication Engineering.* 1(4): 199-206.

Song, N. O., Kwak, B. J., Song, J., and Miller, M. 2003. Enhancement of IEEE 802.11 distributed coordination function with exponential increase exponential decrease backoff algorithm. *Presented at the 57th IEEE Semiannual Conference on Vehicular Technology*, pp. 2775-2778.

Soni, P., and Chockalingam, A. 2003. Analysis of link-layer backoff schemes on point-to-point Markov fading links. *IEEE Transactions on Communications.* 51(1): 29-32.

Srikanth, S., Pandian, P. M., and Fernando, X. 2012. Orthogonal frequency division multiple access in WiMAX and LTE. *IEEE Communications Magazine.* 50(9).

Sundareswaran, N., Riley, G., and Boyd, K. 2007. Improving quality of service in MAC 802.11 layer. *Presented at the 15th International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems*, pp. 38-45.

Tanenbaum, A., and Wetherall, D. 2011. *Computer Networks*. England: Pearson Education.

Tay, Y., and Chua, K. C. 2001. A capacity analysis for the IEEE 802.11 MAC protocol. *Wireless Networks.* 7(2): 159-171.

Tinnirello, I., and Choi, S. 2005. Efficiency analysis of burst transmissions with block ACK in contention-based 802.11e WLANs. *Presented at the IEEE International Conference on Communications*, pp. 3455-3460.

Tsai, J., and Chen, W. 2005. IEEE 802.11 MAC protocol over wireless mesh networks: problems and perspectives. *Presented at the 19th International Conference on Advanced Information Networking and Applications*, 2: pp. 60-63.

Tseng, Y., and Hsieh, T. 2002. Fully power-aware and location-aware protocols for wireless multi-hop Ad-Hoc networks. *Presented at the Eleventh International Conference on Computer Communications and Networks*, pp. 608-613.

Villalon, J., Cuenca, P., and Orozco, L. 2005. QoS provisioning mechanisms for IEEE 802.11 WLAN. *Presented at the 10th International Conference on Personal Wireless Communications*, pp. 205-216.

Vishnevsky, V., and Lyakhov, A. 2002. IEEE 802.11 WLANs: Saturation throughput in the presence of noise. *Presented at the International Conference on Research in Networking*, pp. 1008-1019.

Vukovic, I. N., and Smavatkul, N. 2004. Delay analysis of different backoff algorithms in IEEE 802.11. *Presented at the 60th IEEE Conference on Vehicular Technology*, pp. 4553-4557.

Wang, J., Xie, Y., and Yi, Q. 2015. An all dynamic MAC protocol for wireless body area network. *Presented at the 11th International Conference on Wireless Communications, Networking and Mobile Computing*, pp. 1-6.

Wang, X., Min, G., and Guan, L. 2009. Performance modeling of IEEE 802.11 DCF using equilibrium point analysis. *International Journal of Wireless and Mobile Computing*. 3(3): 201-209.

Weinmiller, J., Woesner, H., and Wolisz, A. 1996. Analyzing and improving the IEEE 802.11 MAC protocol for wireless LANs. *Presented at the Fourth International Workshop on Computer and Telecommunication Systems*, pp. 200-206.

Wesel, E. K., and Khayata, E. 1997. *Wireless Multimedia Communications: Networking Video, Voice and Data*. Boston: Addison Wesley.

Wookey, M. 2017. *Methods and systems for enabling features provided by a first presentation layer protocol in a session implemented according to a second presentation layer protocol*. US Patent 9537958.

Wu, H., Cheng, S., Peng, Y., Long, K., and Ma, J. 2002. IEEE 802.11 distributed coordination function (DCF) analysis and enhancement. *Presented at the IEEE International Conference on Communications*, pp. 605-609.

Xiao, Y., and Pan, Y. 2009. *Emerging Wireless Standard Family*. New York: John Wiley.

Xu, K., Gerla, M., and Bae, S. 2002. How effective is the IEEE 802.11 RTS/CTS handshake in Ad-Hoc networks. *Presented at the IEEE Global Telecommunications Conference*, 1: pp. 72-76.

Xu, S., and Saadawi, T. 2001. IEEE 802.11 MAC protocol in multihop wireless Ad-Hoc networks. *IEEE Communications Magazine*. 39(6): 130-137.

Yang, X., and Vaidya, N. 2006. Priority scheduling in wireless Ad-Hoc network. *Wireless Networks*. 12(3): 273-286.

Yu, X., Navaratnam, P., and Moessner, K. 2013. Resource reservation schemes for IEEE 802.11 based wireless networks. *IEEE Communications Surveys and Tutorials*. 15(3): 1042-1061.

Yuan, Y., Sheng, H., and Shi, H. 2016. Research on mobile internet user behavior preference based on support vector machine. *International Journal of Smart Home*. 10(6): 247-260.

Zhai, H., and Fang, Y. 2003. Performance of wireless LANs based on IEEE 802.11 MAC protocols. *Presented at the 14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications,* 3: pp. 2586-2590.

Zhang, Juan, J., and Adi, A. 2009. QoS guaranteed packet scheduling in wireless networks. *The Journal of China Universities of Posts and Telecommunications.* 16(2): 63-67.

Zhang, D., and Ionescu, D. 2007. QoS performance analysis in deployment of DiffServ-aware MPLS traffic engineering. *Presented at the International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel Distributed Computing,* pp. 963-967.

Zhou, G., Stankovic, J. A., and Son, S. H. 2006. Crowded spectrum in wireless sensor networks. *Presented at the Third Workshop on Embedded Networked Sensors*.