PERFORMANCE ANALYSIS OF FRAME AGGREGATION BASED IEEE 802.11N WIRELESS LOCAL AREA NETWORK (WLAN)

BY

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APPROVAL PAGE

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF THE MASTER OF SCIENCE IN ELECTRONIC ENGINEERING (COMMUNICATION OPTION), UNIVERSITY OF NIGERIA NSUKKA.

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CERTIFICATAION

Ezechi, Nwachukwu Emmanuel, a masterôs degree postgraduate student with registration number PG/MSC/12/61353 in the Department of Electronic Engineering has satisfactorily completed the requirements for the award of Master of Science (M.Sc) in Electronic Engineering.

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DECLARATION

I, **EZECHI NWACHUKWU EMMANUEL**, a masterös postgraduate student in the Department of Electronic Engineering, University of Nigeria Nsukka, declare that the work embodied in this thesis is original and has not been submitted by me in part or in full for any other diploma or degree of this or any other university or institution.Anywork of other authors in any form of ideas, equations, figures, texts, tables, etc. is properly acknowledged.

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DEDICATION

To my father whose prayers and encouragement has brought me this far,

To my family and friends for believing that I can go this far,

And

To my sister whose faith in me also motivates my achievements sofar.

I am truly proud of them.

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I am grateful to God the maker of all we aspire to know and re-create for His grace all through my study period and always.

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EzechiNwachukwu E.

ABSTRACT

The IEEE 802.11 Wireless Local Area Network (WLAN) standard was able to ease the communication difficulty by providing mobility and low cost of system deployment for its users. On the other hand, the WLAN has difficulty in meeting the optimum Quality of Service (QoS)demand for data applications. Consequently, a later variant of the amendment standard, IEEE 802.11n, came with improvement strategies. The introduction of frame aggregation, block acknowledgment and reverse direction protocol techniques at the Media Access Control (MAC) sub-layer of the Datalink layer reduced the overhead cost to an optimum value. This work analyzed the performance of MAC Service Data Unit (MSDU) frame aggregation technique at variable aggregation sizes and number of contending stations in an error-prone WLAN channel. The frame aggregation technique was selected for analysis based on its popularity as compared to other MAC improvement techniques. Firstly, an analytical approach that models the network based on discrete time Markov chain (DTMC) was developed and then simulated in MATLAB environment. The values of the MSDU frame aggregation sizes, the variable number of contending stations and variable bit-error-rate (BER) values of the WLAN channel were chosen arbitrarily but within the practical range for a number of simulation cycles. Based on the generated results, it was observed that the MSDU aggregation size should not be increased beyond 46 for the various BER values of the channel considered for this work else the performance throughput would depreciate. This performance information is very resourceful for optimal design and implementation of frame aggregation technique in the WLAN network.

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ACRONYMS

AC	Access Category
ACK	Acknowledgement
A-MSDU	Aggregate MAC Service Data Unit
A-MPDU	Aggregate MAC Protocol Data Unit
AP	Access point
BACK	Block ACK
BAR	BACK Request
BER	Bit Error Rate
BSS	Basic Service Set
BSA	Basic Service Area
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CW	Contention Window
DA	Destination Address
DCF	Distributed Coordination Function
DIFS	Distributed Inter-frame Space
DS	Distribution Service
DSS	Distribution System Service
DSSS	Direct Sequence Spread Spectrum
DTMC	Discrete-time Markov Chain
EDCA	Enhanced Distributed Channel Access
EIFS	Extended Inter-Frame Space
EP	End Point

ESS	Extended Service Set
FCS	Frame Check Sequence
FHSS	Frequency Hopping Spread Spectrum
FIFO	First In First Out
HCCA	HCF Controlled Channel Access
HC	Hybrid Coordinator
HCF	Hybrid coordination Function
HT	High throughput
IBSS	Independent BSS
IFS	Inter-frame Space
IR	Infrared
ISM	Industrial Scientific and Medical
LOS	Line of Sight
MAC	Media Access Control
MAP	Multiple Access Point
MIMO	Multiple Input Multiple Output
MN	Mobile Node
MS	Mobile Station
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiple
OSI	Open System Interconnection
PC	Point Coordinator
PCF	Point Coordination Function
PHY	Physical
QoS	Quality of Service

RDP	Reverse Direction Protocol
RA	Receiver Address
RF	Radio Frequency
RTS	Request To Send
SA	Source Address
SS	Station Service
STA	Station
TA	Transmitting STA Address
TC	Traffic Category
TS	Traffic Stream
TXOP	Transmission Opportunity
WLAN	Wireless Local Area Network
WM	Wireless Medium

CHAPTER ONE

INTRODUCTION

1.1 Background

Wireless Local Area Network (WLAN) involves the connection of devices without the use of cables [1]. Although the origin of radio frequency based wireless networking can be traced back to the University of Hawaii's ALOHANET research project in the 1970s, but it was until the IEEE 802.11 Wireless standard validated it officially in 1997 that it started recording very fast growth globally [2]. Prior to 1997, the demand for wireless networking was seldom met fully because of challenges like interoperability of products from various manufacturers, security in addition to the very low obtainable performance output compared to the then available 10 Mbps wired Ethernet standard [3]. The most obvious advantage of wireless networking is mobility [4, 5, 6]. Wireless networking relieved users of the restriction of being connected by physical cables which, of course, limits the users' movement dramatically. More so, wireless networks typically have a great deal of flexibility, which can translate into rapid deployment [7, 8]. However, some of the limitations of the network include the fact that the speed of the network is constrained to the available bandwidth [9]. Also, security on the network poses a great challenge since the network transmissions are available to anyone within the range of the transmitter with the appropriate antenna [9].

The operation of WLAN can either be through Infrared (IR) propagation or Radio frequency (RF) propagation methods [9, 10]. The wavelength of the IR is slightly longer than that of the visible light and the link is limited to distances under 15 m [9]. The diffused infrared optical propagation channel is suitable for indoor setup and does not require line-of-sight (LOS) [9]. However, it is seldom used in outdoor topology because it is easily blocked by walls, partitions and other office construction; instead, the RF propagation method is commonly used and can penetrate these barriers and offers wider coverage range [4]. RF propagation method can be deployed in both indoor and outdoor scenario with functional frequencies of 2 GHz and 5 GHz in the unlicensed Industrial Scientific and Medical (ISM) frequency band [10, 11]. The ISM bands are frequency bands that are set aside for communication equipment that support industrial, scientific and medical services.

The WLAN makes use of a contention-based protocol known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [5, 6]. This protocol ensures that the possibility of collision in the network is reduced significantly using control frames. It is very suitable in transmission of asynchronous frames. Asynchronous frame transmission involves orderly and sequential frame exchanges where each frame transmission commences at the end of the previous transmission. This is to avoid a situation whereby simultaneous exchanges are experienced in a time slot. There are three signaling frame types in IEEE WLAN, viz. Data, Control and Management frames [9].

This work analyzed the performance of frame aggregation improvement technique of IEEE 802.11n network at variable aggregation sizes and contending stations for various bit-error-rate (BER) values of the WLAN error-prone channel. The network was modeled based on discrete time Markov chain (DTMC) and then simulated in MATLAB environment. Performance results were generated and inferences were drawn based on observation.

1.2 Problem Statement

The Station (STA) that has successfully seized the communication channel through the CSMA/CA process communicates by exchanging frames during a period of time known as

Transmission Opportunity (TXOP) [12,13]. TXOP is an interval of time when a particular Quality of Service (QoS) STA has the right to initiate frame exchange sequences onto the Wireless Medium (WM) [12]. The process of allowing stations to exchange one pair of frame at a time and then re-start the process of competing for the channel again to resume sending the remaining frames is a characterized inefficiency of the IEEE WLAN legacy network [14]. The IEEE 802.11n standard allows the exchange of multiple frames for the TXOP when the channel is seized. Several sub-frames are concatenated together to form an aggregate frame. The aggregate frame reduces the overhead cost that would have been incurred if the sub-frames were to be transmitted independently. This is a characterized improvement in the IEEE 802.11 WLAN standard. However, this improvement could be marred if the specification for the optimal aggregation value is not adhered to in the application. This work analyzed the performance of the IEEE 802.11n WLAN network by varying the aggregation size of the MSDU frames and the number of contending stations in an error-prone WLAN channel.

1.3 Objectives

The main objective is to determine the effect of these variable system parameters in terms of performance throughput and average access delay in the network. The optimal values of these parameters would be obtained in this work. The result of the analysis would assist in the optimization of the network design parameters.

1.4 Scope

The work is centered on the Media Access Control (MAC) sub-layer of the Data Link layer in the Open System Interconnection (OSI) reference model. The work analysis is carried out only on the frame aggregation improvement technique that is employable at this layer. The reason for choosing frame aggregation technique is basically due to its popularity. The functional area of the analysis implemented in the study resides only on the network performance. The approach adopted in the work is limited to a non-real time analysis only.

1.5 Methodology

The approach adopted for this work is unique. The literature review on the current state of art in the IEEE WLAN works was studied. A physical architecture that comprised of 160 Endpoint stations and one Access point station was adopted and a physical model that represented the network was realized. The specifications for deployment of IEEE 802.11n Wireless LAN base on the IEEE standards were adhered to. There were assumptions made in order to realize the modeled network according to these specifications. Some analytical expressions were generated from these assumptions based on Markov's queuing principle. These expressions were converted into simulation model using MATLAB simulation software. The values of the variable frame aggregation sizes, the variable number of contending stations and variable bit-error-rate (BER) of the error-prone WLAN channel were chosen arbitrarily but within the practical range for the number of simulation cycles. Performance results were generated from the simulation and were used to draw the inference for the work.

1.6 Thesis Outline

This work is organized into five chapters. This chapter one introduced the WLAN, the problem statement, the objectives, the significant, the methodology and the scope. Chapter two fully describes the IEEE 802.11 WLAN technology and the current research contributions from other researchers in the area. More emphasis was made on works that treated IEEE 802.11n MAC improvement techniques. Chapter three modeled the IEEE 802.11n WLAN network. The model is analytical. The analytical approach was based on Markov's queuing principle and the simulation approach involved program scriptingusing MATLAB simulation software. In chapterfour, the model was simulated and validated. Results were generated and analyzed. Then conclusion and recommendation were drawn in chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background on IEEE 802.11 WLAN Technologies

The IEEE 802.11 Wireless Local Area Network (WLAN) is a technology that emerged in 1997 and provides mobility to nodes [15]. It was designed to operate using either diffused Infrared (IR) propagation or Radio Frequency (RF) propagation methods [10]. The RF propagation method has been widely adopted with functional frequencies of 2 GHz and 5 GHz in the unlicensed Industrial Scientific and Medical (ISM) frequency band. The 2 GHz RF propagation is achieved using spread spectrum techniques - Frequency Hopping spread spectrum (FH-SS) or Direct Sequence Spread Spectrum (DSSS), whereas the 5 GHz RF propagation is achieved using Orthogonal Frequency Division Multiplexing (OFDM) techniques [10, 11]. These techniques offer different operation characteristics and Quality of Services (QoS). Therefore, they have some compatibility challenges. Since the inception of WLAN, there have been several developments in the standard that resulted in IEEE 802.11 variations. Most of these development standards were targeted towards achieving improvement in different QoS parameters like throughput, data rate, range, security, etc.

The IEEE 802.11 pioneer standard was only able to offer data rate as high as 2Mbps with the 2.4GHz functional frequency using spread spectrum technique [10, 12]. The IEEE 802.11a development standard was also introduced the same year to improve on the earlier data rate. This standard has the capability to offer higher rate of about 54Mbps that is realizable using OFDM technique at a functional frequency of 5GHz [10]. However, the standard has compatibility challenge with the earlier and some of the subsequent WLAN standards. These challenges are as the result of the technique and the operational frequency used in realizing it. The IEEE 802.11b recommendation standard was introduced in 1999. It uses FH-SS technique and operational frequency of 2.4GHz to realize data rates of up to 11Mbps and yet retains transmission within the same bandwidth [6, 16]. This trend of development has been on-going till date giving rise to several amendment standards that include IEEE 802.11d, IEEE 802.11e, IEEE 802.11g, IEEE 802.11h, IEEE 802.11i, IEEE 802.11j, IEEE 802.11n, IEEE 802.11p, etc. Some of the major proposals for these amendment standards are as follows:

- Specifications for MAC security enhancements.
- Specifications for MAC Quality of Service enhancements.
- Specifications for further higher data rate extension.
- Specifications for transmit power management extension.
- Specifications for higher throughput.
- Specifications for operable frequencies in some countries like Japan, USA, etc.

Among these several amendment standards, IEEE 802.11n amendment standard offers enhancement specifications for higher throughput. Throughput is one of the paramount QoS parameters that measure the efficiency of the communication network. Throughput is the rate of the number of successful service completions, per slot [17]. It is the actual quantity of the total request arrivals on a service facility that was successfully served within the time slot of observation. The service requested can be the communication channel used for frames exchange between/among nodes.

2.1.1 IEEE 802.11n

The IEEE 802.11n came on board in 2003 due to more demand for higher data rate by some applications. Consequently, a task force group known as TGn group was created by the Institute of Electrical and Electronics Engineering (IEEE) to work on this demand. The group was charged with the initial goal of developing a technology to support a data rate of at least 100 Mbps [15]. Their result turned out to be one of the development standards that guarantee higher QoS delivery in terms of throughput, range and then data transfer rate as high as 600Mbps [18].

The QoS delivery improvements result from the enhancement techniques that are introduced at the Physical (PHY) layer and the Data link layer of the Open System Interconnection (OSI) reference model.

Some of the improvement techniques introduced at the physical layer include:

- Multiple Input Multiple Output (MIMO)
- Spatial Multiplexing
- Channel Bonding
- Modulation and Coding Scheme etc.

MIMO refers to the ability to transmit and/or receive data simultaneously using multiple antennas at both the transmitter and the receiver side [7]. The IEEE 802.11n Draft 2 certification requires that systems support at least two (2) spatial data streams which, of course, increase the quality and speed of the PHY dramatically through the creation of multiple simultaneous data streams [19]. Channel bonding is the ability of the network to support both the 20 MHz legacy bandwidth and/or twice of the frequency [20], etc.

The three major QoS improvement techniques implemented at the MAC sub-layer of the Data link layer includes:

- Frame aggregation
- Block Acknowledgement (BACK) and
- Reverse Direction Protocol (RDP)

Frame aggregation is the combination of successive frames [21]. Block acknowledgement is the process of acknowledging multiple transmitted frames with a single block of acknowledgement frame [19]. Reverse Direction Protocol is a bi-directional acknowledged data exchange condition that occurs when data is aggregated with the response BA [13, 22]. RDP reduces idle interval and collision probability [23]. The major contributions of these MAC improvement techniques include reduced overhead and optimization of the channel access time [24]. Figure 2.1 illustrates the three MAC improvement techniques using frame exchange sequence between originating and receiving stations.

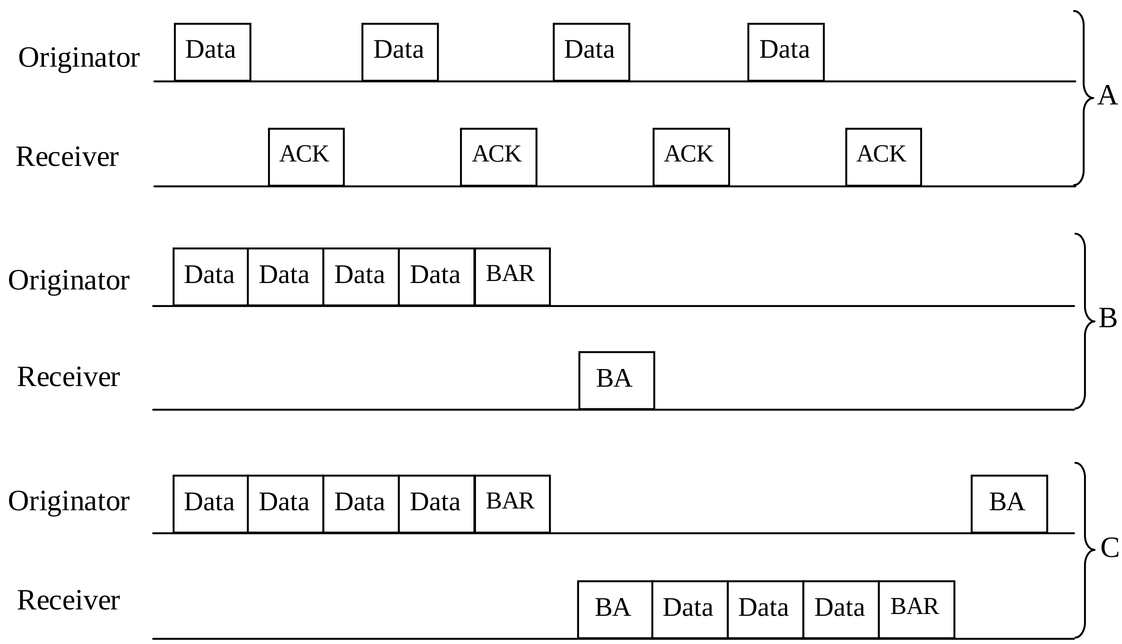


Figure 2.1: Illustrations of Frame aggregation, BACK and RDP.

In the three (3) sequences of communication, the sequence A is the basic communication pattern obtainable in legacy WLAN where every data and its attending acknowledgment (ACK) had to be sent individually. This constitutes to high overhead cost to the network. But in sequence B, the originator sends an aggregated data with an appended Block Acknowledgment Request (BAR) that the receiver acknowledges with only one block acknowledgement (BA). Similarly in sequence C only that the receiver had to use RDP to send its aggregate data with BAR and BA for the block of data it received.

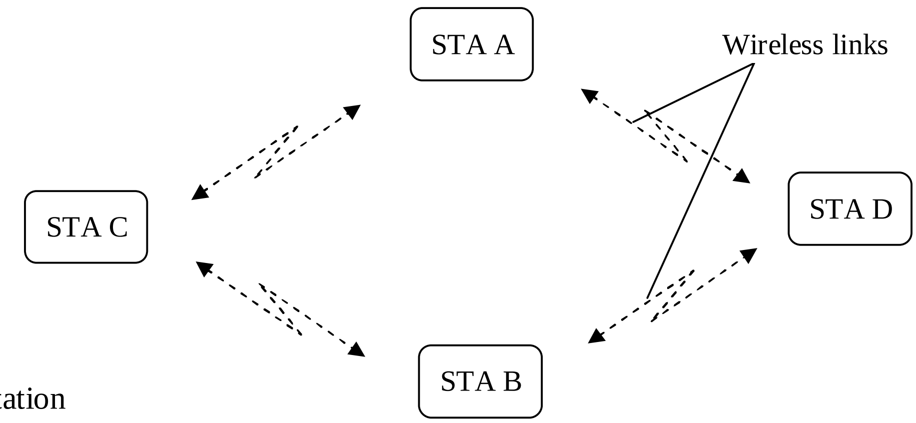
2.1.2 **IEEE 802.11 WLAN Architecture**

The IEEE 802.11 WLAN architecture consists of the network of stations existing in a ring, mesh and star topology groups. Stations are basic components of the wireless network that are used to connect/access the wireless network medium. They are computing devices that contain the IEEE 802.11 specifications for PHY and MAC interface to the WLAN. They are addressable nodes that can either serve as the End Points (EP) or as the Access Points (AP). The EP stations are peer stations in the network that share privileges to the available network resources whereas the AP are any entity that has station functionality and enables access to the network resources through the wireless medium for associated stations [12]. They are stations that have been promoted to servers through which the EPs access the network resources. The existence of the IEEE 802.11 WLAN topology can be classified into two (2) possible connection architectures [1, 6]. They include:

- The Ad Hoc Topology
- The Infrastructure Topology

2.1.2.1 **Ad Hoc Topology**

The Ad Hoc topology consists of two or more wireless nodes or stations that recognize one another and communicate on a peer-to-peer basis within their RF or IR coverage [9, 25]. The term ñAd Hocò is assigned to this type of network because it is commonly formed when two wireless devices come into the range of one another and communicate on a temporary basis until one or more devices depart the area. None of the stations involved in this type of topology is promoted to a server. The setup can be in ring, partial mesh or full mesh form connection. Generally, Ad hoc implementations cover a limited area and are not connected to a large network [6].



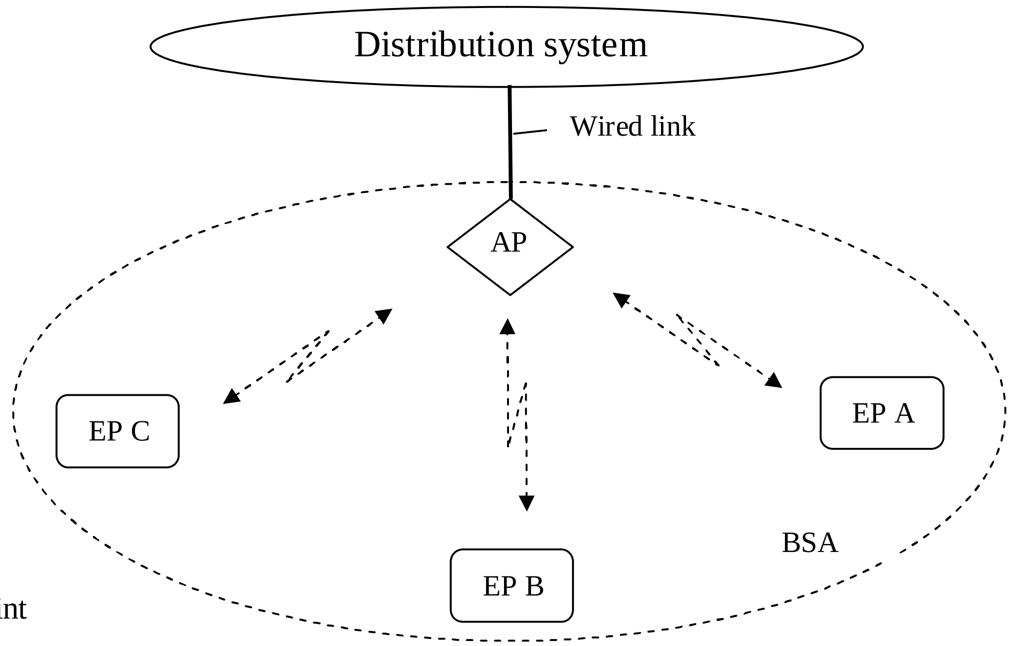
KEY

STA - Station

Figure 2.2: Ad Hoc Topology.

2.1.2.2 **Infrastructure Topology**

The Infrastructure topology involves the network connection of stations in such a way that one or more than one of the stations is/are promoted to server(s). The server is referred to as the Access Point (AP). The Infrastructural topology consists of at least one AP connected to the backbone network and a set of wireless EPs [6, 9, 14]. This topology is shown in Figure 2.3.



KEY

EP ï End Point

AP ï Access Point

BSA ï Basic Service Area

Figure 2.3: Infrastructure Topology.

2.1.2.3 **Service Sets**

The IEEE 802.11 WLAN standard also classified the architecture into service sets. A service set refers to a group of stations that are connected and can reach one another in a network [12]. The service sets include:

- Independent Basic Service Set (IBSS)
- Basic Service Set (BSS)
- Extended Service Set (ESS)

A network of stations is said to be an Independent Basic Service Set (IBSS) if the network exists independently and there are no presence of an access points among them; the network can therefore also be referred to as an ad hoc topology [6]. The IBSS operation is possible when the IEEE 802.11 stations are able to communicate directly and it is often formed without preplanning, for only as long as the network is needed [12]. This type of service set is often referred to as an Ad Hoc network as shown in Figure 2.2.

The BSS is the most basic form of infrastructural topology involving one or more stationary or mobile wireless stations connected to an Access Point (AP) [1]. The BSS often results when two or more mobile nodes come together to communicate or if one mobile client comes into close proximity to an AP [25]. The area of coverage within which the members of a BSS can communicate is referred to as the Basic Service Area (BSA) [9, 12, 25]. This is illustrated with Figure 2.3.

The ESS consists of multiple IEEE 802.11 BSSs forming a single sub-network where the APs communicate with each other to forward traffic from one BSS to another; and provides facility to move mobile stations from one BSS to another. An Extended Service Set (ESS) involves the connection of two or more APs through a Distribution System (DS) [9]. A Distribution system is an architectural component used to interconnect BSSs together [12]. It is a backbone of the network that provides medium service facility through which other BSS networks that are 'anchored' on it can communicate. The Distribution System must not necessarily be an IEEE 802.11 standard compliant [26].

2.1.3 **IEEE 802.11 WLAN Logical Service**

The IEEE 802.11 WLAN specifies a number of logical services that are associated to different components of the architecture. Each service utilizes a set of message with information elements that are pertinent to the services [6]. The services are categories of actions that are executable by both the APs and the EPs in the network. The two categories of the IEEE 802.11 logical services include:

- The Station Service (SS)

- The Distribution System Service (DSS)

The station service (SS) refers to a set of information elements that are common to both the AP and the EPs whereas the DSS refers to the information elements that are applicable to the AP only. Table 2.1 enlists the thirteen (13) logical services specified by the IEEE 802.11 WLAN standards, their functions and the stations that utilize them.

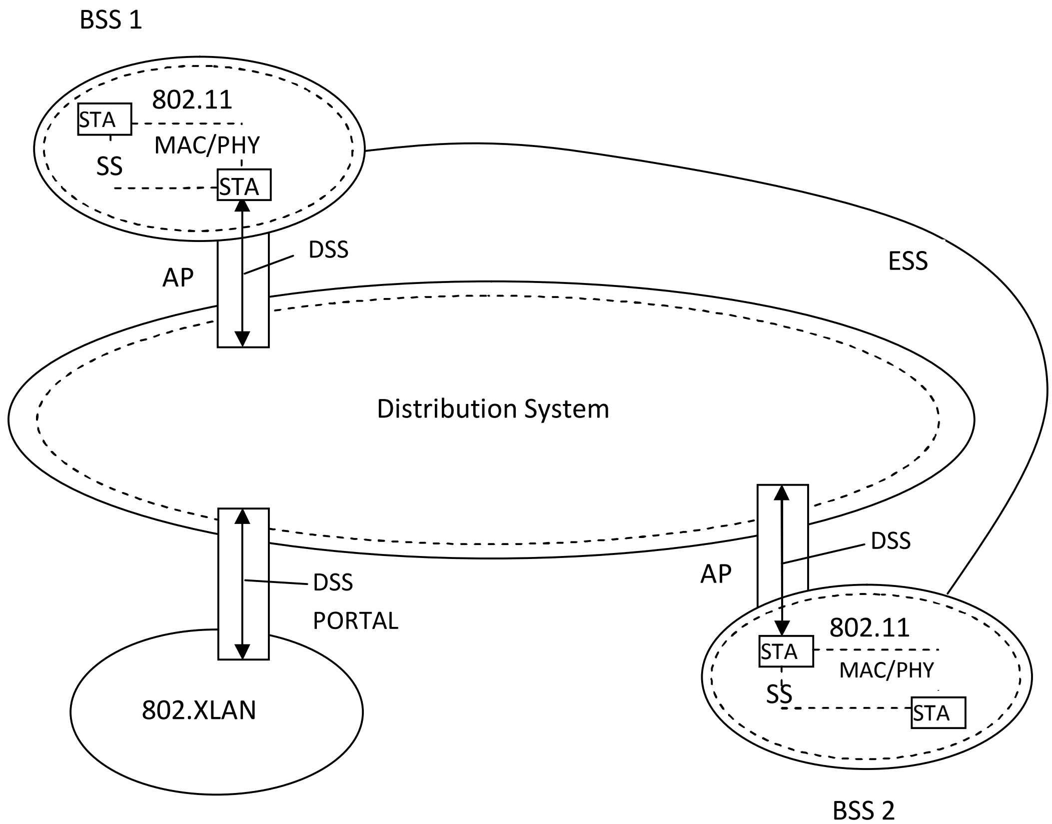
Table 2.1: IEEE 802.11 WLAN Logical Services [6, 12].

MAC Service	**Definition**	**Station Type**
Authentication	This provides access control equal to that of a wired LAN.	EP& AP
Deauthentication	This is used for termination of an existing authentication	EP& AP
Data confidentiality	This is used to prevent unauthorized viewing of the content of the message.	EP& AP
MSDU delivery	Provides transfer of data between stations	EP& AP
Dynamic Frequency Selection (DFS)	Used to implement a mechanism to avoid co-channel operation with radar system and to ensure uniform utilization of the available channels	EP& AP
Transmit Power Control (TPC)	Used to ensure specification for regulatory maximum transmit power and a mitigation requirement for allowed channel, to reduce interference with satellite services.	EP& AP
Higher layer time synchronization (QoS facility only)	It is used to enable the layers above the MAC to accurately synchronize application-dependent timers shared among stations.	EP& AP
QoS traffic scheduling (QoS facility only)	It provides intra-BSS QoS frame transfers under HCF.	EP& AP

Table 2.1: IEEE 802.11 WLAN Logical Services [6, 12] (Continued).

MAC Service	Definition	Station Type
Association	It is used to make a logical connection between station and an AP.	AP
Disassociation	It s either used to force a mobile station to eliminate an association with an AP or for a mobile station to inform an AP that it no longer requires the services of the Distribution System (DS).	AP
Reassociation	Used to transfer an association between APs	AP
Integration	Provides data transfer between the Distribution System (DS) of an IEEE 802.11 LAN and a non-IEEE 802.11 LAN.	AP
Distribution	Provides data transfer between stations through the Distribution System (DS)	AP

The general architecture of the IEEE 802.11 WLAN family comprising of the BSS, the ESS, the Stations (STA) and the portal system all connected through a DS as shown in Figure 2.4. A portal system is an abstract architectural concept that typically resides in the AP. The network uses the portal to communicate to and from a non-IEEE 802.11 compliant network [6]. In other words, a portal is a logical point(s) at which non-802.11 packets enter an ESS [9].



KEY

STA ï Station

AP ï Access Point

SS - Station Service

BSS ï Basic Service Set

ESS ï Extended Service Set

PHY ï Physical

MAC ï Media Access Control

DSS ï Distribution System Service

Figure 2.4: Architecture of IEEE802.11 WLAN [12].

2.1.4 **IEEE 802.11 Protocol of Operation**

The protocol of operation of the IEEE 802.11 network resides at the MAC sub-layer of the Open System Interconnection (OSI) model. The protocol provides both asynchronous (contention-based) and synchronous (contention-free) services. These contention services are provided on top of the physical layer and for different data rates [14]. The asynchronous data transfer applies to applications that are not time-sensitive (e.g., e-mail and file transfer) whereas the synchronous transfer supports time-demanding applications like video and packetized voice [9]. The topology of the MAC sub-layer comprises of the Distributed Coordination Function (DCF), the Point Coordination Function (PCF), the Hybrid Coordination Function (HCF) and their coexistence in the network [12]. This is illustrated in the Figure 2.5.

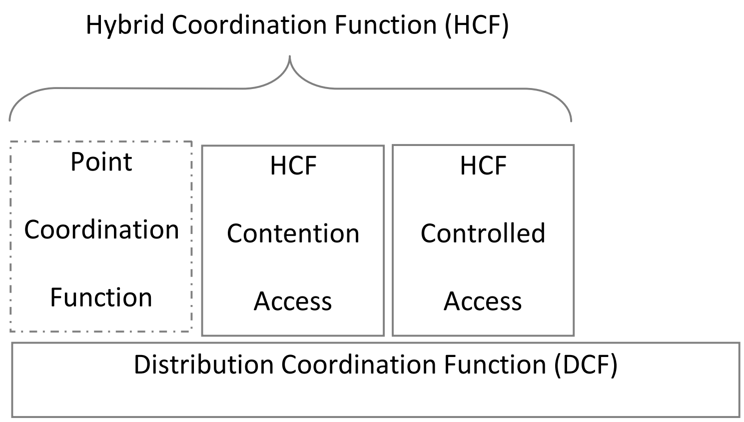


Figure 2.5: IEEE 802.11 MAC Architecture [12].

2.1.4.1 **Distributed Coordination Function (DCF)**

The DCF is the basic access method specified in the 802.11 standard that allows all stations on a wireless LAN network to contend for access on the shared transmission medium using carrier sensing process algorithm known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol [14, 27]. The DCF defines how the access medium should be shared by the provision of the CSMA/CA mechanisms for the access negotiation as well as promising reliable data delivery [6]. The DCF is suitable for transmission of asynchronous frames in all stations within both the IBSS and the Infrastructural configuration [6]. The implementation of DCF is mandatory [14].

2.1.4.1.1 **Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Protocol**

The CSMA/CA was introduced in the network to address two basic problems. These problems include:

- Hidden node problem
- Exposed node problem

Hidden node problem refers to a situation that occurs when two stations, unaware of each other due to their individual coverage areas, sends frame individually to the third party station that both stations can reach [1, 16]. The result of this action would be a propagation of two waves that at a distant point collide, preventing other stations from using the channel [25]. This can be further explained using Figure 2.6. If we assume that each of the stations A, B, C and D can only communicate to the immediate stations at its left and right sides. STA B can therefore exchange frames with STAs A and C but not with STA D. Suppose STAs A and C, unaware of each other, tries to send frames to STA B at the same time, these two frames collide at STA B and neither STA A nor STA C is aware of this collision because they are both hidden nodes with respect to each other.

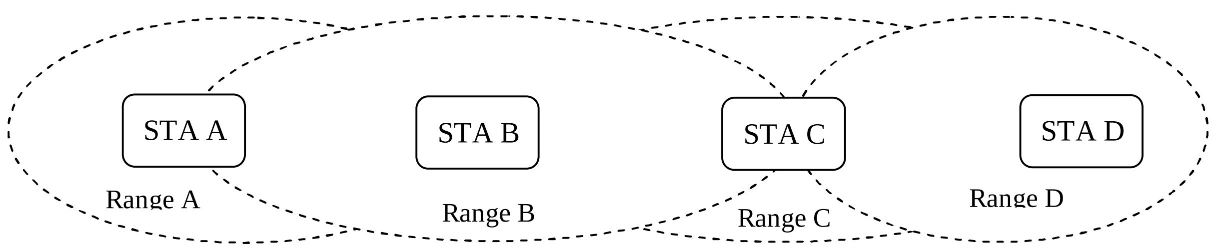


Figure 2.6:Hidden node and Exposed node problems.

Exposed node problem refers to a wrong conclusion made by a station that it cannot transmit to any other node just because it can hear the transmission made by the node at one of its sides [1, 8]. This can also be explained further using Figure 2.6. Suppose STA C is sending frame to STA D, it will be wrong for STA B to conclude that it cannot transmit to STA A just because it can hear the transmission between STA C and STA D.

The idea behind CSMA/CA is for the sender and the receiver to exchange control frames with each other before the sender actually transmits any data [16] and then informs nearby nodes that a transmission is in progress [16, 25]. The control frames used by the CSMA/CA [1, 6, 12, 13, 14, 16, 25] include:

- Request to Send (RTS) frame
- Clear to Send (CTS) frame
- Acknowledgement (ACK) frame

These control frames are examples of one of the three IEEE 802.11 standard frame types known as Control frame (see section 2.1.5.1). The CSMA/CA mandates that a gap of a minimum specified duration known as Inter-frame Spacing (IFS) exists between contiguous frame sequences. The IFS periods provide a mechanism for assigning priority that is then used for implementation of QoS support for time-bounded or other applications [9]. Examples of some of these gap durations include:

- Distributed Inter-frame Spaces (DIFS)
- Point Inter-frame Spaces (PIFS)
- Short Inter-frame Spaces (SIFS)

The DIFS is used for contention-based data spacing that has the lowest priority and longest duration. The SIFS has the lowest duration of time and used for highest priority packets like RTS, CTS, etc. The PIFS duration length and priority falls in-between the DIFS and the SIFS. The communicating nodes establish a handshake using the control frames prior to data transmission to ensure reliability in the network. Firstly, a sending station with data to send transmits an RTS frame to the receiving station and must receive a CTS frame from that receiving station before the actual transmission of the data. The sending station must also receive a non-corrupted ACK frame for every MAC frame it sent; otherwise, the frame will be retransmitted [25]. There is a duration field in the RTS and CTS frames that specifies the time interval necessary to completely transmit the data frame and the related ACK. This information is used by the stations that hear the transmitter or the receiver; and were not able to win the access to update their Network Allocation Vector (NAV) [14]. The NAV is the period of time that is continuously decrementing regardless of the status of the medium until it expires before these stations can re-start the sensing process again [1, 14]. See the illustrations in Figure 2.7

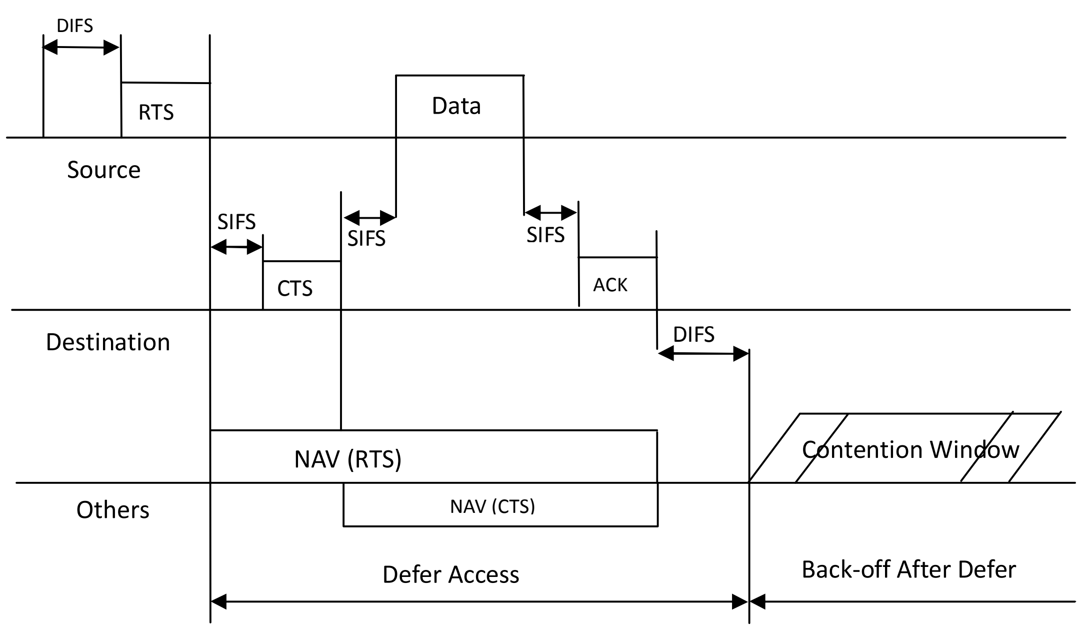


Figure 2.7: RTS/CTS/data/ACK and NAV settings [12].

This Algorithm minimizes the possibility of collision occurrence in the network by the use of control frames, inter-frame spaces, back-offs prior to data transmission and persistence strategy of deferring until the medium becomes idle and the counting down techniques [13].

The operation of the protocol is such that before a station tries to access the medium, it firstly invokes the carrier sense mechanism to determine the state of the medium. If the medium is found to be idle, the STA will wait out a DIFS delay period and if the medium is still free it will then transmits. If otherwise, it will wait until the medium is idle again and then enter a random back-off procedure. The random back-off procedure is designed to prevent multiple stations from seizing the medium immediately after the completion of an in-progress transmission [25]. The back-off process involves the station's back-off time and the stationsô retry count. The station's back-off time is an additional deferral time before transmitting that decrements only when the channel is idle, and it is frozen when another station is transmitting [12, 14]. To reduce the probability of repeated collision, the length of the back-off time is exponentially increased as the terminal goes through successive retransmission [9]. The expressed is as follows:

Backoff Time = Random() x aSlotTime - - - - - (2.1)

where

Random() = Pseudo-random integer drawn from a uniform distribution over the interval 0 and CW.

The contention window CW, is an integer within the range of minimum (aCWmin) and maximum (aCWmax) values.

aSLotTime = The value of the correspondingly named PHY characteristic. It is the maximum round trip delay between two STAs controlled by the same access point [14].

The station's retry count is the record of the number of unsuccessful attempts to transmit that increases as the STA records more unsuccessful attempts [12, 14]. When the retry count reaches a maximum value, the STA resets. The operation of this protocol could be further illustrated with the aid of a flowchart as shown in Figure 2.8.

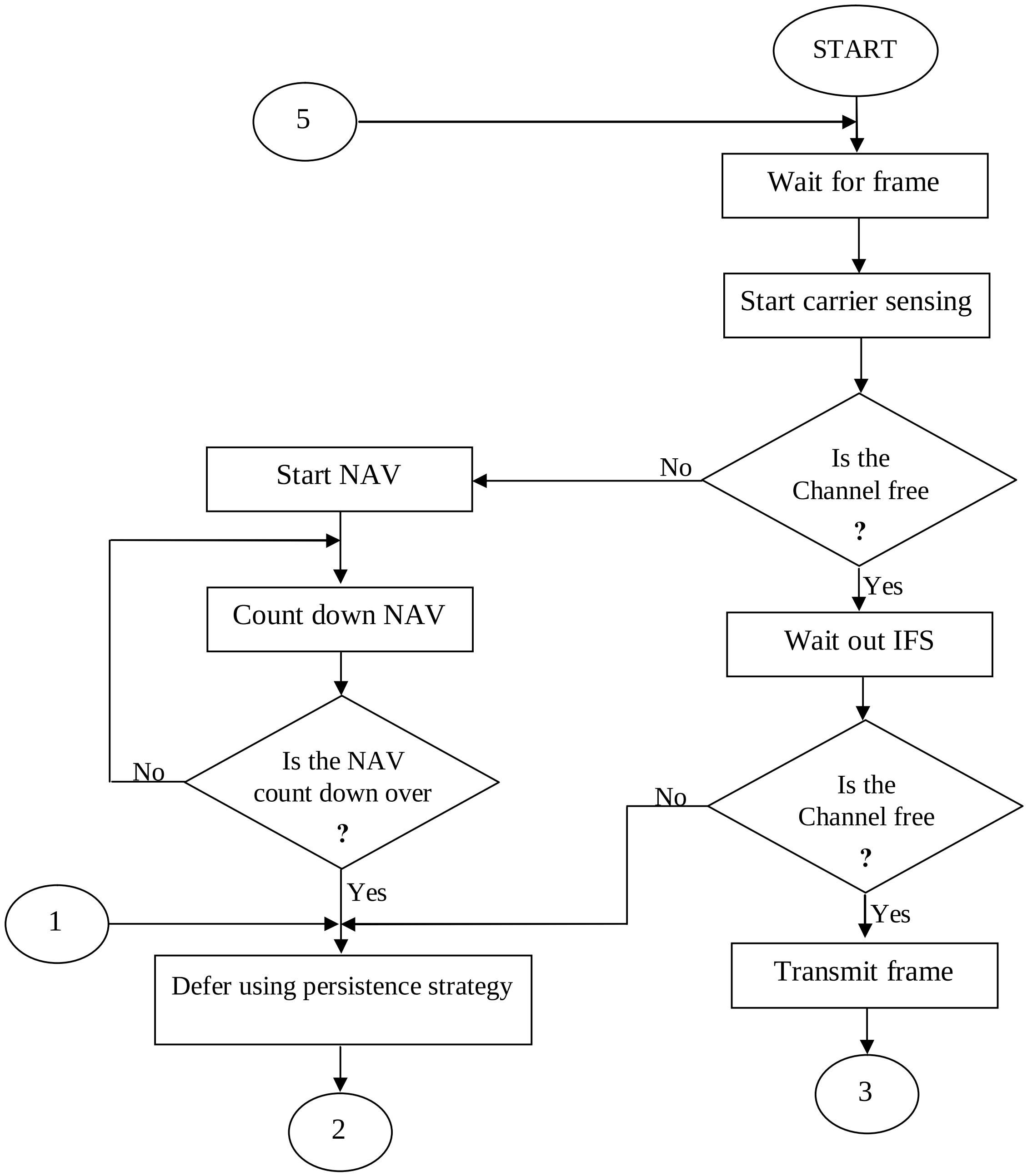


Figure 2.8: Flowchart of CSMA/CA.

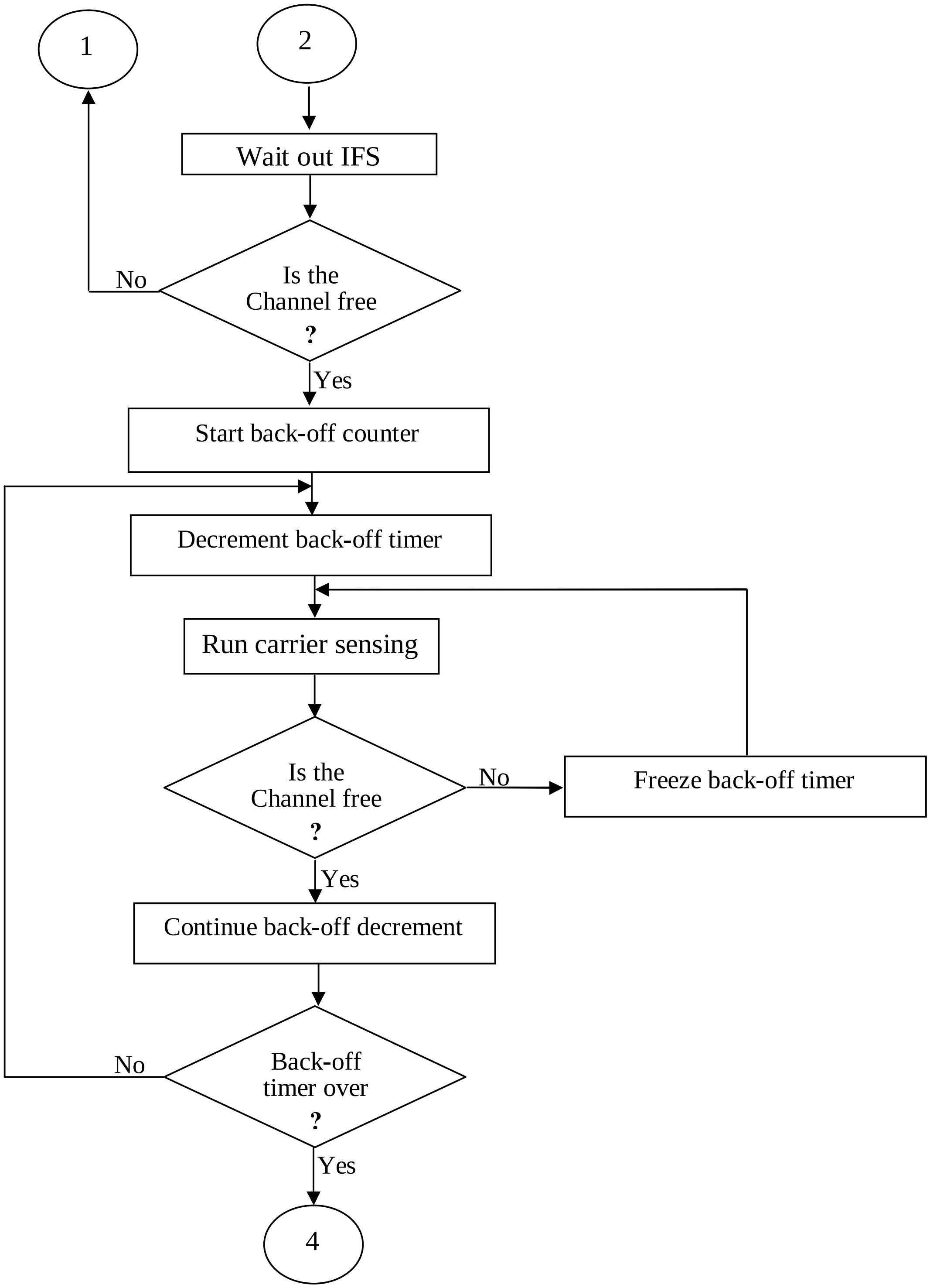


Figure 2.8: Flowchart of CSMA/CA (Continued).

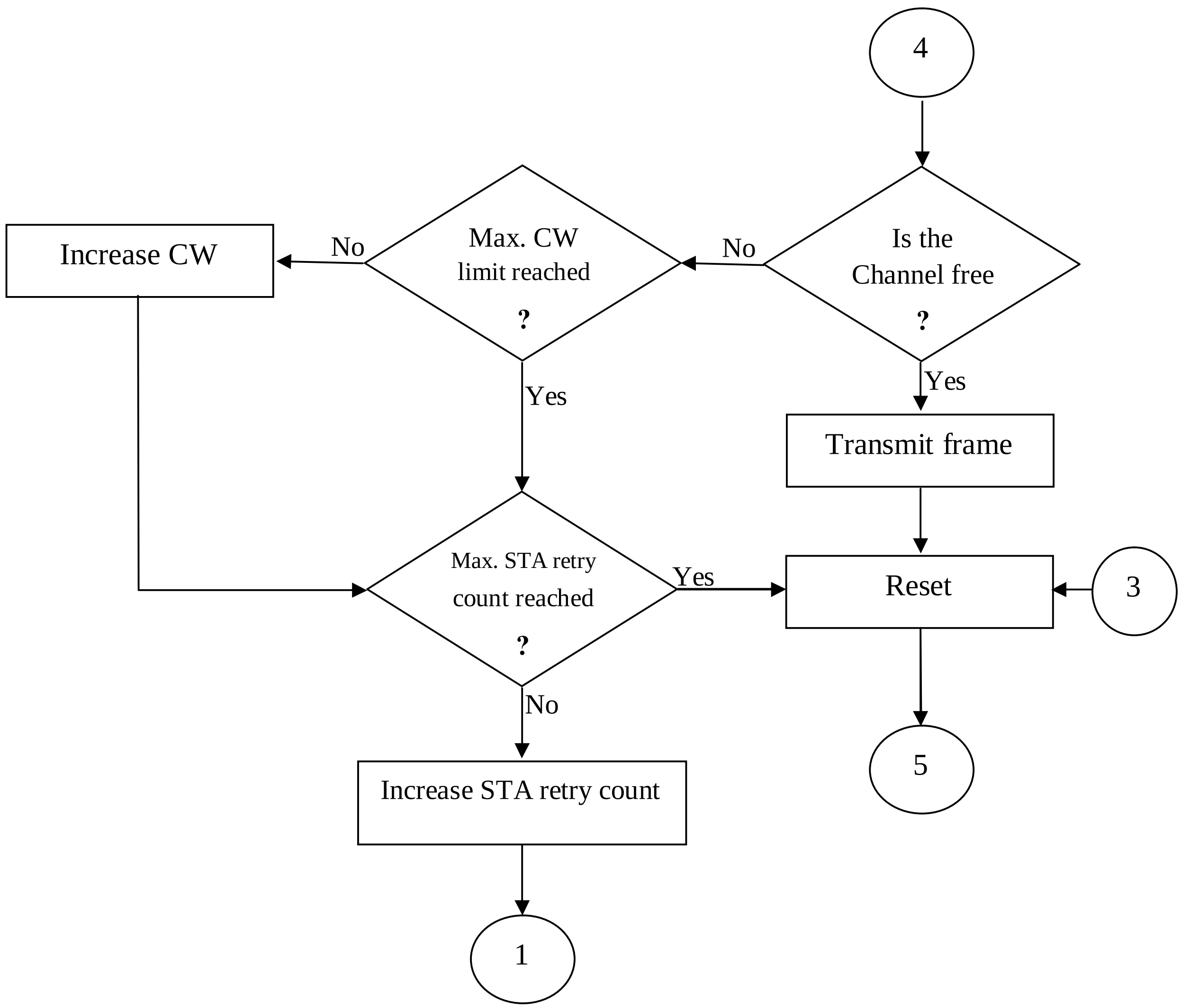


Figure 2.8: Flowchart of CSMA/CA (Continued).

2.1.4.2 **Point Coordination Function (PCF)**

The PCF is an optional access control capability for delay-sensitive traffic. It can only be implemented on an infrastructural network [12]. It uses contention-free polling process where access is controlled or coordinated from a single point. A station that is performing PCF traffic management is called Point Coordinator (PC) [6]. It has priority over the DCF's contention-based transmission therefore it can override it. In order to prevent the PCF from locking out the DCF traffic indefinitely from using the medium, a repetitive time is defined [1]. This time covers both the contention-free and contention-based traffic during which the PC can send a poll frame, receive data, send ACK, receive ACK, etc. At the end of this interval, the PC frees the medium for the contention -based stations to initiate the carrier sensing process for winning the medium.

2.1.4.3 **Hybrid Coordination Function (HCF)**

The HCF is a function that is only usable in a QoS network configuration [12,14]. It combines functions from the DCF and the PCF with some enhanced, QoS ï specific mechanisms and frame subtypes to allow a uniform set of frame exchange sequences to be used for QoS data transfer during both the contention-based period and contention free period [12]. It makes use of Enhanced Distributed Channel Access (EDCA) and the HCF Controlled Channel Access (HCCA) [12].

The EDCA is the contention-based transfer function of the HCF that defines four access categories (ACs) for traffic delivery with usersôpriority at the STA. The access categories include voice, video, best effort and background [12]. The exact time that a STA can obtain the channel is unpredictable in EDCA transfer function because it is contention-based. The implication is that delay and jitter between two consecutive frames will be difficult to predict, and that means that EDCA is not suitable for real-time applications with strict delay and jitter requirements [14].

The HCCA is the contention-free transfer function of the HCF that allows each STA to negotiate with the AP and generates a contention free period. The mechanism uses a QoS-aware centralized coordinator known as Hybrid Coordinator (HC) [12].

2.1.5 IEEE 802.11 WLAN Frame Format

The basic frame format of IEEE WLAN is made up of ten (10) fields with an introduction of an additional High Throughput (HT) control field used by the IEEE 802.11n for High Throughput communications [12] as illustrated in Figure 2.9. Frames are used to transmit information between stations [12, 25].

Frame Control (2 bytes)	Duration /ID (2 bytes)	Addr. 1 (6 bytes)	Addr. 2 (6 bytes)	Addr. 3 (6 bytes)	Sequence Control (2 bytes)	Addr. 4 (6 bytes)	QoS control (2 bytes)	HT control (4 bytes)	Frame Body (0-7955) bytes	FCS (4 bytes)

Versio n (2 bits)	Type (2 bits)	Subtype (4 bits)	To DS (1 bit)	From DS (1 bit)	More frag (1 bit)	Retry (1 bit)	Pwrmgt (I bit)	More data (1 bit)	WEP (1 bit)	Order (1 bit)

Figure 2.9: Frame format of IEEE 802.11n [13].

The Frame control field, Duration/ID field, Address 1 field and the FCS field are the basic frame format that must be present in every frame transmission [13].

The frame is basically classified into three (3) parts:

a. The Frame Header: This comprising of the frame control, the duration/ID, the Sequence control, QoS Control and four (4) address fields.
b. The Frame Body
c. The Frame Check Sequence (FCS)

The frame control field is a two (2) byte length field that bears such information that determines the type of frame that is being transmitted, the address management for the parties involved in the communication [1] and how the frame will be interpreted when received at the destination and some control functions.

The Duration/ID field is a 2 bytes length field that bears information about the duration of the transmission that is used to set the value of the NAV [1]. It also indicates the station identification (ID) [25] depending on the type and subtype of the frame control [12].

The Address fields are four (4) in number and each of them consists of six (6) bytes length field used to indicate the source address (SA), destination address (DA), transmitting station address (TA) and the receiving station address (RA) [12,13]. The interpretation of these addresses depends on the values of the ToDS and the FromDS sub-fields of the frame control field [14, 16]. The ToDS and the From DS sub-fields of the frame control field offers information on the address management interpretations for communications that might involve the AP(s) or contained within a BSS. The contents of the Address 1 and the Address 2 always hold the addresses of the intended receiving station(s) and the transmitting station respectively [13, 25]. This is shown in Tables 2.2 and 2.3.

Table 2.2: To/From DS Combinations in Data Frames [13].

To/From DS values	Meaning
ToDS = 0 FromDS = 0	A data frame direct from one STA to another STA within the same IBSS, or a data frame direct from one non-AP STA to another non-AP STA within the same BSS, as well as all management and control frames.
ToDS = 1 FromDS = 0	Data frame destined for the DS or being sent by a STA associated with a an AP to the port Access entity of that AP.
ToDS = 0 FromDS = 1	Data frame exiting the DS or being sent by the Port Access Entity in an AP.
ToDS = 1 FromDS = 1	A data frame using the four-address format. This standard does not define procedures for using this combination of the field values.

Table 2.3: Contents of the Address Field [13].

To Ds	FromDS	Address 1	Address 2	Address 3	Address 4
0	0	RA = DA	TA = SA	BSSID	Not Applicable
0	1	RA = DA	TA = BSSID	SA	Not Applicable
1	0	RA = BSSID	TA = SA	DA	Not Applicable
1	1	RA	TA	DA	SA

The Sequence control field is a two bytes field that provides a mechanism to represent the order of different fragments that are part of a frame [25]. It indicates the sequence number of the MSDU and the fragment number of each of the MSDU transmitted [12, 25]. It is not present in the control frames [12].

The QoS control field is a two (2) bytes length field that is used in data frames to identify the traffic category (TC) or traffic stream (TS) to which the frame belongs [12, 13].

The High Throughput (HT) control field is a four (4) bytes length field used for high throughput communication present in QoS Data and management frames [13].

The Frame body field is a variable length field that contains information specific to individual frame types and subtypes [13].

The FCS is a four (4) bytes length field that is used for error detection in the frame transmission [16].

2.1.5.1 **Frame Types**

The two (2) bits length Type sub-field and the four (4) bit length Subtype sub-fields of the frame control field is used to determine the function of frame involved in the communication. There are three (3) possible types of frames transmittable in the network [12, 13]. They include:

1. Data frame
2. Control frame
3. Management frame

Each of these frame types has several subtypes. The frame types and subtypes could be signified using any of the possible permutations of the bits of the Type and Sub-type sub-fields of the frame control field. The various sub-types of each of the frame types and their basic descriptions can be outlined in Table 2.4 as shown:

Table 2.4: Frame Types and their Sub-types [12, 13].

Type value	Type description	Subtype value	Subtype description
00	Management	0000	Association request
00	Management	0001	Association response
00	Management	0010	Reassociation request
00	Management	0011	Reassociation response
00	Management	0100	Probe request
00	Management	0101	Probe response
00	Management	0110-0111	Reserved
00	Management	1000	Beacon
00	Management	1001	ATIM
00	Management	1010	Disassociation
00	Management	1011	Authentication
00	Management	1100	Deathentication
00	Management	1101	Action
00	Management	1110	Action No Ack
00	Management	1111	Reserved
01	Control	0000-0110	Reserved
01	Control	0111	Control Wrapper
01	Control	1000	Block Ack Request (BlockAckReq)
01	Control	1001	Block Ack (BlockAck)
01	Control	1010	PS-Poll
01	Control	1011	RTS
01	Control	1100	CTS
01	Control	1101	ACK
01	Control	1110	CF-End
01	Control	1111	CF-End + CF-Ack

Table 2.4: Frame Types and their Sub-types [12, 13] Continued.

Type Value	Type Description	Subtype Value	Subtype Description
10	Data	0000	Data
10	Data	0001	Data + CF-Ack
10	Data	0010	Data + CF-Poll
10	Data	0011	Data + CF-Ack + CF-Poll
10	Data	0100	Null (no data)
10	Data	0101	CF-Ack (no data)
10	Data	0110	CF-Poll (no data)
10	Data	0111	CF-Ack + CF-Poll (no data)
10	Data	1000	QoS Data
10	Data	1001	QoS Data + CF-Ack
10	Data	1010	QoS Data + CF-Poll
10	Data	1011	QoS Data + CF-Ack + CF-Poll
10	Data	1100	QoS Null (no data)
10	Data	1101	Reserved
10	Data	1110	QoS CF-Poll (no data)
10	Data	1111	QoS CF-Ack + CF-Poll (no data)
11	Reserved	0000-1111	Reserved

2.1.5.2 **Frame Aggregation**

This is the process of concatenating two or more sub-frames in a network to realize a super-frame in order to improve the throughput and reduce the overhead cost that would have been incurred if the sub-frames were to be sent individually across the network. The frame aggregation mechanisms include [26]:

- Aggregate MAC Service Data Unit (A-MSDU) and
- Aggregate MAC Protocol Data Unit (A-MPDU) schemes.

2.1.5.2.1 **Aggregate MAC Service Data Unit (A-MSDU)**

The A-MSDU is a super-frame containing the concatenation of several MSDUs coming from the upper layer into a single frame. Each comprises of a header that contains the Destination address (DA), Source address (SA) and a length field followed by the MSDU and a 0 to 3 bytes of padding field. The length field contains the length in octet of the MSDU. The padding field is used to ensure that the length of the sub-frame is a multiple of four. This super-frame is appended with Frame Check Sequence (FCS) for error detection. The maximum length of an A-MSDU is 7935 bytes [26]. This is illustrated in Figure 2.10.

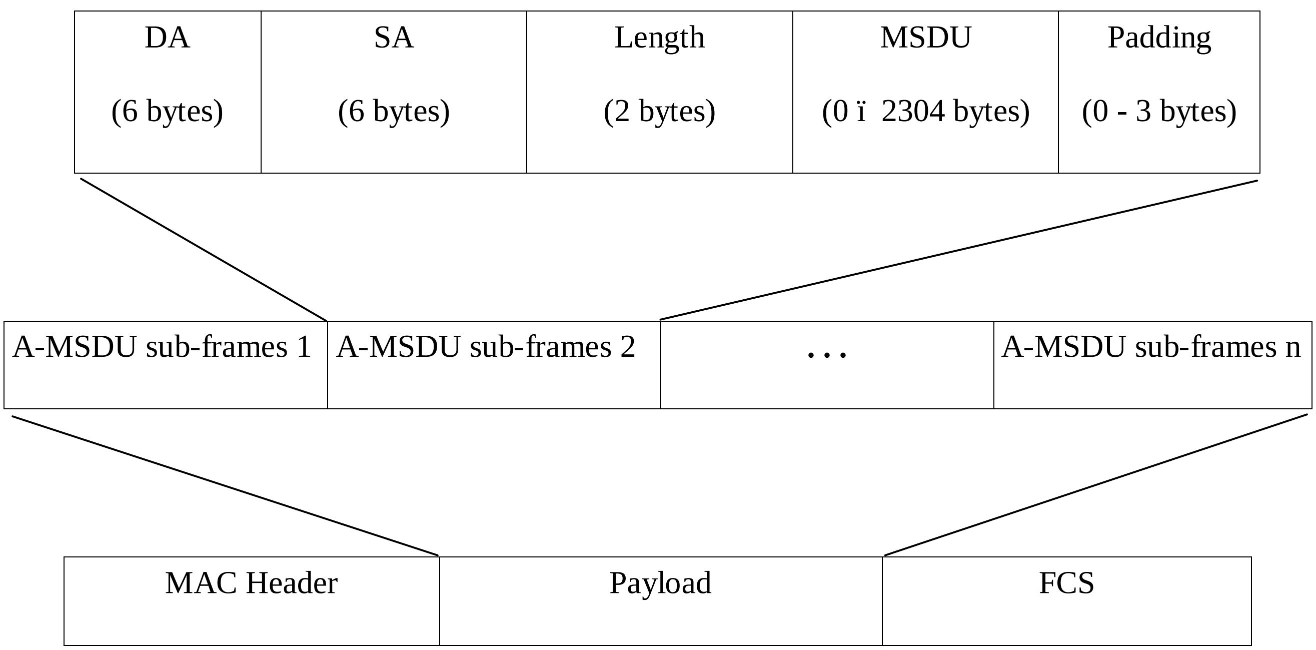


Figure 2.10:A-MSDU Frame Structure [13].

2.1.5.2.2 **Aggregate MAC Protocol Data Unit (A-MPDU)**

The A-MPDU is created between the MAC layer and physical (PHY) layer of the OSI reference model. It consists of one or more A-MPDU sub-frames as shown in Figure 2.7. Each sub-frame contains a delimiter field followed by an MPDU and then 0 to 3 padding. The delimiter field contains the Cyclic Redundancy Check (CRC) that is used as a FCS for error detection. The maximum length of an A-MPDU is 65535 bytes [13].

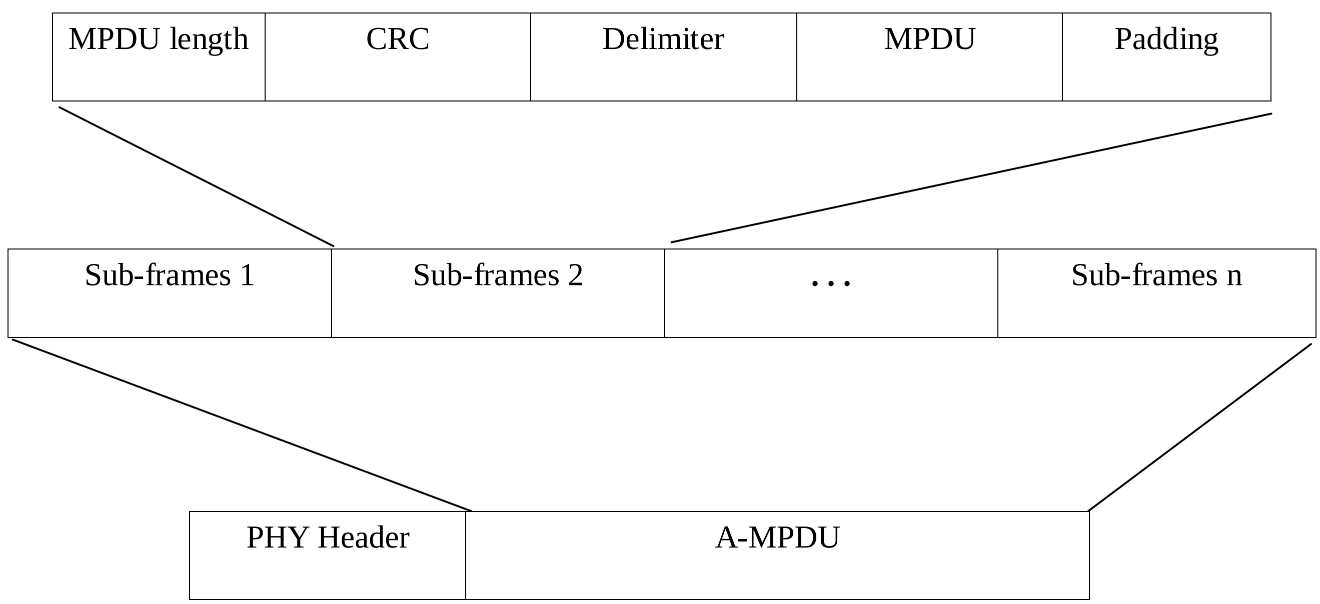


Figure 2.11: A-MPDU Frame Structure [13].

Nowadays, considering the much attractive benefits peculiar to this new improvement IEEE 802.11n standard compared to the legacy type in terms of QoS delivery, network system vendors like Aerohive, Bluesocket, Cisco, Enterasys, Motorola, etc have started deploying the technology in their products [8]. Although the technology has created great attraction, there are still some fundamental challenges that have to be addressed when deploying it. Some of these challenges include problem of co-channel interference, problem of migration, etc. [19].

2.1.6 **IEEE 802.11 MAC Management Mechanisms**

This sub-layerôs mechanisms handle the establishment of communication between STAs and APs in a mobile environment [9]. The sub-layer may include:

- Stations Registration Mechanism
- Stations Handoff Mechanism

2.1.6.1 **Stations Registration Mechanism**

This management mechanism defines how STAs identify and associate with the APs in a BSA. Association is a procedure by which a STA 'registers' with an AP [9]. It involves a technique referred to as scanning. Scanning is simply a process by whereby STAs listen to available beacons that advertise network information about an AP or the STA sends probe request to targeted APs that are capable of receiving its probe. STA engages in scanning process whenever it joins the network and also whenever it becomes 'unhappy' with its current AP (maybe due to signal weakness) therefore looking out for another AP [16]. There are two types of scanning [9, 16]. They include:

- Active scanning
- Passive scanning

Active scanning is a situation whereby STA continuously search for AP by sending out a probe frame that makes all APs within reach to reply with Probe Response frame. The STA selects one of the APs and then sends it an Association Request frame. The AP will then reply with an Association Response frame.

Passive scanning is a situation whereby APs periodically send out a Beacon frame that advertises the capability of the AP, which may include the transmission rate it supports [16]. A node can change to another AP based on the Beacon frame advert simply by sending an Association

Request frame to the AP if it wants to associate with that AP [9]. The AP can then grant permission to the STA using Association Response frame.

2.1.6.2 **Stations Handoff Mechanism**

This management mechanism defines the mobility of the STA in the network. There are three (3) mobility types in IEEE 802.11 network [9]. They include

- No Transition
- BSS Transition
- ESS Transition

A station is said to be experiencing ñNo Transitionò when its movement is still within a BSA [9, 14]. A BSS transition is experienced when STA moves from one BSS to another but within the same ESS. The ESS transition is experienced when the STA moves from an AP in one ESS to an AP in another ESS.

Whenever a STA acquires a new AP, the new AP notifies the old AP of the changes through a DS.

2.2 Research Works in the Area

There has been a series of research contributions at the different areas of the wireless network system. The research works are discussed in the proceeding sub-sections based on their performance, design and development issues. In this work, researches on performance issues are favored. Such performance issues include performance analysis and performance improvement.

2.2.1 Performance Analysis

A control MAC protocol that accommodates the coexistence of 20 MHz and 40 MHz channel bandwidth of the legacy and green field stations of the IEEE 802.11n network was proposed [20]. The Access Point (AP) controls this coexistence by setting the Network Allocation Vector (NAV), a MAC layer protection control mechanism, to them. The performance of the proposed protocol with the conventional method was compared. It was observed that the proposed method offers higher throughput performance and efficiency than the later.

The performance benefit of the reverse direction technique application was obtained using a model of the 802.11n protocol developed for the Opnet simulation software [22]. Result comparisons of the aggregated throughput in one involve reverse direction and in another that does not, were carried out. Observation results showed that reverse direction provides more performance benefit ranging from about 8 to 30% in a mixed traffic scenario. This was attributed to the functionality of the technique to reduce the number of contentions by a factor of 1.5 to 2, which therefore, reduces the number of collisions within WLAN during EDCA phase.

An analytical approach to calculate the 802.11 DCF throughputs under a saturated condition based DTMC model in an ideal channel was developed [28]. The model was applied to the two access mechanisms of IEEE 802.11 standard to observe an extensive throughput performance evaluation of them.

An investigation of the throughput and delay performance improvement of MAC protocol using a two-frame aggregation technique for a uni-directional and bi-directional data transfer was presented [29]. Also, a proposal of an optimal frame size algorithm with A-MSDU under an error-prone channel was presented. An analytical model of the system using an extension of [28] model was firstly developed and validated using an ns-2 software simulator. The observation made was that throughput is improved significantly when compared with the randomized and fixed frame aggregation algorithm.

An analytical model of IEEE 802.11 DCF protocol for both saturated and unsaturated traffic load conditions for a single hop scenario was proposed [30]. The saturation traffic model was built from a model in earlier work with an introduction of freezing probability that handles the possibility of nodes in back-off state freezing its counter because of third party activity that is going on in the channel [28]. This model was further extended to unsaturated load conditions using an iterative algorithm to compute the binomial distribution of the number of the contending nodes. The models were validated using Qualnet simulator software. The proposed models were shown to be able to accurately estimate the performance of the network [30].

The impact of an error-prone channel over throughput and delay performance measures in traffic saturated IEEE 802.11 WLAN was presented [31]. The stationsô transmission probability was realized using a two-dimensioned Markov chain model of the back-off window size that considers the frame-error rates and maximal allowable number of retransmission attempts. It was observed that the frame-error rate has a significant impact over the theoretical throughput, mean frame delay, and the discard probability.

A study of the MAC layer throughput with Distributed Coordination Function (DCF) protocol in the IEEE 802.11a/g/n-based mobile LAN was presented using theoretical analysis approach method [32]. The study was evaluated in Rayleigh fading wireless channel and a two-dimensioned Markov chain model was used to realize the contention window size. The work considered a number of stations with both variable payload size and mobile speed on the condition that fading margin and transmission probability are fixed. The results obtained showed that there exist an optimal number of stations (or sub-frames) to maximize the saturation throughput of the network under the error-prone channel.

The performance analysis of IEEE 802.11n WLAN protocol was evaluated using OPNET Modeler event simulation software to model the infrastructure topology [33]. Four scenarios were modeled using this software viz. A wired LAN and three access points which are connected through a central WLAN controller and three Wireless workstations connected at each access points, A wired LAN and three access points which are connected through a central WLAN controller and five Wireless workstations connected at each access points, A wired LAN and three access points which are connected through a central WLAN controller and seven Wireless workstations connected at each access points and A wired LAN and two access points which are connected through a central WLAN controller and one mobile workstations with a roaming capability. It was observed that when the number of connected workstation increases, the total throughput and access delay on the WLAN network increases. Also, the possibility of collisions, congestions and buffer overflow problem increases too.

A research work on investigation of the performance effects of most of the proposed IEEE 802.11n WLAN MAC and PHY layer features on an ad hoc network topology was experimented in real conditions using a certain D-Link USB adapter [34]. The adapter has the capacity to support the IEEE 802.11n system conditions. Iperf software was used to measure the throughput metric parameter obtained from the experiment. It was observed that the aggregation techniques can enhance the throughput but if the packet loss is high, network performance can suffer degradation. A scheduler was therefore proposed to handle the frame aggregation process to improve the network efficiency.

A distributed and adaptive cross-layer dynamic mapping technique that maps the arriving video packets into different Enhanced Distributed Channel Access (EDCA) Access Categories (AC) was proposed [35]. The aim was to evaluate the QoS performance of these mapping techniques for layered video to different AC categories that were considered in the work. An EDCA analytical model that estimates the QoS parameters based on Markov chain was presented and then validated using MATLAB. The result shows that canonical mapping strategy is the best recommendation for high data rate and high number of layers used for video coding.

An analytical work on the block ACK scheme of IEEE 802.11e network was presented [36]. The throughput and delay performance of the scheme according to various channel access modes and in an erroneous channel environment was modeled and validated using ns-2 simulator. Observation results showed that increasing the size of the data block improves the aggregate throughput performance with better efficiency for the MAC level acknowledgement but at the cost of a longer frame delay.

A work on the performance enhancement of Block-ACK in IEEE 802.11n network using Markov's discrete time system model was presented [37]. The model was validated using NS-2 simulation tool. Results showed that the application of Block-ACK constitutes improvement in performance. It was also observed that the larger the block size is, the higher the improvement.

A performance study of the two IEEE 802.11n frame aggregation mechanisms: A-MPDU and A-MSDU was presented [38]. The analysis was done using a DTMC model of the aggregation process. Results showed that the throughput performance of the A-MSDU mechanism outperformed the A-MPDU mechanism, as the frame aggregation size grows larger under an error-free environment.

A comparison of the performance of the aggregation mechanisms: A-MSDU and A-MPDU along with the two-level aggregation was studied using OPNET Modeler simulator developed by Intel [39]. Results showed that though the MAC frame aggregation methods according to 802.11n standard draft offer improvement in throughput and efficiency, the two-level aggregation is most efficacious.

An experimental work on the MAC frame aggregation implementation in 802.11 WLAN standard using open source drivers was presented [40]. An ORBIT testbed facility was used to setup the 802.11 wireless network scenario and the traffic on the network was generated using Iperf Internet traffic generator tool. The results obtained quantify typical QoS performance measurement variations observed with and without aggregation using both a theoretical and experimental models.

The effect of frame aggregation scheme on IEEE 802.11 WLAN was also illustrated using an off-the-shelf IEEE 802.11 wireless LAN product [41]. The implementation of the scheme was done through the product's device driver's modifications. An observation of a high throughput and high efficiency was recorded due to the introduction of this scheme.

An analytical model to estimate the performance of an IEEE 802.11n high throughput link between a station and an Access Point (AP) was presented [42]. The efficiency behavior of the MAC layer of the network under TCP and UDP traffic based on the aggregation size, packet error rate and PHY settings was studied in both ideal and noisy channel conditions. The percentage performance improvement achievable in the two channel conditions in the introduction of aggregation was shown. The results also showed that the A-MPDU aggregation outperformed the A-MSDU aggregation scheme for high packet error rate and PHY settings.

An experiment study to evaluate the performance of the frame aggregation enhancement in the new IEEE 802.11n WLAN was presented [43]. The focus was on the effect of frame aggregation in the support of voice and video applications in wireless network. More so, the work was to examine the interoperability and fairness of the 802.11n network. The experiment was performed using the D-Link DWA-160 Xtreme N Dual Band Draft 802.11n USB Adapters (revision B) with RAlink RT2870STA driver for all the scenarios of the experiment in a real indoor ad hoc setup. Results showed that the aggregation scheme is very effective in case of high rate traffic but can degrade the QoS by increasing the frame delay when it is used in low rate applications like Voice over Internet Protocol (VoIP). Therefore, a simple scheduler that combines the 802.11e service differentiation and 802.11n frame aggregation was proposed and it showed improvement in terms of QoS parameters.

The interaction between the MAC frame aggregation and the Transmission Control Protocol (TCP) congestion control mechanisms was investigated and presented [44]. An NS-2 discrete event simulator was used to model a scenario comprising of a single wireless node and an access point. A simulation of the MAC frame aggregation techniques with their interactions with different TCP congestion control mechanisms was carried out. It was observed that NewReno and SACK outperformed the other congestion techniques in terms of throughput.

A new model that examines the capability of IEEE 802.11n network that is operated in the Mobile Networking Architecture was proposed [45]. The idea was to evaluate whether IEEE

802.11n WLAN can overcome the current fixed operating mode and then escalate the IEEE 802.11n to the Vehicular Internet Environment under the Mobile Networking Architecture. The work was carried out on an emulation LAB scenario that presents the IEEE 802.11n Mobile Nodes (MN) and IEEE 802.11n Mobile Station (MS). The former operated under the Multiple Access Point (MAP) mode within the signal coverage of 3.6KM per AP and the later moving in the dedicate rate of Vehicular internet Environment. The experiment result showed that the IEEE 802.11n can achieve optimal capability in the low-rate Vehicular Internet Environment.

The performance analysis on the effect of interferences due to coexistence of Ultra Wide Band (UWB) with IEEE 802.11n was presented [46]. MATLAB/Simulink was used to set up the UWB and the 802.11n systems PHY layer. The emission limits for multiple UWB interference was obtained and as long as the UWB power is no more than these emission limit, UWB can coexist with the IEEE 802.11n systems.

A testbed to evaluate the impact of IEEE 802.11n operation on IEEE 802.15.4 performance during an overlap between the two channels was studied [47]. The testbed consisted of 15 IEEE 802.15.4 nodes sending packet to their common coordinator using beaconless mode operation and two IEEE 802.11n nodes acting as a client/server pair. Iperf utility simulation software was used to generate traffic between the IEEE 802.11n client and server machines. The experiment was carried out in two scenarios. It was observed that the presence of IEEE 802.15.4 traffic does not have any significant impact on the IEEE 802.11n traffic loads. However, there was a recorded impact of the IEEE 802.11n traffic on the IEEE 802.15.4 traffic load in terms of increase in loss rate and latency.

A testbed experiment to evaluate the empirical performance comparison of wireless IEEE 802.11n encryption methods on four operating systems viz. Windows XP, Vista, Server 2008 and

Ubuntu was presented [48]. The idea was to evaluate their performance differences on the four operating systems due to different encryption methods. The wireless encryption methods that were implemented on the operating systems include Wired Equivalent Privacy (WEP-64 and WEP -128) and Wi Fi Protection Access (WPA and WPA2). The performance metric was measured using Iperf 2.0.3 simulator software. It was observed that for all the operating systems, as the packet size increases, throughput values increase. However, the operating systems performance varies for some other QoS metric for different security protocols.

An experimental work on the performance and limitation of the IEEE 802.11n devices in vehicular network was studied [49]. The experiment was done both in an indoor and outdoor scenario using some of the devices obtainable in the market. It was reported that the tested devices can communicate over large distances in indoor environment with high throughput performance.

An experimental comparative study of the performances of IEEE 802.11n and the IEEE 802.11g networks in a real outdoor scenario with less reflecting surfaces was presented [50]. One station served as the base station and two stations as the clients. The clients have IEEE 802.11n and IEEE 802.11g standard individually implemented in their respective configurations with Vistumbler and Jperf software programs installed respectively in them. Observation showed that the IEEE 802.11n offers more performance in terms of throughput, range and SNR compare to the IEEE 802.11g standard.

More so, an investigation of the performances of Destination Sequence Distance Vector (DSDV) and Ad hoc On Demand Vector (AODV) routing algorithms were studied [51]. The algorithms were deployed at the IEEE 802.11 MAC layer of both the IEEE 802.11n and the IEEE 802.11 legacy networks using NS-2 simulator. An observed increment in throughput and decrement in delay for the IEEE 802.11n compared to the legacy network was made. This improvement was attributed to the unfair channel allocation to the traffic flow.

The MAC layer throughput performance of IEEE 802.11n on a Radio over Fiber (RoF) network with the application of Multi-packet reception (MPR) in data transmission was presented [52]. An analytical expression was developed and the performance was considered in both ideal and error-prone channel conditions. It was observed that the maximum throughput increases roughly linearly with the number of antennas used at the remote antenna units but decreases gradually with increasing fiber propagation delay and number of active stations in an ideal channel condition. However, in an error-prone channel condition, the throughput is suppressed with increasing amount of errors in the transmission channel over all available range of fiber propagation delay.

The design and implementation of high-throughput MAC system architecture for IEEE 802.11n WLAN was proposed [53]. The MAC architecture was built using Xilinx embedded Reduced Instruction Set Computer (RISC) architecture powerPC440 and verified using System Verilog software simulator. The result recorded an achievable 462Mbps throughput.

A performance measure on the achievable throughput of the infrastructure IEEE 802.11n network was carried out using some commercially available 802.11n devices [54]. An analysis on the packet transfer over the air which was captured using AirMagnet Wi-Fi analyzer tool was made. It was observed that the performance variations depends on how the devices might have been differently programmed by the manufacturers to employ different modulation rates, frame aggregation schemes, and block acknowledgement mechanisms for different wireless environment and conditions

A performance analysis of several representative dual-radio relay networks (DRRN) topology was presented [55]. The topology consists of Dual-Radio Relay (DRR) nodes that are interconnected in multihop manner to form a Dual-Radio Multihop Relay (DRMR) network; and is verified using Qualnet 5.2 event driven simulator. It was observed that throughput is fairly shared among the clients in AP and Relay stations as long as the total aggregated client throughput does not exceed the first hop link maximum throughput capacity for the multihop configuration.

An experiment to evaluate the empirical performance comparison of wireless IEEE 802.11n encryption methods on Windows Vista and Window Server 2008 was presented [56].An Iperf 2.0.3 simulator software was used as the primary tool to measure the performance metrics in the research study. The observation made showed different performance metrics for the operating systems in wireless network.

2.2.2 **Performance Improvement**

A proposal on the novel way of achieving improved performance in data transmission in the IEEE 802.11n network based on Reverse Direction (RD) protocol was presented [21]. The proposed scheme achieves the improvement by supporting ñon-demandò bi-directional data flow using the existing two-way RTS/CTS handshake without any additional control frame. OPNET simulation engine was used in obtaining the QoS parameters of the scheme. Result findings showed that the RD protocol greatly improves the performance capacity of the network.

An analytical model of IEEE 802.11 MAC CSMA/CA was presented [57]. This model is a further modification from the developed model [28]. It was validated using ns2 based IEEE

802.11 WLAN simulator software. The model was observed to capture many interesting features of non-saturated operation of the network.

A dynamic aggregation selection and scheduling (DASS) algorithm was presented [58]. The algorithm has the capability of dynamically adopting an appropriate aggregation mechanism for IEEE 802.11s mesh network based on some network parameters. The performance verification was simulated using ns-2 simulator software. It was observed that DASS could improve the overall throughout of the 802.11s mesh network.

A study on the requirement for efficiency in MAC of IEEE 802.11n network was made [59]. It was observed that the major cause of inefficiency in MAC layer of the network is due to overheads in data transmission. Therefore, various strategies to achieve improvement through frame aggregation were proposed.

An extension of the analytical model [28] was presented in a proposed block ACK scheme [60]. The proposed work increases the system capacity and reduces the overhead in the MAC layer of the WLAN. The scheme also aims to limit the back-off to a finite state for block ACK with an AP using Markov's approach on an error-free communication channel. The performance analysis of the proposed approach was carried out using MATLAB tools. The results showed how the total throughput of the basic access mode degrades as the number of mobile host increases.

A proposed compressed Block ACK mechanism that works as a selective repeat mechanism to be adapted to the frame aggregation scheme was presented [61]. The performance analysis of the proposed scheme was compared with the legacy method. Observation results showed that the proposed method offers a higher improvement on the total throughput.

An investigation on the impact of the aggregation headers of IEEE 802.11n aggregation scheme on small MSDUs was presented [62]. The study was made on an assumed error-free channel. An analytical expression was developed to determine the Header-to-Data Ratio (HDR) for the different aggregation schemes. The model was validated using ns-2 network simulator software. It was observed that though the aggregation might be beneficial for some type of applications however, it will produce more headers and delay for others. A proposal to either develop aggregation schemes that mainly support small MSDUs, or to make the existing schemes adaptive in order to dynamically select the appropriate aggregation parameters based on the MSDU size, delay constraints and traffic class was presented.

A work that introduces fragmentation before aggregation (AFR) was presented [63]. An analytical model was developed to evaluate the throughput and delay performance of AFR in a noisy channel. The model was validated using NS-2 simulator software. Observation showed that AFR results to the retransmission of the fragment containing error only in case of a corrupted transmission. This will save the system resources to a greater value compared to retransmission of the whole frame. The model also calculates the optimal frame and fragment size with additional function of minimizing transmission delay using zero waiting mechanism.

A study of the impact of frame aggregation size in data transmission was presented [64]. An analytical model of the transmission queue at the MAC layer of the IEEE 802.11n stations as a batch service queue system based on Markov's queuing process was developed and validated using Opnet simulator. The dfittool included in MATLAB Statistics toolbox was used to analyze the findings based on latency and channel utilization performance metrics. It was observed that there is no unique aggregation size that maximizes utilization under the study scenarios. Instead, the dynamic assignment of aggregate size based on traffic arrival rate and data frame size was suggested.

A simple scheduler for frame aggregation techniques was proposed [65]. The scheduler determines the size of the aggregated frame, and then chooses the particular aggregation scheme based on the time deadline required to transmit the aggregated frame. It was developed using C language. The performance of the scheduler with a fixed size aggregation scheme was compared. It was reported that the proposed scheduler method is superior to the fixed method under lightly loaded conditions.

A bi-scheduler algorithm for frame aggregation in IEEE 802.11n was studied and presented [66]. The idea was to use the scheduling algorithm to decide the type of the aggregation mechanism (A-MSDU or A-MPDU) to implement based on the Access Category (AC) in order to ensure improvement on the throughput of the WLAN.

A simple reference scheme that covers the fundamental properties of packet aggregation and MU-MIMO transmission was presented [67]. The aim was to demonstrate the significant improvement on the system performance in terms of packet loss (blocking probability) and delay due to combination of both techniques. The work was carried out using a C++ simulator. The observation results showed that the use of packet aggregation significantly improves the performance of the system.

An adaptive learning process that constructs the receiver list based on the dynamic channel-state diversity of candidate receivers was proposed [68]. The objective was to tackle the head-of-line (HOL) blocking problem. This is a situation that occurs when frame currently at the head of the queue in the sender's MAC layer could not be transmitted successfully due to temporary unavailability of the receiving station. The HOL blocking problem can lead to bottle-neck on the queue during the persistence and back-off process. The operation of the proposed work is such that the system firstly records the information about the channel diversity using counter, selects a subset of neighbors from the record, sends Multicast RTS (MRTS) and then computes its list based on the feedback on the current network condition. A comparison of a fixed length and variable length channel-state-based schemes against random scheduling schemes in the basic MRTS was made using ns-2 simulator. Result showed that a short fixed length MRTS receiver list outperformed the random scheme with an equal or even longer list.

A set of PHY layer and MAC layer enhancements that allows IEEE 802.11 network to achieve an application layer high throughput greater than 100Mb/s was presented [69]. The model was simulated using NS version 2.26 event simulator. It was observed that the enhancements enable the support of several flows with high throughput and low latency.

A performance study on incorporation of multiuser capabilities in 802.11n-based WLAN was presented [70]. Four MAC schemes that use Adaptive Modulation and Coding (AMC) strategy was proposed and evaluated with a link-layer simulator implemented in C++. The proposed schemes were observed to offer a significant QoS performance enhancement in terms of throughput compared to the theoretical maximum value.

2.2.3 **Conclusion**

The earlier sections of this chapter introduced the IEEE 802.11n amendment standard proposed specifications for higher throughput. This review shows that in-line with the WLAN proposal the effort has been on improving the performance of the WLAN technology and also analyzing the performance of the achieved improvements. These have been of paramount importance to research and development in the network. Statistics show that frame aggregation improvement technique is very popular. This is because frame aggregation offers higher throughput than others. This work focused on analyzing the performance of the frame aggregation technique with respect to throughput, access delay and blocking probability performance measure in an IEEE 802.11n WLAN. The work adopted only the MSDU aggregation scheme for the analysis. The analysis was considered over an error-prone channel unlike other research contributions that were based on error-free channels [28, 30, 38]. However, only the error due to noise was considered among other channel error causes [31]. There has not been any research work that analyzed the frame aggregation technique with respect to these parameters in the network. Therefore, the work aimed to define the optimal performance of the frame aggregation based IEEE 802.11n network for various QoS parameter values in an error-prone WLAN channel.

CHAPTER THREE

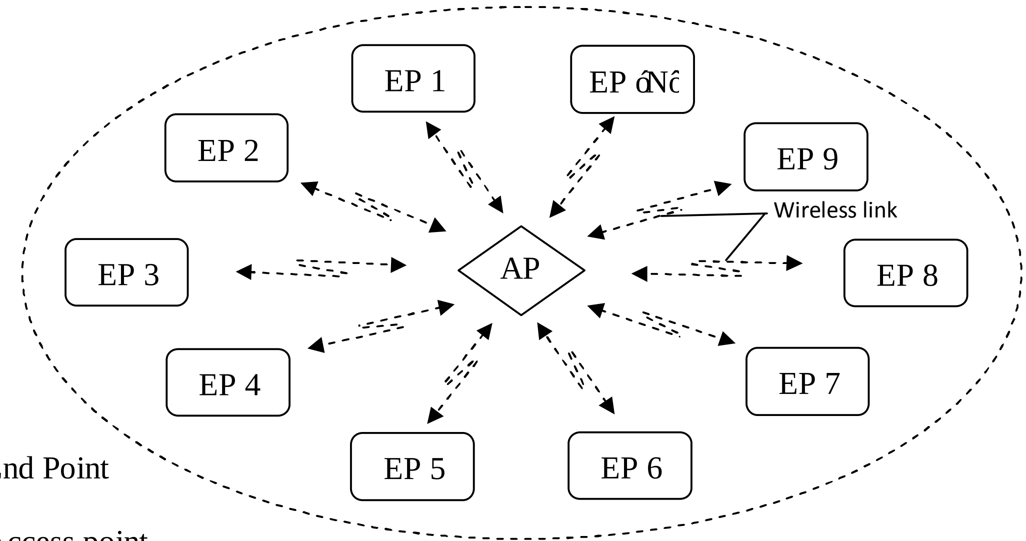
METHODOLOGY

3.1 Background

In the previous chapter, it was concluded that the performance of the IEEE802.11n WLAN frame aggregation technique would be the object of study for this work. Therefore, the first step in the modeling of the IEEE 802.11n WLAN is to adopt a typical network in which the frame aggregation technique performance would be investigated. This typical physical network would be modeled in this chapter.

3.2 IEEE 802.11n Network Architecture

The work considered a typical IEEE 802.11n WLAN Basic Service Set that comprises of an Access Point and ôNô number of contending End Point (EP) stations as illustrated in Figure 3.1.The EPs were homogenous stations that shared similar properties and equal privilege on the network. Also, the work considered the communication that exists between the AP and the EP stations only. More so, the RTS/CTS access method that allows all the EP stations to contend for access on the shared error-prone transmission channel using CSMA/CA protocol was adopted.



KEY

EP – End Point

AP – Access point

Figure 3.1: A Typical IEEE 802.11n Architecture.

3.3 System Modeling

The network architecture presented in Figure 3.1 was modeled for the purpose of the study. There are lists of modeling approaches to problem solving [71]. The approach adopted for this work is unique. It included the combination of physical, mathematical, graphical and computer simulation modeling approaches.

The physical model approach involved an actual physical representation of the network using functional blocks. The mathematical approach involved the realization of the physical model using mathematical equations that depicts and predicts the network's behavior. The graphical approach involved the realization of model using graph-based representation of the network. The computer simulation approach involved the use of the computer simulator software to realize the network performance.

This section introduces the combination of these modeling approaches to realize the network architecture presented in Figure 3.1. The overall system data flow diagram of the work is illustrated with Figure 3.2.

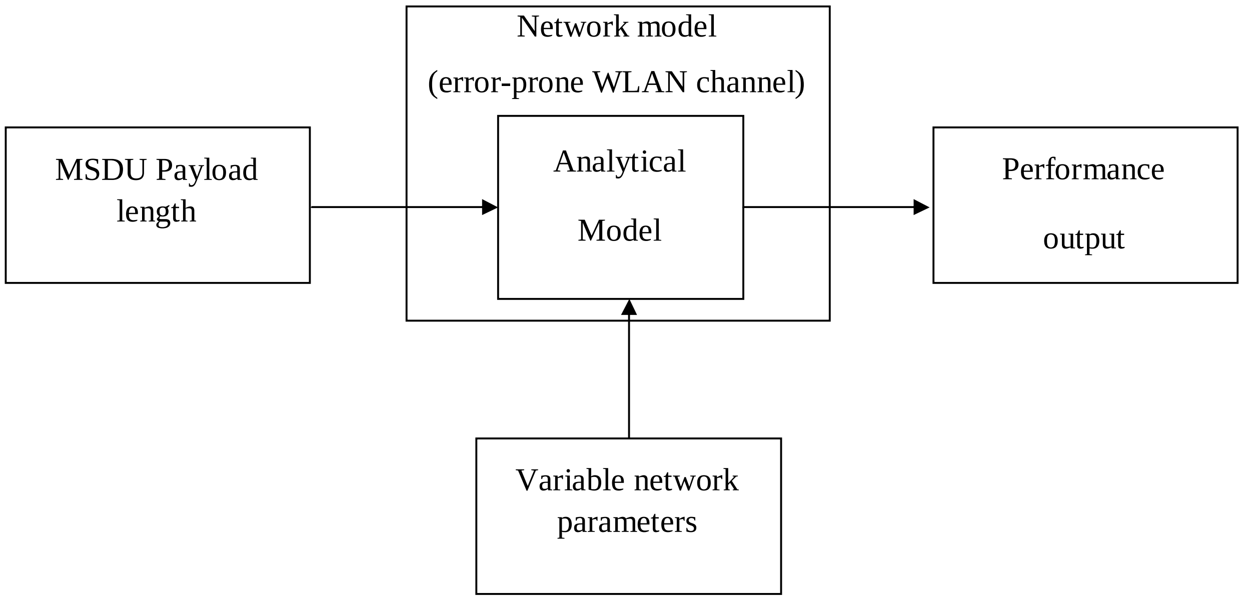


Figure 3.2: Data Flow Diagram.

3.3.1 **Analytical Model**

The analytical model of the frame aggregation process based on Markovȏs queuing process was developed with some attending assumptions that are outlined in the later part of this section. The Markov's process is a process that is used to describe a system moving over time between different states. It is a process that passes through a number of states in a finite time. The Markov's theory was adopted for the analysis in order to properly depict the state transition of the aggregate frame over the network.

A communication network with a unity server that services all the aggregate frame arrival requests originating from the ôNôcontending EP stations was considered as shown in Figure 3.3. The outlined assumptions made in modeling the network are as follows:

<u>Assumptions</u>

- Request arrivals on the system are random Poisson-based and are in aggregate of frames with rate λ_{agg}.
- Services are discharged at the rate, ε_{agg}.
- A finite buffer capacity, C and a single batch server.
- FIFO service discipline on the buffer.
- Requests queue up only when the frame aggregation capacity, λ_{agg}, is reached.
- EP contending stations have similar features and the same frame aggregation size, k.
- Each station meets the aggregation conditions before initiating carrier sensing.

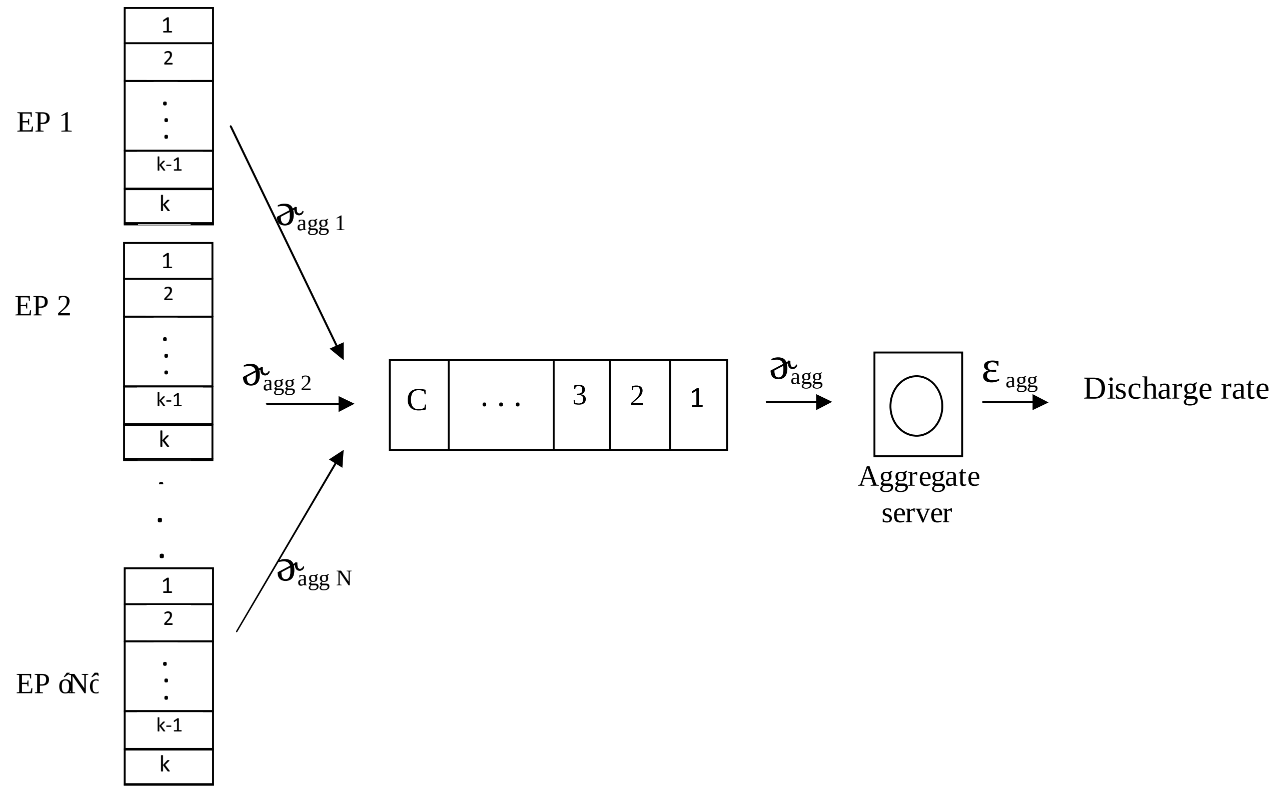


Figure 3.3: Model of Frame Aggregation.

The resultant state transition diagram can be expressed as shown in Figure 3.4 using the Markov chain principle

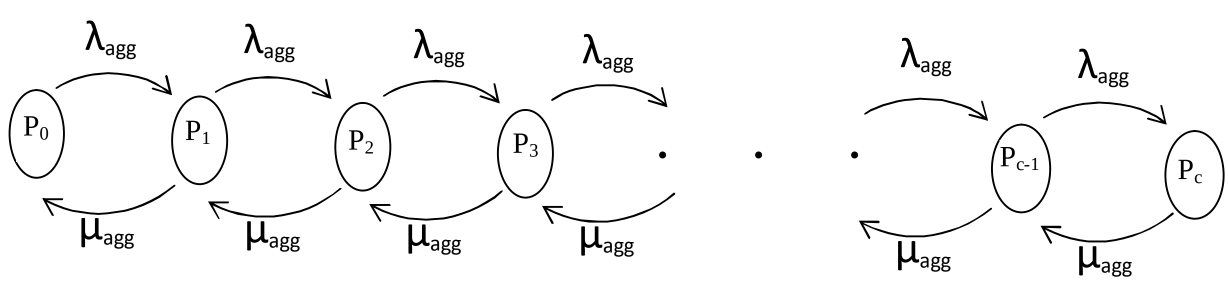


Figure 3.4: State Transition Diagram.

Where P_i is the probability of the system being in varied states 0, 1, 2, é , c-1 and c.

The analysis of the state transition of these aggregate frames based on Markov's theory leads to the realization of a mathematical equation that models the network as follows:

The application of the equilibrium principle for conservation of flow on each of the states in Figure 3.4 results to the following expressions: [17, 72].

At state 0:

$$\lambda_{□□□}P_{□} = \mu_{□□□}P_{□}$$

$$\Rightarrow \quad □_{□} = \frac{□_{□□□}}{□_{□□□}}□_{□} \quad - - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.0$$

At state 1:

$$\lambda_{□□□}P_{□} + \mu_{□□□}P_{□} = \lambda_{□□□}P_{□} + \mu_{□□□}P_{□} \quad - \quad - \quad - \quad - \quad - \qquad 3.1$$

Similarly for state 2:

$$\lambda_{□□□}P_{□} + \mu_{□□□}P_{□} = \lambda_{□□□}P_{□} + \mu_{□□□}P_{□} \quad - \quad - \quad - \quad - \quad - \qquad 3.2$$

And for state c – 1:

$$\lambda_{□□□}P_{□□\,□} + \mu_{□□□}P_{□} = \lambda_{□□□}P_{□□\,□} + \mu_{□□□}P_{□\,□\,□} \quad - \quad - \quad - \quad - \qquad 3.3$$

Solving recursively will result in equation 3.4, which is a function of P_0

$$\Rightarrow \quad P_{□} = \left(\frac{∂_{□□□}}{\varepsilon_{□□□}}\right)^{□}P_{□} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.4$$

P_0 can be defined through the application of probability normalization principle [73] as follows:

$$P_0 + P_1 + P_2 + P_3 + \ldots + P_{c-2} + P_{c-1} + P_c = 1 \quad - \quad - \quad - \quad - \quad - \qquad 3.5$$

Then substituting the expressions from the solutions of equations 3.0 to 3.4, the equation 3.6 will result as follows:

$$P_{\square} + \square\frac{\partial_{\square\square\square}}{\varepsilon_{\square\square\square}}\square P_{\square} + \left(\frac{\partial_{\square\square\square}}{\varepsilon_{\square\square\square}}\right)^{\square}P_{\square} + \left(\frac{\partial_{\square\square\square}}{\varepsilon_{\square\square\square}}\right)^{\square}P_{\square} + \left(\frac{\partial_{\square\square\square}}{\varepsilon_{\square\square\square}}\right)^{\square}P_{\square} + \ldots + \left(\frac{\partial_{\square\square\square}}{\varepsilon_{\square\square\square}}\right)^{\square\square\square}P_{\square} + \left(\frac{\partial_{\square\square\square}}{\varepsilon_{\square\square\square}}\right)^{\square}P_{\square} = 1$$

$$P_{\square}(1 + \square + \square^{\square} + \square^{\square} + \square^{\square} + \ldots + \square^{\square\square\square} + \square^{\square\square\square} + \square^{\square}) = 1 \qquad - \quad - \quad - \qquad 3.6$$

Where traffic intensity, $\square = \frac{\partial_{\square\square\square}}{\varepsilon_{\square\square\square}}$

Therefore,

$$P_0 \left(\sum_{\square\square\square}^{\square} \square^{\square}\right) = 1$$

$$\Rightarrow \qquad P_0 = 1 / \left(\sum_{\square\square\square}^{\square} \square^{\square}\right) \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.7$$

Substituting equation 3.7 into equation 3.4:

$$P_c = \frac{\square^{\square}}{\left(\sum_{\square\square\square}^{\square} \square^{\square}\right)} \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.8$$

Equation 3.8 is the analytical expression modeling the network.

3.3.2 **Aggregate Frame Model**

Further analysis on the aggregation process using an illustration for the individual aggregate frame arrivals shown in Figure 3.5 leads to the expansion of the analytical model as follows:

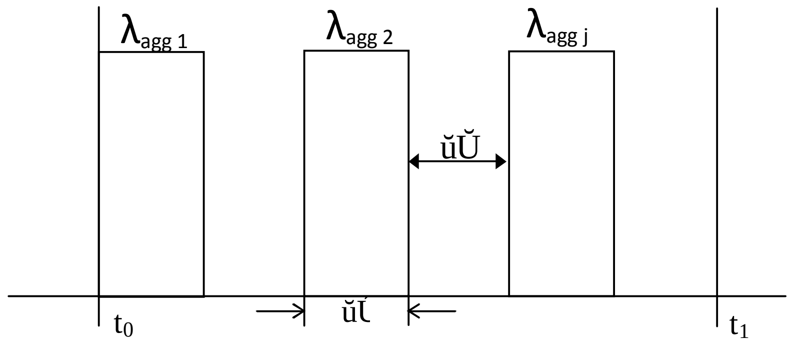


Figure 3.5: Frame Arrival Rate.

If it is assumed that within a space of time, t_1 ï t_0, that jthnumber of aggregate frame arrivals, ǝ$_{aggj}$was recorded by the server. Also, if the times between every consecutive arrival, ŭŬ, are neglected, it can then be deduced that:

Frame arrival rate, ǝ$_{agg}$ = $\frac{[illegible] * [illegible]}{[illegible] - [illegible]}$ - - - - 3.9

Where n_j is a positive integer representing the variable values of the buffer capacity ranging from the least value, j = 1 to the maximum value, j = C.

More so, if an equal number of sub-frames build-up rate is assumed over a period of time, ŭŰfor all the stations in the network, therefore, it can be deduced that:

$[illegible] = \frac{[illegible] * [illegible]}{[illegible]}$ - - - - - - - - - 3.10

Where F_{agg}= Sub-frame

k_j= Discrete quantity representing the number of aggregation (1,2,3,é ,max)

ŭŰ= Time taken to concatenate ớkônumber of sub-frames.

Therefore, equation 3.9 can be modified by substituting equation 3.10 into it as follows:

$$\vartheta_{agg} = \frac{(\square_{\square\square\square} * \square_{\square_{\square\square}}) * \square_{\square}}{\square_{\square}\square\,\square_{\square}}$$

$$= \frac{\square_{\square\square\square} * \square_{\square} * \square_{\square}}{\square\square(\square_{\square}\square\,\square_{\square})} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.11$$

The model realized in substituting equation 3.11 into equation 3.8 is as follows:

$$\square_{\square} = \frac{\left\{\left(\frac{\square_{\square\square\square} * \square_{\square} * \square_{\square}}{\square\square(\square_{\square}\square\,\square_{\square})}\right)^{\square} \square_{\square\square\square}\right\}^{\square}}{\sum_{\square\square\,\square}^{\square}\left\{\left(\frac{\square_{\square\square\square} * \square_{\square} * \square_{\square}}{\square\square(\square_{\square}\square\,\square_{\square})}\right)^{\square} \square_{\square\square\square}\right\}^{\square}} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.12$$

3.3.3 **Stations Contention Model**

Furthermore, the saturated throughput and the average access delay QoS performance metrics of the network could be realized if the contention process of the station is considered. Then again, the finite state model of the collision avoidance window size for each station could be represented with a two-dimensional Markov chain as shown in Figure 3.6. The additional assumptions made on the network are as follows:

- The channel is a noisy error-prone channel type with bit-error-rate value, P_b
- The network is at saturated condition where each station has aggregated frame to transmit after successful transmission or discard of aggregated frame.

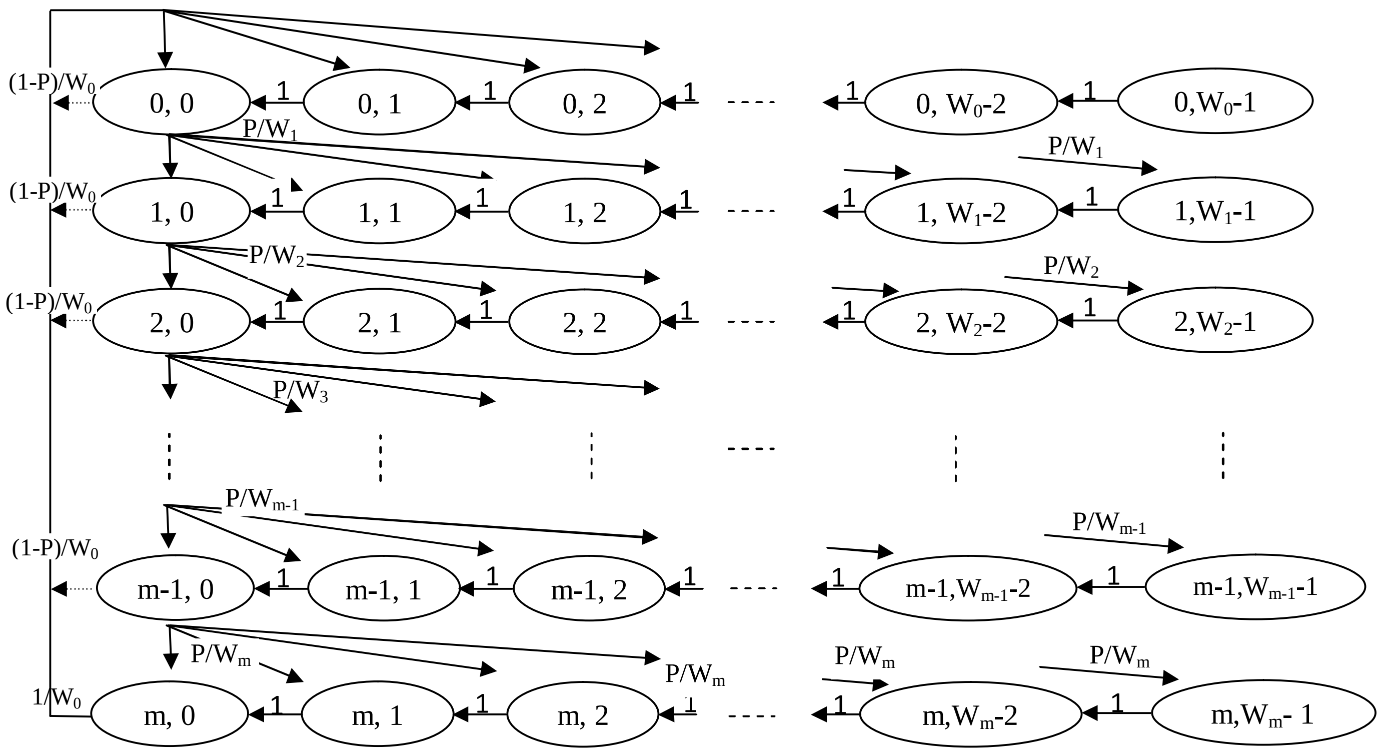


Figure 3.6: Markov Chain for the Finite-State Model of the Back-off Process.

It is reasonable to assume that any station intending to transmit would find the channel occupied after performing carrier sensing and would therefore start the exponential back-off algorithm collision avoidance procedure [31].

The current state (i, q) of a station is determined by the current value of its back-off timer after it has suffered óiôprevious unsuccessful transmission attempts.

Where

i = Back-off stage ranging from zero and increments by unity to a maximum value, m.

q = Back-off timer ranging from W_i ï 1 and decrements uniformly by a unit to zero.

And $W_i = \{ W \times 2^{i}; 0 \le i \le m$ 3.13

W = Initial contention window

The process is such that the back-off stage increments by a unity to a new stage (and its corresponding back-off time is re-initialized to a new integer value within a certain range of values) when there is an unsuccessful transmission attempt after the back-off timer had decremented from $W_i - 1$ to 0. The increment to any state in the new stage (i, q) after back-off expiration and (re)transmission failure in state (i-1, 0) is with the probability of P/W_i [31]. If the station records a successful transmission after the back-off timer, the station will return to the stage 0 and the back-off timer uniformly selects an integer value in the range of $(0, W_0 - 1)$ with the probability of $(1 - P)/W_0$ [28, 31, 32]. However, if unsuccessful retransmission attempts were recorded all through the incremented stages to the maximum stage m, the station will then return to the back-off stage 0 (and its back-off timer is uniformly chosen again in the range of $(0, W_0 - 1)$) with the probability of $1/W_0$ irrespective of successful nor unsuccessful recorded transmission after that mth stage [31].

The transition probability P of a test station to move from one stage to another due to unsuccessful transmission or retransmission of the aggregated frames in a time slot is a function of two independent events. These events include [31]

1. The collision probability P_1 of the test station colliding with at least one of the $N - 1$ remaining stations.
2. The probability of error $P_e$on the transmitted frame due to the channel conditions (fading, noise, etc).

Therefore, P is given as follows:

$$P = 1 - \square 1 - P_{\square}\square(1 - P_{\square}) \qquad - \quad - \quad - \quad - \quad - \qquad 3.14$$

Where

$$P_{\square} = 1 - (1 - Ǘ^{\square\square\square} \qquad - \quad - \quad - \quad - \quad - \quad - \qquad 3.15$$

And τ isthe transmission probability that is expressed as follows [29, 30, 38, 58]:

$$\tau = \frac{\square\square\square\square\ \square\square\square}{\square\square\square\ \square\square\square\square\ \ \square\ \square\square\square\ \square\square\ (\square\square(\square\square)^{\square})} \quad - \quad - \quad - \quad - \quad - \qquad 3.16$$

The probability of observing at least one transmission in a time slot is given [28, 29, 38] as follows:

$$P_{\square\square} = 1 - (1 - Ǘ^{\square} \qquad - \quad - \quad - \quad - \quad - \quad - \qquad 3.17$$

Then the probability of having an empty slot is expressed as follows [28, 29]:

$$P_{\square\square\ \square\square} = 1 - P_{\square\square}$$

$$= 1 - (1 - \square 1 - \square\square^{\square})- \qquad - \quad - \quad - \quad - \quad - \qquad 3.18$$

The probability that there is a single successful transmission given that at least one station out of the óNônumber of stations [28, 29] is transmitting is expressed as follows:

$$P_{\square} = \frac{\square\ \square(\square\square\ \square)^{\square\ \square\ \square}}{\square_{\square\square}} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.19$$

The probability of successful transmission in a time slot [29, 38] is given as follows:

$$= P_{\square\square}P_{\square}(1 - P_{\square}) \qquad - \quad - \quad - \quad - \quad - \quad - \qquad 3.20$$

The probability of unsuccessful transmission due to simultaneous transmissions in the same time slot [29, 30, 38] is given as follows:

$$= P_{\square\square}(1 - P_{\square}) - \quad - \quad - \quad - \quad - \quad - \qquad 3.21$$

The probability of unsuccessful transmission due to aggregated frame error [29] is expressed as follows:

$$= P_{\square\square}P_{\square}P_{\square} \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.22$$

The saturated throughput, S [28, 63] is expressed as follows

$$S = \frac{\square\square\square\square}{\square[\square]} \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.23$$

Where

E[L] = the expected payload size of a successful transmitted frame in a virtual time slot.

E[T] = the expected time length of a virtual time slot.

3.3.3.1 **Throughput**

The expected payload size of a successful transmitted frame in a virtual time slot for the A-MSDU type of aggregation mechanism is expressed as follows [29, 58]:

$$E[L]_{AMSDU} = k_{\square\square\square}P_{\square\square}P_{\square}E[L_{\square}] \qquad - \quad - \quad - \quad - \quad - \qquad 3.24$$

Where k_{agg} = the number of aggregation size

$$E[L_p] = (L - L_{hdr})(1 - P_e) \quad - \quad - \quad - \quad - \quad - \qquad 3.25$$

L = Aggregated MAC frame size

L_{hdr} = Total length of the MAC header including the FCS

And the probability of error in the transmitted frame P_e is expressed as follows [29]:

$$P_e = 1 - (1 - P_b)^L \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.26$$

Equation 3.27 is realized by substituting equation 3.25 into equation 3.24 as follows:

$$E[L]_{A\text{-}MSDU} = k_{\square\square\square} P_{tr} P_s (L - L_{hdr})(1 - P_e) \quad - \quad - \quad - \qquad 3.27$$

The expected time length of the virtual time slot for the A-MSDU aggregation mechanism, $E[T]_{A\text{-}MSDU}$ is as follows [29, 38, 58]

$$E[T]_{A\text{-}MSDU} = T_{idle} P_{idle} + T_s P_{tr} (1 - P_e) + T_c P_c + T_e P_e \quad - \qquad 3.28$$

T_s, T_c, T_e and T_{idle} are the average time the channel is sensed busy by each station because of successful transmission, the average time the channel is sensed busy during a collision, the average time the channel is sensed busy from a frame which suffered transmission error and the duration of the idle channel slot respectively.

This work considered only a uni-directional RTS/CTS access method.The RTS/CTS access method is generally more efficient than the contemporary basic access method for a large aggregated frame size [29]. Therefore, the values of the T_s, T_c, T_e and T_{idle} duration periods were realized using the timeline for the RTS/CTS access method [58, 32] as follows:

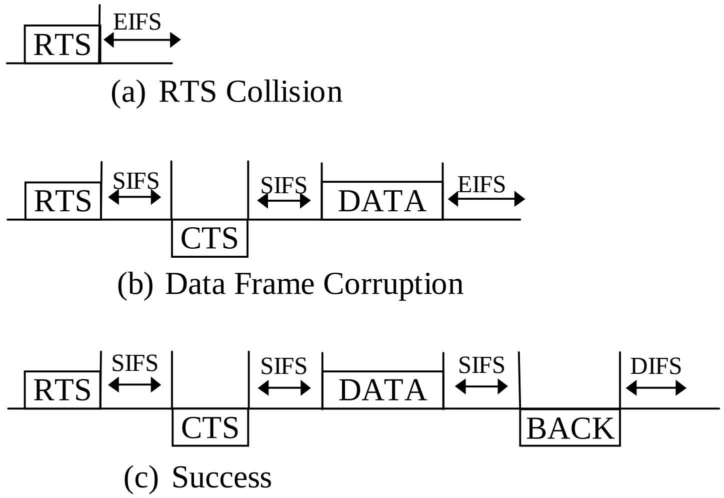


Figure 3.7: Uni-directional RTS/CTS Access Scheme [29, 32].

T_c = RTS + EIFS

T_e = RTS + CTS + DATA + 2SIFS + EIFS

T_s = RTS + CTS + DATA + BACK + 3SIFS + DIFS

The general expression for throughput $S_{A\text{-}MSDU}$ for the A-MSDU aggregation mechanism in a contention-based WLAN channel is realized by substituting equations 3.27 and 3.28 into equation 3.23 yields equation 3.29 as follows:

A-MSDU Throughput, $S_{A\text{-}MSDU}$= [illegible] - - 3.29

3.3.3.2 **Average Access Delay**

The access delay of the network is defined as the delay between the time when an aggregate frame reaches the head of the MAC queue and the time when the frame is successfully received by the receiverôs MAC [29]. This could be expressed as follows [29, 32, 58]:

$$d = N\frac{L_p}{S} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3.30$$

whereL_p= the payload length of the aggregated frame

S = Saturated throughput

d = Average Access Delay

3.3.4 **Simulation Program Model**

The simulation model was obtained using MATLAB simulation software version 7.10.0.499, February 2010 released. MATLAB is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numerical computing [74]. It is used in a wide range of applications, including signal and image processing, communications, control designs, test and measurement, etc. MATLAB system consists of Mathematical functional library for computational algorithm ranging from elementary functions, like sum, sine, etc to more sophisticated functions. It also consists of a high-level matrix/array language part with control flow statements, functions, data structures, etc. More so, it consists of a graphic part for displaying vectors and matrices as graph in both two-dimensional and three-dimensional view. Again, it has an external interface that allows interaction with other programs. The steps used in developing the model are outlined as follows:

- At the MATLAB menu, click on ôNew scriptôicon button.
- An editor window pops up.
- Save the window with the filename ôFrame_aggregation_analysisô
- Observe that a file extension *.m* is appended to the filename by default.

- Write the program that depicts the IEEE 802.11n analytical model (see appendices).
- At the editorǿs menu, click on óSave and Runôicon button.
- The performance results would then be generated for analysis.

The script generated for this work contains the MATLAB code that realizes the model of the equations 3.29 and 3.30. The conditions outlined in section 3.3.1 were achieved using C programming language expressions, operators and program control statements. The developed model uses some network parameters to generate information about the performance results of the network. The basic and common property of all the parameters used in the network is that they comprise of real positive integers.

The operation of the script is illustrated using a flowchart as shown in Figure 3.8.

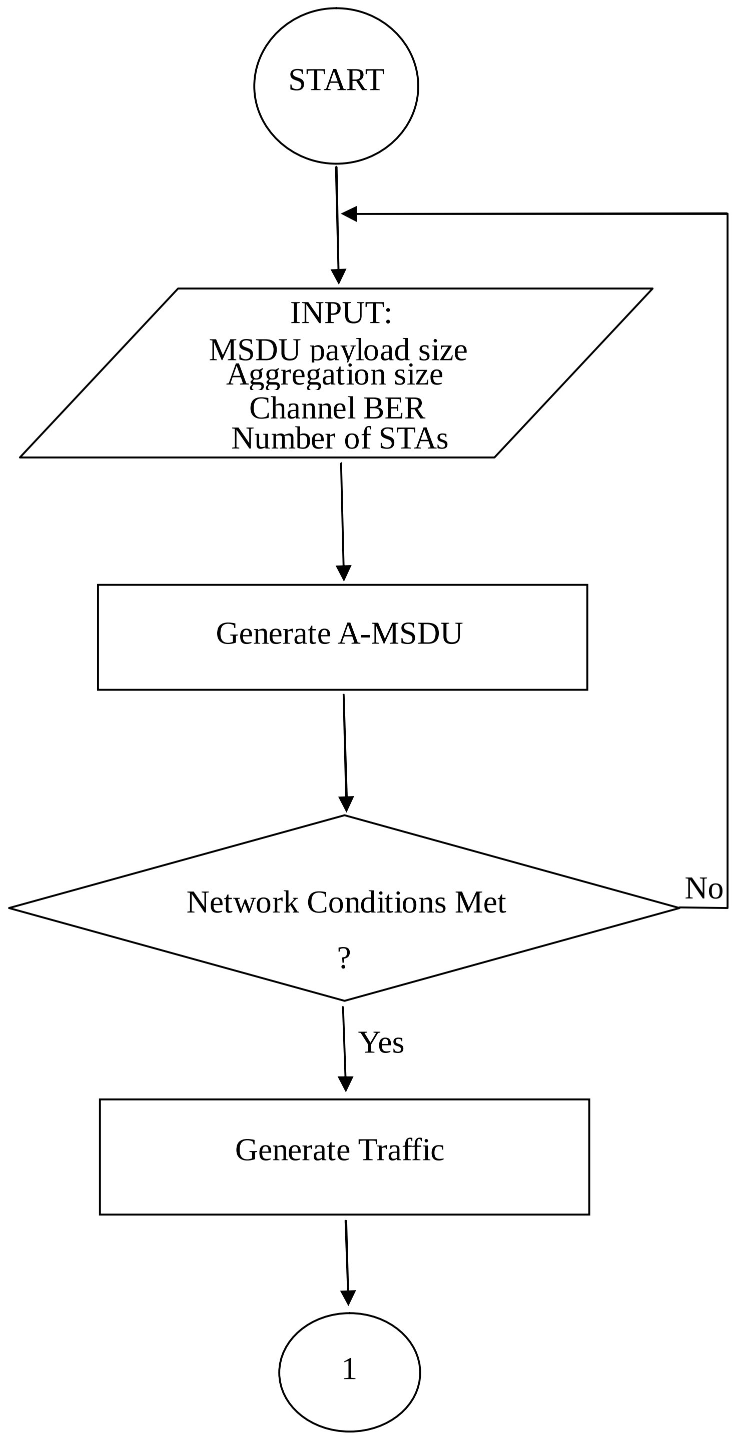


Figure 3.8: Flowchart of the MATLAB Simulation Script.

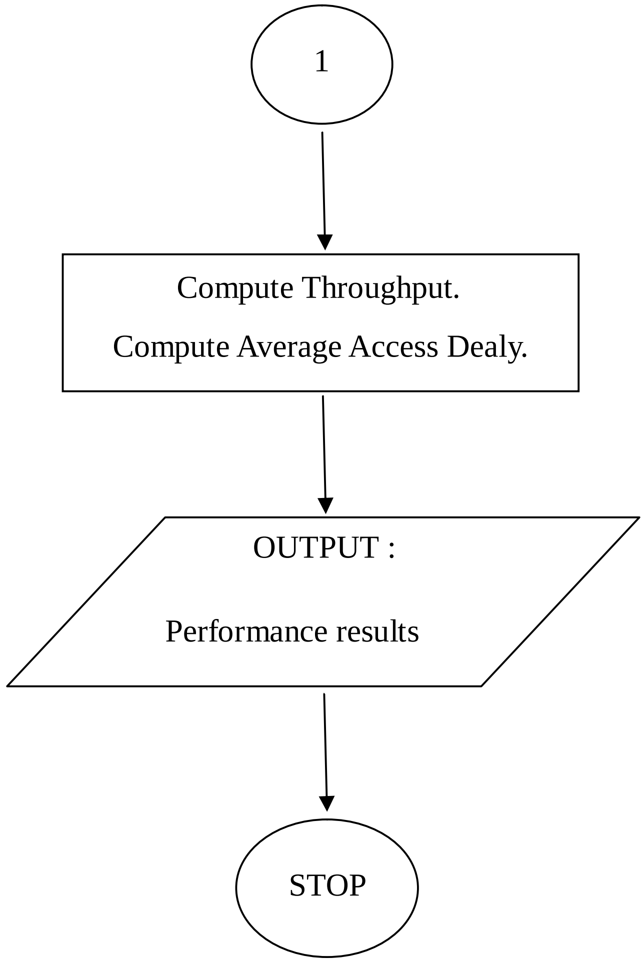


Figure 3.8: Flowchart of the MATLAB Simulation Script (Continued).

The output result shows the performance curves obtained for the saturated throughput of A-MSDU and the Access delay in an error-prone 802.11n WLAN channel.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Background

The work considered the performance effects of varying the aggregation size and the number of STAs in a DCF contention-based IEEE 802.11n WLAN network. These performance effects were studied at different BER values of the WLANerror-prone channel. The study was achieved through simulation in a MATLAB environment. Simulation is the imitation of real-world system through the computational re-enactment of its behavior according to the rules described in a mathematical model [75]. It is important for designers, researchers, engineers, etc. to evaluate the performance of the real-world system through the simulation process prior to the actual development and deployment. This is because simulation could be used, among other things, to identify bottlenecks in a process, provide a safe and relatively cheaper (in terms of both cost and time) test bed to evaluate the side effects, and optimize the performance of the system-all before realizing these systems in the physical world [75]. This chapter presents the simulation of the system as modeled in chapter three.

4.2 Simulation of Models

This section analyzed the performance of the system by varying the aggregation size and the number of contending stations in an IEEE 802.11n error-prone channel at various BER values. These were realized in two scenarios as outlined below:

- Simulation of an increasing number of aggregations in a fixed number of stations.
- Simulation of an increasing number of stations when the aggregation size is fixed.

Aggregation size refers to the number of concatenation of the MSDU sub-frame. The saturated throughput and the average access delay are the performance metrics used to illustrate the effects of these parameters on the system. The parameters used for the simulation are as stated in Table 4.1.

Table 4.1: Simulation Parameters.

MSDU Payload size	1024 byte	
MSDU header size	14	
Duration for successful transmission, T_s	2589.1µs	
Duration for unsuccessful transmission due to collision, T_c	256.5µs	
Duration for idle slot, T_{idle}	9µs	
Duration for unsuccessful transmission due to channel error, T_e	256.5µs	
Number of STA, N	Fixed Value = 80	Variable Values = Range of 5 to 160
Channel BER values	Variable: 10µ, 12µ, 14µ, 16µ and 18µ	
Aggregation sizes	Fixed Value = 50	Variable Values = Range of 2 to 120
Max. Contention Window, CW	128	
Max. Contention Stage, m	4	

4.2.1 **Scenario One:Simulation of an Increasing Number of Aggregations And a Fixed Number of Contending Stations.**

This scenario considered a fixed number of eighty contending stations in the WLAN network. The stationsôcontention for aggregate frame transmission through an error-prone WLAN channel was simulated in a MATLAB environment. Each of the stations has equal MSDU payload size of 1024byte. The simulation was carried out for an increasing number of the MSDU aggregation sizes. The systemô performance over different BER values of the WLAN error-prone channel was considered. This scenario presents the performance results realized from the simulation.

4.2.1.1 **Throughput**

Figure 4.1 shows the throughput performance metric for various MSDU aggregation sizes in the IEEE 802.11n WLAN network.

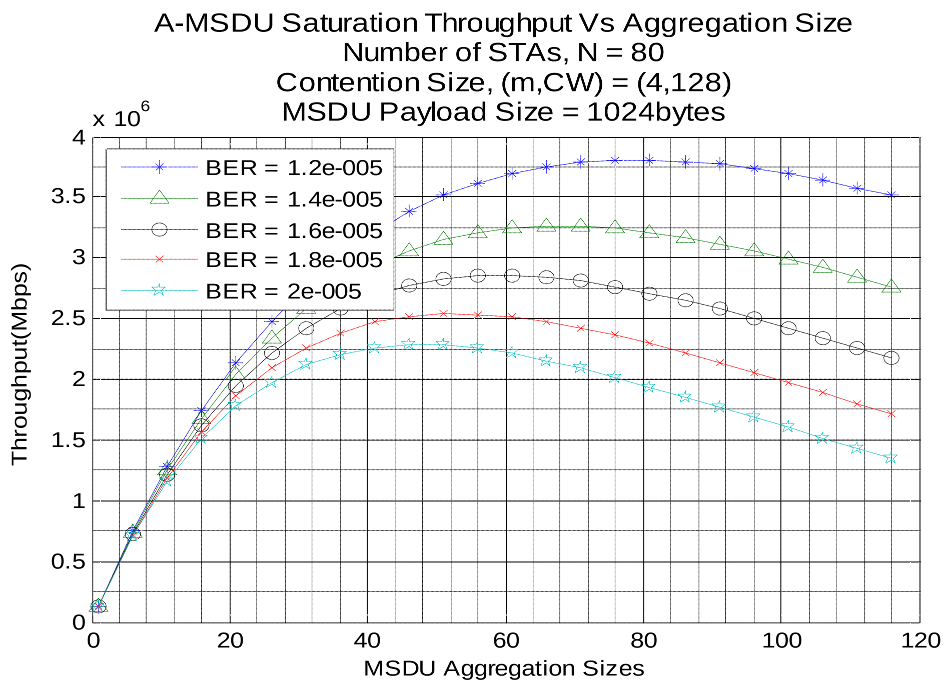


Figure 4.1: Throughput Performance Metric over MSDU Aggregation Sizes for Different BER Values of the WLAN Channel.

The work considered 80 number of contending stations with equal payload size of 1024byte. Figure 4.1 shows their performance behavioral curves in different BER values of the WLAN channel. It was clearly observed that the network recorded highest throughput performance values at the least value of the channelôs BER. The throughput performance values decrease as the BER value was slightly increased to 0.000014. Further increase in the BER to the values of 0.000016, 0.000018 and 0.000020 showed a corresponding decrement in the throughput performance values. This shows the effect of channel noise in frame transmission; the extent of failure leading to unsuccessful transmission of the MSDU aggregate frames due to noise in an error-prone channel.

More so, it was observed that for all the values of the channelôs BER considered for the work, the network recorded a significant increase in throughput for the corresponding increase in the aggregation size until the aggregation size was increased to 40. The implication of this is that increase in the MSDU aggregation size increases the throughput performance metric of the network.

However, further observation showed that the performance throughput started to depreciate at some certain points for each of the performance curves as the aggregation size was increased further. The implication of this is that larger aggregation size does not always guarantee performance improvement in terms of throughput in the network. This is because larger aggregation size could impose high traffic load on the network. Consequently, undesirable depreciation in the systemôs QoS parameters would manifest.

Additionally, critical observation on the curves shows thatthe network started recording depreciation in the throughput QoS parameter values when the aggregation size was increased to 46 when the BER value of 0.00002 of the channel was considered. When the BER value of 0.000018 was considered for the channel, it was observed that the throughput depreciation started to manifest when the aggregation size was increased to 51. Similar depreciation in throughput started to manifest when the aggregation size was increased to 61 for the BER value of 0.000016. Likewise, throughput depreciation started to appear at the aggregation sizes of 66 and 81 for the BER values of 0.000014 and 0.000012 respectively.

Therefore, it is recommended that the aggregation size values should not exceeded 46, 51, 61, 66 and 81 for the respective channelӧs BER values of 0.00002, 0.000018, 0.000016, 0.000014 and 0.000012 else throughput QoS depreciation would be experienced in the network.

4.2.1.2 **Average Access Delay**

The average access delay performance metric of the network due to MSDU aggregate frame sizes is as illustrated in Figure 4.2.

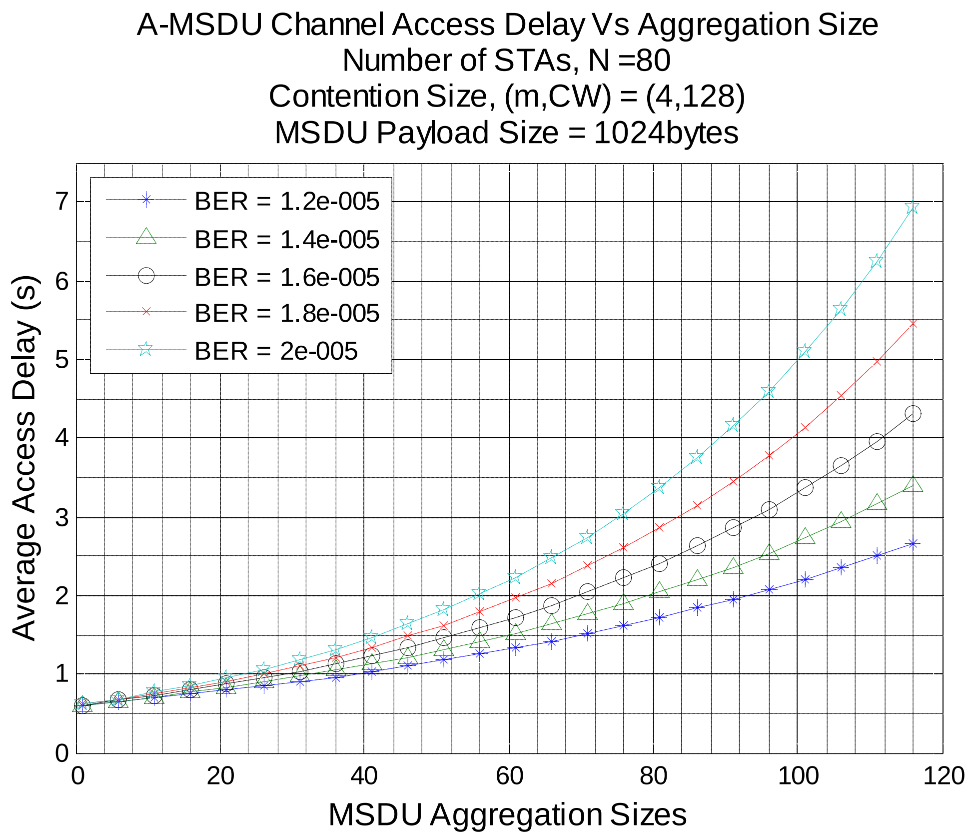


Figure 4.2: Average Access Delay Performance Metric over MSDU Aggregation Sizes for Different BER Values of the WLAN Channel.

It was observed that the network recorded increase in the average access delay value as the number of the MSDU aggregation size increases. This observation was made for all the BER values of the WLAN channel. This behavior was attributed to the increased traffic load the MSDU aggregate frame introduced in the network channel. Again, observation on the performance curves shows that average access delay increases gently with increase in the MSDU aggregation size. Closer observation shows that for the average access delay value of 1.5s, the slope of the performance curves were most gentle when the MSDU aggregation size was below 40. These values are within the acceptable QoS performance threshold. A steeper increment in the average access delay was observed when the MSDU aggregation size increased beyond 40.

Further observation on the performance curves reveals that at the maximum MSDU aggregation size value of 116, the system recorded a maximum average access delay value of about 2.7 when the channelös BER value was 0.000012. This value is approximately 0.7s less than the value that was obtained when the BER value was increased to 0.000014. Also, the system recorded the highest average access delay values of 4.3s and 5.5s for the BER values of 0.000016 and 0.000018 respectively. The highest average access delay value of 7s was recorded for the BER value of 0.00002. It therefore follows that the average access delay increases as the aggregation size increases. In addition, the average access delay also increases as the BER value of the WLAN channel increases.

It was shown in this scenario that the channel saturated throughput increases initially as the MSDU aggregation increases but the value started to decrease at some point as further increase in the MSDU aggregation size was recorded for all the BER values of the WLAN channel. More so, the channel average access delay increases gently as MSDU aggregation sizes increase initially. The increment became steeper as the MSDU aggregation size increases further. Again, this behavior was observed for all the BER values of the WLAN error-prone channel. However, for each of the BER values considered, there exist an optimal MSDU aggregation size that balances the tradeoff between the traffic load due to the aggregate frames and the desirable QoS parameters.

4.2.2 Scenario Two: Simulation of an Increasing Number of Contending Stations and a Fixed Aggregation Size.

This scenario considered the performance of the system over an increasing number of the contending stations in an error-prone WLAN channel. Each of the stations has a fixed MSDU aggregation size of 50 and an equal payload size of 1024byte. Again, the simulation was carried out in a MATLAB environment for different BER values of the WLAN channel. The performance results realized from the simulation is as presented therein in this scenario two.

4.2.2.1 **Throughput**

Figure 4.3 shows the throughput performance metric of the system over an increasing number of contending stations in an error-prone channel.

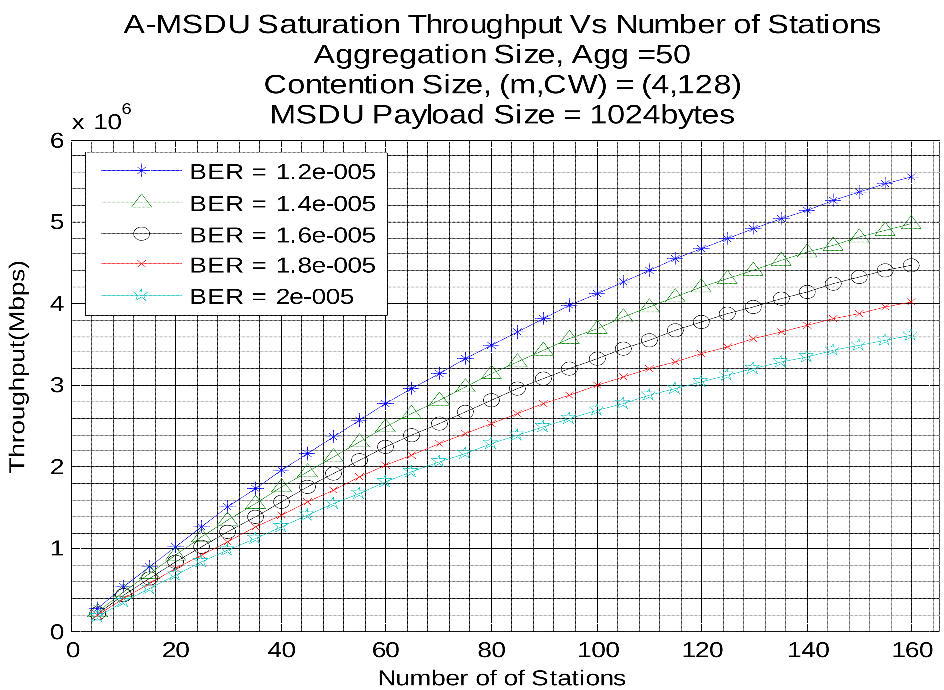


Figure 4.3: Throughput Performance Metric over Increasing Number of Contending Stations for Different BER Values of the WLAN Channel.

It was observed that the systemôs saturated throughput increases as the number of contending station increases. The performance curves obtained for all the BER values appear gentle in an increasing slope pattern. The throughput values for all the values of the channelôs BER used in the simulation were closely related when the corresponding number of contending stations were initially kept below 22 stations. However, when the number of stations was increasedbeyond this value, a significant difference was observed among these performance curves. Observation shows that the system recorded highest throughput performance metric when the value of the BER of the WLAN channel was 0.000012. The performance curve obtained when the BER value was increased to 0.000014 shows a significant depreciation in throughput as the number of contending stations increased. Subsequently, this performance pattern was observed for all the increasing BER values of the WLAN channel. This performance behavior could be attributed to the effect of channel noise on the transmitted aggregate frame. Channel noise is one of the fundamental issues affecting the aggregation scheme in an IEEE 802.11n WLAN network.

4.2.2.2 **Average Access Delay**

Figure 4.4 shows the average access delay performance curves obtained for varying number of contending stations at different BER values of the channel. The maximum number of the contending stations used for the observation is 160.

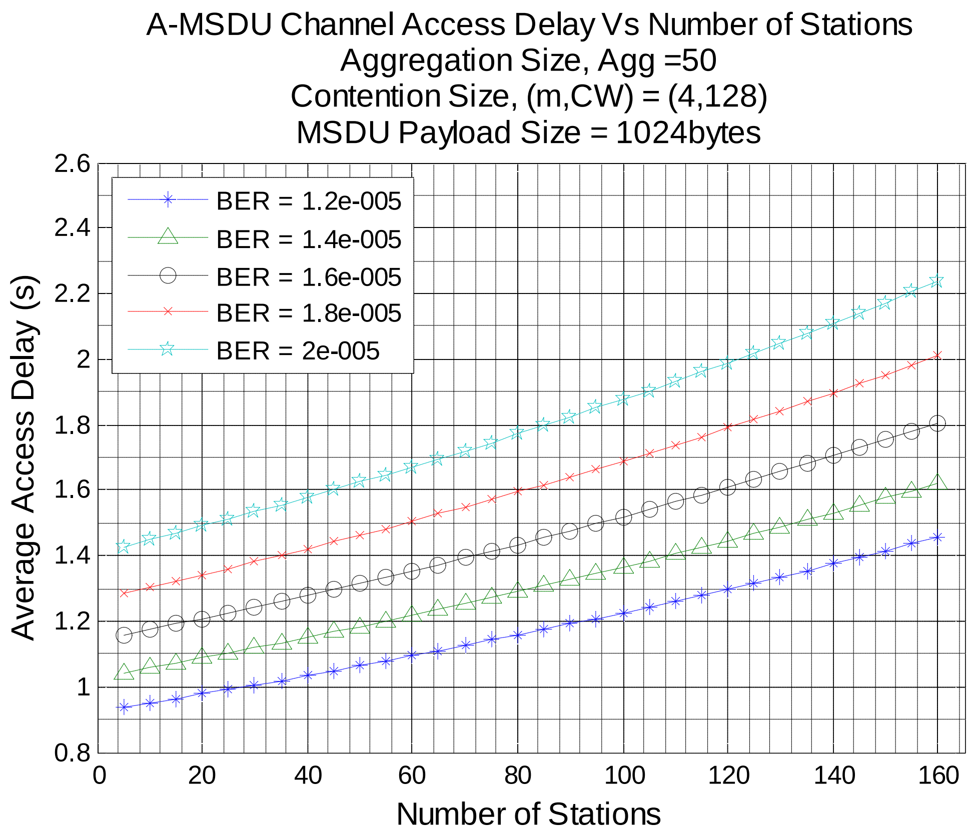


Figure 4.4: Average Access Delay Performance Metric over Increasing Number of Contending Stations for Different BER Values of the WLAN Channel.

The curve obtained when the BER value of the channel was 0.000012 started with an access delay value of about 0.94s with five corresponding number of the contending station. It appears to be increasing linearly as the number of the contending stations increases. The average access delay recorded when the maximum number of the contending stations was considered was about 1.45s. It implies that the systemôs performance at this BER value of the channel falls within the acceptable QoS demand for all the number of contending stations considered to transmit their MSDU aggregated frames.

The performance curve obtained when 0.00014 BER value of the channel was considered shows that the average access delay of about 1.04s was obtained when the number of contending stations was 5. The performance curve increases almost linearly as the number of the contending stations were increased. However, it was observed that the system exceeded the 1.5s average access delay when number of contending stations was increased beyond 133. At the maximum value of 160 contending stations, the corresponding access delay obtained was about 1.62s. Therefore, it can be deduced that for the considered BER value of the channel, the system performs within the acceptable value of the access delay QoS performance metric provided that the number of contending stations does not exceeded 133 stations.

The observation result obtained when 0.000016 BER value of the channel was considered shows that the average access delay value of about 1.16 was recorded when 5 numbers of contending stations were considered. Subsequently, the system recorded increase in the average access delay due to the corresponding increase in the number of contending stations. The access delay of 1.5s was recorded when the number of contending stations was increased to 96. The corresponding access delay value of about 1.81s was recorded when the contending station was increased to a maximum value of 160 stations. It can therefore be deduced that for the considered BER value of the channel, the system can perform within the acceptable QoS performance metric provided that the contending stations does not increase beyond 96 stations.

Then again, when 0.000018 BER value of the WLAN channel was considered, it was observed that the system recorded 1.29s average access delay for 5 number of contending stations. The performance curve also increased as the number of contending stations were increased. The average access delay of 1.5s was recorded by the system when the number of contending stations was increased to 59 stations. The system would cease to operate within the acceptable QoS performance metric for the considered BER value of the channel if the number of contending stations were increased beyond this value. The system recorded a maximum access delay value of 2.01s at the maximum number of contending stations considered in the work.

Finally, when the 0.00002 BER value of the WLAN channel was considered, it was also observed that the system recorded an access delay value of 1.43s for 5 number of contending stations. The performance curve also increased as the number of contending stations were increased. The system ceased to perform within the acceptable QoS performance metric of 1.5s average access delay when the number of contending stations was increased beyond 22 stations for the considered BER value of the channel. The maximum recorded access delay of 2.24s was recorded at the maximum value of the contending stations considered in the work.

Therefore, the observation result shows that for each of the performance curves obtained for the various BER values of the channel considered, there is a threshold value for the increasing number of contending stations beyond which the system would cease to perform within the acceptable QoS demand.

The chapter presented the QoS performance metric for varying number of MSDU aggregation sizes and the varying number of contending stations in an error-prone WLAN channel. The BER values of the channel considered for the work include: 0.000012, 0.000014, 0.000016, 0.000018 and 0.00002. The work was simulated in a MATLAB environment and results were generated. It was observed that increase in the MSDU aggregation size results to a corresponding increase in the throughput performance metric and a consequent increase in the average channel access delay. More so, it was also observed that there is an optimal value of the MSDU aggregation size and the number of contending stations for each of the BER values of the channel considered beyond which the performance results would show depreciation. This optimal value was observed for each of the individual performance curves obtained from different BER values of the WLAN channel.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Background

The previous chapter presented the various QoS performance results for the varying MSDU aggregation size and the varying number of contention-based stations in an error-prone WLAN channel. The major findings of the work are summarized in this chapter. More so, recommendations for improving the quality of service of the 802.11n WLAN are specified.

5.2 Conclusion

This thesis presented the performance analysis of frame aggregation based IEEE 802.11n WLAN. The thesis reviewed in great detail the Wireless LAN standards, the state-of-art WLAN protocol, performance analysis and improvement. The design approach used to model the system was based on the IEEE design specifications. The model was simulated for each of the variable system parameters. The system parameters considered are the varying MSDU aggregation sizes, the varying number of contending stations and the varying BER values of the error-prone WLAN channel. The saturated throughput and the average access delay quality of service parameters were used as the performance metrics to determine the effect of these variable system parameters.

When the varying values of the MSDU aggregation sizes were considered in the WLAN channel for different BER values, the following inferences were drawn based on observation.

- There is corresponding increase in the values of the saturation throughput of the system when the values of the MSDU aggregation sizes were increased.

- There is a threshold value that the MSDU aggregation size should not exceed otherwise the systemôs throughput would depreciate.
- This performance behavior was observed for all the BER values of the error-prone WLAN channel.
- Higher throughput values were obtained at the least BER values of the WLAN channel.
- The average channel access delay increases as the number of the MSDU aggregation size increases.
- The access delay value of about 1.5s was recorded in all the performance curves obtained for the various BER values considered when the aggregation size was kept below 40.
- The access delay curves showed a significant divergence from each other when the MSDU aggregation size was increased beyond 40.
- The system showed the highest value of the average access delay performance result when the highest BER value of the channel was considered.

Also, when the varying number of the contending stations was considered in the WLAN channel for different BER values, the following outlined inferences were drawn from the observation result.

- The saturated throughput increases as the number of contending station increases for all the various BER values of the channel considered in the work.
- The obtained throughput values for the channelôs BER values considered in the work started with close values but diverged gradually away from each other as the number of contending stations increase. A significant divergence was observed when the number of contending stations was increased beyond 22 stations.

- The performance curve obtained when the least BER value of the channel was considered recorded the most throughput performance value.
- The average access delay of the system increases as the number of contending stations increases.
- The average access delay increases as the BER value of the channel increases.
- There is a certain value for the increased number of the contending station for each of the BER values of the channel considered beyond which the system would cease to perform within the acceptable value of the performance demand.

5.3 Recommendation

The performance analysis of the frame aggregation based IEEE 802.11n WLAN in an error-prone channel has been studied. The performance effects of the increased MSDU aggregation size and the increased number of contending stations in the error-prone WLAN channel have been obtained in this work. It has been shown that there is an increased saturation point for each of these network parameters beyond which reduction in the QoS performance metrics would be inevitable in the system. Therefore, it is recommended that network designers and researchers should take cognizance of the effects of these system parameters and their optimal values when working on the IEEE 802.11n WLAN network.

5.4 Further Work

The work studied the performance analysis of frame aggregation based IEEE 802.11n WLAN network. Herein, MAC Service Data Unit (MSDU) type of aggregation technique was used as a variable parameter for the performance analysis. Recommendation for further work should consider using the MAC Protocol Data Unit (MPDU) type of aggregation technique as the variable parameter under the same network conditions. The performance result that would be obtained could be compared with the corresponding results obtained in this work.

References

[1] B. A. Forouzan and S. C. Fegan, ñWireless LANs,ò in *Data Communication and Networking,* 4th ed. New York: McGraw ï Hill, 2007, pp. 421 ï 434.

[2] S. Rackley, òIntroducing Wireless networking,ò in *Wireless Networking Technology from Principle to Successful Implementation,* 1st ed. Oxford, Great Britain: Newnes Publisher 2007, pp. 1 ï 3.

[3] W. Stallings, ñEthernet and Fast Ethernet (CSMA/CD),ò in *Data and Computer Communications,* 5th ed. India: Prentice-Hall, Inc., 2007, pp 402 ï 412.

[4] M. Gast, ñIntroduction to Wireless Networking,ò in *Wireless Networking: The Definitive Guide,* O'Reilly Publisher 2002.

[5] J. S. Beasley and G. M. Miller, ñNetwork Communications,ò in *Modern Electronic Communication,* 9thed. New Delhi, India: PHI Learning Private Ltd, 2010, pp 494 ï 556.

[6] F. Ohrtman, ñ802.11: Alternative Access,ò in *Voice over 802.11*, Boston, London: Artech House, 2004, pg. 5 ï 24.

[7] *Practical Considerations for Deploying 802.11n,* Siemens Ent., Feb. 2008.

[8] *802.11n Challege,* Layland Consulting, Joanie M. Wexler & Assoc. and Webtorials, North Carolina. 2010.

[9] S. Sharma, ñWireless Local Area Networks,ò in *Wireless & Cellular Communications*, 2nded. New Delhi, India: S. K. Kataria& Sons, 2007, pp 611 ï 633.

[10] M. Duck and R. Read, ñLAN standards,ò in *Data Communications and Computer Networks for Computer scientists and Engineers*, 2nd ed. Edinburgh Gate, England: Pearson Education, 2003, pp. 228 ï 238.

[11] C. S. R. Prabhu and A. P. Reddi, ñOther Wireless Technologies: IrDA, Home RF, WLANs and Jini,ò in *Bluetooth Technology and its Applications with Java and J2ME,* New Delhi, India: Prentice Hall, 2007, pp. 281 ï 311.

[12] IEEE 802.11 *Standard Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Amendment 5, Sept. 2007.

[13] *IEEE 802.11 Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,* ANSI/IEEE Std. 802.11, Sept. 2009.

[14] A. Hac, ñWireless Local Area Networks,ò in *Mobile Telecommunications Protocols for Data Networks,* Southern Gate, Chichester, West Sussex, England: John Wiley & Sons, Ltd, 2003, pp 33 ï 51.

[15] T. Paul and T. Ogunfunmi, ñWireless LAN Comes of Age: Understanding the IEEE 802.11n Amendments,ò IEEE Circuits and System Magazine. First Quarter 2008, pp 28 ï 54.

[16] L. L. Peterson and B. S. Davie, ñDirect Link Networks,ò in *Computer Networks: A system Approach,* 3rd ed. San Francisco: Morgan Kaufmann Publishers, 2003, pp. 131 ï 137.

[17] G. R. Dattatreya, ñAnalysis of Fluid Flow Models,ò in *Performance Analysis of Queuing and Computer Networks,* USA: Chapman & Hall/CRC, 2008, pp. 363 ï 395.

[18] *802.11n Primer,* Airmagnet Inc., UK, Aug. 2008.

[19] *IEEE 802.11n Wireless LANs: Opportunity and Challenges,* Novarum Inc., 2007.

[20] Y. Utsunomiya, T. Tandai, T. Adachi and M. Takagi, ñA MAC Proposal to IEEE802.11n High-Throughput WLAN for 20/40 MHz Coexistence,ò *Electronics and Communications in Japan*, Part 1, 2007, vol. 90, No. 1, pp. 1 - 12.

[21] *IEEE 802.11n Wireless LANs: Opportunity & Challenge,* Novarum Inc. 2007.

[22] D. Akhmetov, ñ802.11N: PERFORMANCE RESULTS OF REVERSE DIRECTION DATA FLOW,ò *IEEE Annu. Inter. Symp. Personal, Indoor and Radio Commun.(PIMRC'06),* 2006.

[23] M. Özdemir, D. Du, A. B. McDonald and J. Zhang, ñEnhancing MAC Performance with a Reverse Direction Protocol for High-Capacity Wireless LANs,ò *Vehicular Technology Conf.*, 2006.

[24] *WiFi CERTIFIED 802.11n draft2.0: Longer-Range, Faster-Throughput, Multimedia-Grade Wi-Fi Networks.,* Wi-Fi Alliance, USA, 2007.

[25] G. Held, ñWireless Ethernet,ò in *Ethernet Networks Design, Implementation, Organization & Management,* 4th ed. Southern Gate, Chichester, West Sussex, England: John Wiley & Sons, Ltd, 2003, pp. 407 ï 441.

[26] M. Samih and E. Al-Hemiary, ñImpact of TCP Congestion Control Algorithms on IEEE 802.11n MAC Frame Aggregation,ò *Inter. Journal Computer Science and Engineering Technology (IJCSET),* Sept. 2012, vol. 2, Issue 9, pp. 1410 - 1414.

[27] *Certified Wireless Network Administrator Official Study Guide.,* Planet3 Wireless, Inc. USA, 2002, pp 201 ï 221.

[28] G. Bianchi, ñPerformance Analysis of the IEEE 802.11 Distributed Coordination Function,ò *IEEE Journal. Sel. Areas Communic.* Vol. 18. Mar. 2000, pp. 3670 ï 3675.

[29] Y. Lin and V. W. S. Wong, ñFrame Aggregation and Optimal Frame Size Adaptation for IEEE802.11N WLANs,ò in *Proc. IEEE GLOBECOM*, 2006 pp. 1 ï 6.

[30] E. Felemban and E. Ekici, ñSingle Hop IEEE 802.11 DCF Analysis Revisited: Accurate Modeling of Channel Access Delay and Throughput for Saturated and Unsaturated Traffic Cases,ò *IEEE Trans. Wireless Commun.,* vol. 10, Oct. 2011, pg 3256 ï 3266.

[31] Z. Hadzi-Velkov and B. Spasenovski, ñSaturation Throughput-Delay Analysis of IEEE 802.11 DCF in Fading Channel,ò in *IEEE ICC.,* May 2003, pp.121 ï 126.

[32] H. L. Lee, ñDCF Throughput Analysis of IEEE 802.11a/g/n-based Mobile LAN over Correlated Fading Channel,ò in *Inter. J. Elect Engineering and Informatics,* Vol.3, Iss. 4, 2011, pp. 415 ï 430.

[33] A. Eisenhofer and D. Yohannes, ñPerformance Analysis of the Next generation WLAN Protocol (IEEE802.11n 2.4 GHz) using OPNET Modeler,ò *Downloaded online from www.th-nuernberg.de/fileadmin/Fachbereiche/.../Performanceanalysis.pdf.*

[34] N. Hajlaoui and I. Jabril, ñOn the Performance of IEEE 802.11n Protocol,ò *IEEE WMNC*, Bratislava, Sept. 2012, pp 64 ï 69.

[35] L. Romadhani and A. Mohamed, ñAn analytical study of a distributed EDCA-basdQoS mapping for layered video delivery in WLAN,ò *Int. conf. Peformance Evaluation and Modeling in Wireless Networking PEMWN,* Tunisia, Nov. 2012.

[36] H. Lee, I. Tinnirello, J. Yu and S. Choi, ñA Performance Analysis of Block ACK Scheme for IEEE 802.11e Network,ò *Computer Networks*, Apr. 2010, pp. 2468 ï 2481.

[37] H. Chen, ñThroughput Analysis of Block-Ack in IEEE 802.11n,ò *IEEE 2nd Inter. Conf. Computer Application and System Modeling*. 2012.

[38] B. S. Kim, H. Y. Hwang and D. K. Sung, ñEffect of Frame Aggregation on the Throughput Performance of IEEE 802.11n,ò *IEEE Proc. Commun. Soc. WCNC,* 2008.

[39] D. Skordoulis and Q. Ni, ñIEEE 802.11n MAC Frame Aggregation Mechanisms for Next-Generation High -Throughput WLANs,ò *IEEE Wireless Communications*.vol. 3, Feb. 2008, pp. 40 ï 47.

[40] G. Bhanage, R. Mahindra, I. Seskar and D. Raychaudhuri, ñImplication of MAC Frame Aggregation On Empirical Wireless Experimentation,ò in *Proc. IEEE GLOBECOM*, 2009.

[41] Y. Kim, S. Choi, K. Jang and H. Hwang, ñThroughput Enhancement of IEEE802.11 WLAN via Frame Aggregation,ò *IEEE J. Vehicular Tech. Conf.* 2004, vol. 4, pp. 3030 ï 3034.

[42] B. Ginzburg and A. Kesselman, ñPerformance Analysis of A-MPDU and A-MSDU Aggregation in IEEE802.11n,ò *IEEE Sarnoff Symp.*, May 2007.

[43] N. Hajlaoui, I. Jabri and M. B. Jemaa, ñExperimental Performance Evaluation and Frame Aggregation Enhancements in IEEE 802.11n WLAN,ò *IJCNIS,* Vol. 5, No. 1, Apr 2013, pp 48 ï 58.

[44] M. Samih and E. Al-Hemiary, ñImpact of TCP Congestion Control Algorithms on IEEE 802.11n MAC Frame Aggregation,ò *Inter. Journal Computer Science and Engineering Technology (IJCSET),* Sept. 2012, vol. 2, Issue 9, pp. 1410 - 1414.

[45] M. Lin, J. Tzu, L. Lin and H. Lee, ñThe IEEE802.11n Capability Analysis Model Based on Mobile Networking Architecture,ò in *Proc. IEEE Trans. Syst. Man Cyber. Int. Conf.,* TX, USA, Oct. 2009, pp 1857 ï 1860.

[46] Z. Li, F. Zhao, Z. Zhou, W. Zou, B. Li and C. Zhao, ñAnalysis on the Coexistence of UWB with IEEE802.11n,ò *IEEE EMC Int. Symp.,*FL. Jul. 2010, pp 807 ï 812.

[47] B. Polepalli, W. Xie, D. Thangaraja, M. Goyal, H. Hosseini and Y. Bashir, ñImpact of IEEE802.11n Operation on IEEE802.15.4 Operation,ò *Int. Conf. IEEE WAINA,* Bradford, May 2009, pp 328 ï 333.

[48] S. Narayan, T. Feng, X. Xu and S. Ardham, ñImpact of Wireless IEEE802.11n Encryption Method on Network Performance of Operating System,ò 2nd *Int. Conf. IEEE ICETET,* Nagpur, Dec. 2009, pp 1178 ï 1183.

[49] A. Matsumoto, K. Yoshimura, S. Aust and T. Ito, ñPerformance evaluation of IEEE802.11n devices for vrhicular networks,ò *IEEE Worksop ON-MOVE,* Switzerland, Oct. 2009, pp. 669 ï 670.

[50] J. Jansons, T. Doris and N. Bogdanovs, ñAnalyzing the basic performance of IEEE802.11g/nò *Int. Journal New Computer Architectures Applications (IJNCAA),* 2012, pp. 464 ï 469.

[51] M. Effatparvar and B. Golaminia, ñReview on IEEE 802.11n Operation Base on MANET Routing Protocols,ò *Int. Conf. Computer Technology (ICCIT),* Bangkok, June 2012.

[52] A. M. Alsahlany, H. M. AlSabbagh and S. A. Alseyab, ñMultipacket Reception for Multiple Antenna Systems in IEEE802.11n-over- Fiber Network,ò *IEEE TELFOR,* Nov. 2011, pg. 599 ï 602.

[53] T. H. Khine, Y. Nagao, M. Kurosaki and H. Ochi, ñA Highthroughput MAC Layer for 600Mbps IEEE 802.11n Wireless LAN,ò *APSIPA ASC*, 2011.

[54] V. Visoottiviseth, T. Piroonsith and S. Siwamogsatham, ñAn Empirical Study on Achievable Throughputs of IEEE 802.11n Devices,ò *IEEE WiOPT Int. Symp.,* Seoul Jun. 2009, pp 1 ï 6.

[55] D. Chieng, A. Ting, K. H. Kwong and M. Abbas, òAnalysis of IEEE802.11n Dual Radio Relay Network Topologies,ò *Int. conf. Networks and Information (ICNI),* Singapore, 2012, pp 53 ï 59.

[56] S. Narayan, T. Feng, X. Xu and S. Ardham, ñNetwork Performance evaluation of wireless IEEE802.11n encryption methods on Windows Vista and Windows Server 2008 operating systems,ò *Int. Conf. IEEE WOCN,* Cairo, April, Apr. 2009, pp 1 ï 5.

[57] D. Malone, K. Duffy and D. Leith, ñModeling the 802.11 Distrinuted Coordination Function in Non-saturated Heterogenous Conditions,ò *IEEE/ACM Trans.,* Vol. 15, Iss. 1, Feb. 2007, pp 159 ï 172.

[58] Y. Lin, J. Yeh, T. Yang, C. Ku, S. Tsao and Y. Lai, ñEfficient Dynamic Frame Aggregation in IEEE 802.11s Mesh Networks,ò *Int. J Commun. Syst.* 2009, pp. 1319 ï 1338.

[59] Y. Xiao, ñIEEE802.11n: Enhancements for higher throughput in Wireless LANs,ò *IEEEWireless Communications*, Dec. 2005, pp. 82ï91.

[60] Y. Wen, F. Y. Lin and K. Lai, ñAccess Delay and Throughput Evaluation of Block ACK under 802.11 WLAN,ò *Inter. Ass.Sc. and Tech. for Development (IASTED) Communic.and Computer Ntwks,* 2004.

[61] T. Nakajima, Y. Utsunomiya, Y. Nishibayashi, T. Tandai, T. Adachi and M. Takagi, ñCompressed Block Ack, an efficient selective repeat mechanism for IEEE802.11n,ò *IEEE PIMRC*, Sept. 2005.

[62] A. Saif, M. Othman, S. Subramaniam and N. AbdulHamid,ñImpact of aggregation headers on aggregating smallMSDUs in 802.11n WLANs,ò *IEEE Inter. Conf. Computer Applications and Industrial Electronics (ICCAIE 2010),* Malaysia. December 2010.

[63] T. Li. Q. Ni, D. Malone, D. Leith Y. Xiao and T. Turletti, ñAggregation with Fragment Retransmission for Very High-Speed WLANs,ò*IEEE/ACM Transactions on Networking*, 2009, pp. 591ï 604.

[64] S. Kuppa and G. R. Dattatreya, ñModeling and Analysis of Frame Aggregation in Unsaturated WLANs with Finite Buffer Stations,ò *IEEE ICC*, vol. 3, Jun. 2006, pp. 967 ï 972.

[65] S. T and S. Srikanth, ñA Frame Aggregation Scheduler for IEEE 802.11nò *Nat. Conf. Communications (NCC)*. 2010.

[66] V. Ramaswamy, A. Sivarasu, B. Sridharan and H. Venkatesh, ñA Bi-Scheduler Algorithm for Frame Aggregation in IEEE 802.11n,ò *IJWMN* vol. 5, Dec. 2013, pp 91 ï 99.

[67] B. Bellalta, J. Barcelo, D. Staehle, A. Vinel and M. Oliver, ñOn the Perfrmance of Packet Aggregation in IEEE 802.11ac MU-MIMO WLANs,ò *IEEE Commun. Letters,* vol. 16, Oct. 2012, pp 1588 ï 1591.

[68] J. Zhang, Y. P. Chen and I. Marsic, ñMAC Scheduling Using Chanel State Diversity for High-Throughput IEEE802.11 Mesh Networksò *IEEE Communications Magazine,* Nov. 2007, pp. 94 ï 99.

[69] S. Abraham, A. Meylan and S. Nanda, ñ802.11n MAC Design and System Performance,ò *Int. Conf. IEEE ICC.*Vol.5, May 2005, pp 2957 ï 2961.

[70] E. Kartsaki, N. Zorba, L. Alonso and C. Verikoukis, ñMuitiuser MAC Protocol for 802.11n Wireless Networks,ò *IEEE Proc. Commun.Soc.ICC,* 2009.

[71] J. W. Satzinger et al., ñApproaches to System Development,ò in *Systems Analysis & Design in a Changing World,"* 4th ed., Canada: Thompson Learning, Inc., 2007, pp. 34 ï 71.

[72] L.Kleinrock, ñDeath-Birth Queueing Systems in Equilibrium,ò in *Queueing Systems Volume J: Theory,* Canada: John Wiley & Sons, Inc., 1975, pp. 89 ï 114.

[73] R. B. Cooper, ñBirth-and-Death Queueing Models,ò in *Introduction to Queueing Theory* 2nd ed., NY USA: Elsevier North Holland, Inc., 1981, pp. 73 ï 122.

[74] *MATLAB Technical help manual*, The MathWorks, Inc., USA, R2010a.

[75] M. Guizani et al., ñBasic Concepts and Techniques,ò in *Network Modeling and Simulation. A Practical Perspective,* UK: John Wiley & Sons Ltd., 2010, pp. 1 ï 24.

[76] A. B. Shiflet and G. W. Shiflet, ñThe Modeling Process,ò in *Introduction to Computational Science*, Princeton University Press, 2006, pp. 6 ï 11.

Appendix

Matlab Script for the Simulation Model

```
clc
%   Created on 02/03/2015.
%   Performance Analysis of Frame Aggregation Based IEEE 802.11n WLAN
%   Part of my MSc project work.
%   The program computes the performance metrics for variable aggregation
%   sizeand variable number contending stations in an error-prone channel
%   Enjoy
%   ---------------------------------------------------------------------
%%    CONTENTION WINDOW SPECIFICATIONS.
CW = 128;      %   Backoff Window size
m = 4;      %   Backof stage
%-----------------------------------------------------------------------
%%  NUMBER OF STATIONS
n = 80;          % Fixed value
nn = 5:5:160;    % Increasing values
%-----------------------------------------------------------------------
%%  AGGREGATION SIZES
Agg_n = 50;      %   Fixed value
Agg = 1:5:120;   %   Increasing value
%-----------------------------------------------------------------------
%%  MSDU FRAME SIZE
%l = input('MSDU length = ');
l = 1024;        % MSDU size
l_hdr = 14;      %   MSDU Subframe header size
%-----------------------------------------------------------------------
%%
L = l .* Agg;    %  Aggregated MAC Frame size
L_n = l * Agg_n;

L_hdr = l_hdr .* Agg;      %   Aggregated Header size
L_n_hdr = l_hdr * Agg_n;   %   Aggregated Header size due to variable STAs

LL = L - L_hdr;         % Payload sizes
LL_n = L_n- L_n_hdr;    % Payload sizes due to variable STAs
%-----------------------------------------------------------------------
%%  BIT ERROR RATE OF THE CHANNEL
Pb = 0.000012;
Pb1 = 0.000014;
Pb2 = 0.000016;
Pb3 = 0.000018;
Pb4 = 0.000020;
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%%  DURATIONS
slot_time = 0.000009; % Idle time for the network or Slot duration
T_s = 0.0025891;  % Duration for a single successful transmission, at least
T_c = 0.0002565;  % Duration for unsuccessful transm. due to collision
T_e = 0.0002565;  % Duration for unsuccessful transm. due to channel error
T_idle = slot_time; % Duration for idle slot
%-----------------------------------------------------------------------
%   TRANSMISSION PROBABILITIES
```

```
P = 0.49; % Transition from one contention stage to another.
%--------------------------------------------------------------------------
num = (2 * (1 - (2*P)));
den = ((1 - (2 * P )) * (CW + 1)) + (P * CW * ((1 - ((2 * P)^m))));
P_transmission = num /den;  %
%--------------------------------------------------------------------------
%   Transmission with error at various BER values
Pe = 1 - (1 - Pb).^LL;
Pe_n = 1 - (1 - Pb).^LL_n; %    Due to variable STAs

Pe1 = 1 - (1 - Pb1).^LL;
Pe1_n = 1 - (1 - Pb1).^LL_n;%    Due to variable STAs

Pe2 = 1 - (1 - Pb2).^LL;
Pe2_n = 1 - (1 - Pb2).^LL_n;%    Due to variable STAs

Pe3 = 1 - (1 - Pb3).^LL;
Pe3_n = 1 - (1 - Pb3).^LL_n;%    Due to variable STAs

Pe4 = 1 - (1 - Pb4).^LL;
Pe4_n = 1 - (1 - Pb4).^LL_n;%    Due to variable STAs
%--------------------------------------------------------------------------
%   Atleast, one unsuccess.trans. due to collision
Pn_conditional_collision = 1 - (1 - P_transmission)^(n-1);
Pnn_conditional_collision = 1 - (1 - P_transmission).^(nn-1);
%--------------------------------------------------------------------------
%   Probability of idle slot
Pn_idle = (1 - P_transmission)^n;
Pnn_idle = (1 - P_transmission).^nn;%    Due to variable STAs
%--------------------------------------------------------------------------
%   Probability of at least one transmission in an observed time slot
Pn_tr = 1 - Pn_idle;
Pnn_tr = 1 - Pnn_idle; %    Due to variable STAs
%--------------------------------------------------------------------------
%   Probability of a single successful transmission
Pn_s_succ = (n * (P_transmission * (1 - P_transmission)^(n - 1))) / Pn_tr;
% due to increasing no. of STA
Pnn_s_succ = (nn .* (P_transmission * (1 - P_transmission).^(nn - 1))) ./
Pnn_tr;
%----------------------------------------
%Pn = 1 - (1 - Pn_conditional_collision).*(1 - Pe); % Unsucc. transmi. prob.

%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
%%  THROUGHPUT FOR A-MSDU
%    Due to variable Aggregation size
Et = Pn_idle*T_idle + Pn_s_succ*T_s + T_c*Pn_tr*(1 - Pn_s_succ) + T_e*Pe;
Ep = LL * Pn_tr * Pn_s_succ .* (1 - Pe);
Sn = Ep ./Et;

%    Due to variable STAs
Et_n = Pnn_idle*T_idle + Pnn_s_succ*T_s + T_c.*Pnn_tr.*(1 - Pnn_s_succ) +
T_e*Pe_n;
Ep_n = LL_n .* Pnn_tr .* Pnn_s_succ .* (1 - Pe_n);
Sn_n = Ep_n ./Et_n;
%--------------------------------------------------------------------------
%    Due to variable Aggregation
```

```
Et1 = Pn_idle*T_idle + Pn_s_succ*T_s + T_c*Pn_tr*(1 - Pn_s_succ) + T_e*Pe1;
Ep1 = LL * Pn_tr * Pn_s_succ .* (1 - Pe1);
Sn1 = Ep1 ./Et1;

%    Due to variable STAs
Et1_n = Pnn_idle*T_idle + Pnn_s_succ*T_s + T_c.*Pnn_tr.*(1 - Pnn_s_succ) +
T_e*Pe1_n;
Ep1_n = LL_n * Pnn_tr .* Pnn_s_succ .* (1 - Pe1_n);
Sn1_n = Ep1_n ./Et1_n;
%-------------------------------------------------------------------------
%    Due to variable Aggregation
Et2 = Pn_idle*T_idle + Pn_s_succ*T_s + T_c*Pn_tr*(1 - Pn_s_succ) + T_e*Pe2;
Ep2 = LL * Pn_tr * Pn_s_succ .* (1 - Pe2);
Sn2 = Ep2 ./Et2;

%    Due to variable STAs
Et2_n = Pnn_idle.*T_idle + Pnn_s_succ.*T_s + T_c*Pnn_tr.*(1 - Pnn_s_succ) +
T_e.*Pe2_n;
Ep2_n = LL_n .* Pnn_tr .* Pnn_s_succ .* (1 - Pe2_n);
Sn2_n = Ep2_n ./Et2_n;
%-------------------------------------------------------------------------
%    Due to variable Aggregation
Et3 = Pn_idle*T_idle + Pn_s_succ*T_s + T_c*Pn_tr*(1 - Pn_s_succ) + T_e*Pe3;
Ep3 = LL * Pn_tr * Pn_s_succ .* (1 - Pe3);
Sn3 = Ep3 ./Et3;
%    Due to variable STAs
Et3_n = Pnn_idle.*T_idle + Pnn_s_succ*T_s + T_c*Pnn_tr.*(1 - Pnn_s_succ) +
T_e.*Pe3_n;
Ep3_n = LL_n .* Pnn_tr .* Pnn_s_succ .* (1 - Pe3_n);
Sn3_n = Ep3_n ./Et3_n;
%-------------------------------------------------------------------------
%    Due to variable Aggregation
Et4 = Pn_idle*T_idle + Pn_s_succ*T_s + T_c*Pn_tr*(1 - Pn_s_succ) + T_e*Pe4;
Ep4 = LL * Pn_tr * Pn_s_succ .* (1 - Pe4);
Sn4 = Ep4 ./Et4;
%   Due to variable number of STAs
Et4_n = Pnn_idle.*T_idle + Pnn_s_succ.*T_s + T_c.*Pnn_tr.*(1 - Pnn_s_succ) +
T_e.*Pe4_n;
Ep4_n = LL_n .* Pnn_tr .* Pnn_s_succ .* (1 - Pe4_n);
Sn4_n = Ep4_n ./Et4_n;
%+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
%%  AVERAGE ACCESS DELAY FOR A-MSDU
D = LL ./Sn;
Access_delay = D * n; %    Due to variable Aggregation
%   due to variable STAs
D_n = LL_n ./Sn_n;
Access_delay_n = D_n .* nn; %  Access delay
%-------------------------------------------------------------------------
D1 = LL ./ Sn1;
Access_delay1 = D1 * n; %    Due to variable Aggregation

D1_n = LL_n ./ Sn1_n;
Access_delay1_n = D1_n .* nn; %   Due to variable number of STAs
%-------------------------------------------------------------------------
D2 = LL ./ Sn2;
Access_delay2 = D2 * n;%    Due to variable Aggregation
```

```
D2_n = LL_n ./ Sn2_n;
Access_delay2_n = D2_n .* nn; %   Due to variable number of STAs
%--------------------------------------------------------------------------
D3 = LL ./ Sn3;
Access_delay3 = D3 * n;%    Due to variable Aggregation

D3_n = LL_n ./ Sn3_n;
Access_delay3_n = D3_n .* nn; %   Due to variable number of STAs
%--------------------------------------------------------------------------
D4 = LL ./ Sn4;
Access_delay4 = D4 * n;%    Due to variable Aggregation

D4_n = LL_n ./ Sn4_n;
Access_delay4_n = D4_n .* nn;  %   Due to variable number of STAs
%++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
%%  PERFORMANCE PLOTS
%   THROUGHPUT
%   Due to variable Aggregetion sizes
plot(Agg,Sn,'-*',Agg,Sn1,'-^',Agg,Sn2,'-ko',Agg,Sn3,'-x',Agg,Sn4,'-p')
legend({['BER = ' num2str(Pb)];['BER = ' num2str(Pb1)];['BER = '
num2str(Pb2)];...
    ['BER = 'num2str(Pb3)];['BER = ' num2str(Pb4)]},'Location','NorthWest');
xlabel('MSDU Aggregation Sizes');ylabel('Throughput(Mbps)')
title({['A-MSDU Saturation Throughput Vs Aggregation Size']; ['Number of
STAs, N = ', num2str(n)];...
    ['Contention Size, (m,CW) = ','(' num2str(m),',' num2str(CW),')'];...
    ['MSDU Payload Size = 'num2str(l),'bytes']},'fontsize', 12);
gridminor
%   Due to variable STAs
figure (2)
plot(nn,Sn_n,'-*',nn,Sn1_n,'-^',nn,Sn2_n,'-ko',nn,Sn3_n,'-x',nn,Sn4_n,'-p')
legend({['BER = ' num2str(Pb)];['BER = ' num2str(Pb1)];['BER = '
num2str(Pb2)];...
    ['BER = 'num2str(Pb3)];['BER = ' num2str(Pb4)]},'Location','NorthWest');
xlabel('Number of of Stations');xlim([0 165]);
ylabel('Throughput(Mbps)')
title({['A-MSDU Saturation Throughput Vs Number of Stations'];...
    ['Aggregation Size, Agg = ', num2str(Agg_n)];...
    ['Contention Size, (m,CW) = ','(' num2str(m),',' num2str(CW),')'];...
    ['MSDU Payload Size = 'num2str(l),'bytes']},'fontsize', 12);;
gridminor

%--------------------------------------------------------------------------
%%  ACCESS DELAY
%   Due to variable Aggregetion sizes
figure(3)
plot(Agg,Access_delay,'-*',Agg,Access_delay1,'-^',Agg,Access_delay2,'-ko',...
    Agg,Access_delay3,'-x',Agg,Access_delay4,'-p')
legend({['BER = ' num2str(Pb)];['BER = ' num2str(Pb1)];['BER = '
num2str(Pb2)];...
    ['BER = 'num2str(Pb3)];['BER = ' num2str(Pb4)]},'Location','NorthWest');
xlabel('MSDU Aggregation Sizes','fontsize',12);ylim([0 7.5]);
ylabel('Average Access Delay (s)','fontsize',12)
title({['A-MSDU Channel Access Delay Vs Aggregation Size'];...
    ['Number of STAs, N = ', num2str(n)];...
```

```
    ['Contention Size, (m,CW) = ','(' num2str(m),',' num2str(CW),')'];...
    ['MSDU Payload Size = 'num2str(l),'bytes']},'fontsize', 12);
gridminor
%   Due to variable Number of STAs
figure(4)
plot(nn,Access_delay_n,'-*',nn,Access_delay1_n,'-^',nn,Access_delay2_n,'-
ko',...
nn,Access_delay3_n,'-x',nn,Access_delay4_n,'-p')
legend({['BER = ' num2str(Pb)];['BER = ' num2str(Pb1)];['BER = '
num2str(Pb2)];...
    ['BER = 'num2str(Pb3)];['BER = ' num2str(Pb4)]},'Location','NorthWest');
xlabel('Number of Stations','fontsize',12);xlim([0 165]);
ylabel('Average Access Delay (s)','fontsize',12)
title({['A-MSDU Channel Access Delay Vs Number of Stations'];...
    ['Aggregation Size, Agg = ', num2str(Agg_n)];...
    ['Contention Size, (m,CW) = ','(' num2str(m),',' num2str(CW),')'];...
    ['MSDU Payload Size = 'num2str(l),'bytes']},'fontsize', 12);
gridminor
%--------------------------------------------------------------------------
```