

DOCTOR OF PHILOSOPHY

Performance Modeling and Enhancement for IEEE 802.11 DCF

Alkadeki, Hatm

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**Performance Modeling
and
Enhancement for IEEE 802.11
DCF**

By

Hatm Hussin Zayed Alkadeki

October 2015



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***A thesis submitted in partial fulfilment of the University's requirements for the
Degree of Doctor of Philosophy***

Abstract

The most important standard in wireless local area networks (WLANs) is IEEE 802.11. For this reason, much of the research work for the enhancement of WLANs is generally based on the behaviour of the IEEE 802.11 standard. This standard is divided into several layers. One of the important layers is the medium access control (MAC) layer. It plays an important role in accessing the transmission medium and data transmission of wireless stations. However, it still presents many challenges related to the performance metrics of quality of service (QoS), such as system throughput and access delay.

Modelling and performance analysis of the MAC layer are also extremely important. Thus, the performance modelling and analysis have become very important in the design and enhancement of wireless networks. Therefore, this research work is devoted to evaluate and enhance the performance modelling of IEEE 802.11 MAC-distributed coordination function (DCF), which can lead to the improvement of the performance metrics of QoS.

In order to more accurately evaluate the system performance for IEEE 802.11 DCF, a new analytical model to compute a packet transmission probability for IEEE 802.11 DCF has been proposed based on difference probabilities in transmission mechanism. The performance saturated throughput is then evaluated with the proposed analytical model. In addition, a new analytical model for estimating the MAC layer packet delay distribution of IEEE 802.11 DCF is also proposed. The performance results highlight

the importance of considering the different probabilities between events in transmission mechanism for an accurate performance evaluation model of IEEE 802.11 DCF in terms of throughput and delay.

To enhance the effectiveness of IEEE 802.11 DCF, a new dynamic control backoff time algorithm to enhance both the delay and throughput performances of the IEEE 802.11 DCF is proposed. This algorithm considers the distinction between high and low traffic loads in order to deal with unsaturated traffic load conditions. In particular, the equilibrium point analysis (EPA) model is used to represent the algorithm under various traffic load conditions. Results of extensive simulation experiments illustrate that the proposed algorithm yields better performance throughput and a better average transmission packet delay than related algorithms.

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List of Abbreviations

Wi-Fi Wireless Fidelity

WLANs Wireless Local Area Networks

IEEE Institute of Electrical and Electronics Engineers

CSMA/CD Carrier Sense Multiple Access with Collision Detection

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

LBT Listen before Talk

PHY Physical

MAC Medium Access Control

DCF Distributed Coordination Function

PCF Point Coordination Function

ACK Acknowledgment

RTS Request to Send

CTS Clear to Send

CW Contention Window

EIFS Extended Inter Frame Space

DIFS Distribution Inter Frame Space

PIFS Point Inter Frame Space

SIFS Short Inter Frame Space

RTDF Packet Delay Right Tail Distribution Function

QoS Quality of Service

EDCA Enhancement Distributed Channel Access

BEB Binary Exponential Backoff

ELBA Exponential Linear Backoff Algorithm

DCBTA Dynamic Control Backoff Time Algorithm

List of Publications

Alkadeki, H., Wang, X., and Odetayo, M. (2013a) ‘A New Analytical Model to Compute a Packet Transmission Probability for IEEE 802.11’. *Proc. of World Cong. on Multimedia and Computer Science* [online] 1 (15), 94-102. available from <<http://searchdl.org/index.php/conference/conferenceList/35>>.

Alkadeki, H., Wang, X., and Odetayo, M. (2013b) ‘A New Performance Evaluation Model for IEEE 802.11 DCF’. *Progress in Computing Applications (PCA)* [online] 2 (2), 80-90. available from <<http://www.dline.info/pca/v2n2.php>>.

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Alkadeki, H., Wang, X., and Odetayo, M. (2015) ‘Improving Performance of IEEE 802.11 by a Dynamic Control Backoff Algorithm under Unsaturated Traffic Loads’. *Ad Hoc & Sensor Wireless Networks* <under consideration>.

Introduction

1.1 Introduction

The focus of this thesis is on the performance modelling and enhancement of IEEE 802.11 DCF. For this reason, the performance modelling of IEEE 802.11 is studied under different traffic load conditions. Firstly, the main difference in the transmission mechanism between the busy probability and the collision probability is taken into consideration. Then, a new analytical model to compute a packet transmission probability for IEEE 802.11DCF is proposed. In addition, the proposed model is used to evaluate the saturated throughput performance of IEEE 802.11 DCF.

Secondly, an accurate analytical model for estimating the MAC layer packet delay distribution of IEEE 802.11 DCF is proposed.

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Finally, a new backoff algorithm to achieve a better system performance in terms of throughput and time delay under non-saturated traffic load conditions is proposed.

1.2 Motivation

Recently, wireless local area networks (WLANs) have become very important and extensively applied all over the world. The WLANs provide a very simple way for flexible wireless access, such as Internet or LANs. The most important standard in WLANs is IEEE 802.11 which is known as wireless fidelity (Wi-Fi) networks (Ming et al. 2008). The Wi-Fi is widely deployed in WLANs. This is the reason why IEEE 802.11 has become very important standard and attracted much research attention. In addition, the quality of service (QoS) over IEEE 802.11 standard still poses a challenging task and has become an active research area.

The IEEE 802.11 standard includes comprehensive MAC layer and physical (PHY) layer. The IEEE 802.11 standard still presents many challenges; most of them are related to the MAC layer. The MAC layer specifies two types of mechanism for accessing the media. Fundamental access mechanism is called distribution coordination function (DCF) and an optional mechanism is called point coordination function (PCF). The DCF uses a carrier sense multiple access with collision avoidance (CSMA/CA) scheme and binary exponential backoff (BEB) algorithm (Madhavi et al. 2011). It enables a station to listen before talking (LBT) and deals with multiple stations over the same transmission medium because the DCF gives equal priority to all stations. A collision will occur when multiple stations try to access the medium simultaneously. Therefore, the DCF helps to reduce the number of collisions and thus

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increases the transmission medium utilization by using CSMA/CA and BEB. Consequently, the DCF mechanism plays a major role in MAC layer.

On the other hand, the MAC in PCF is centralized, which gives various priorities to all stations. However, due to the complexity of implementing PCF, the IEEE 802.11 standard supports the DCF function as a default access mechanism (Ming et al. 2008). Therefore, the focus of this thesis will be on the primary access mechanism for MAC layer. Specifically, the research work is focused on the standard IEEE 802.11 DCF based MAC protocol.

1.3 Research Questions

As mentioned in the above section, there are many challenges related to the standard IEEE 802.11 DCF. Most of them relate to the MAC layer which can act to guarantee the performance metrics of QoS in IEEE 802.11 DCF such as system throughput and access delay. The analysis of IEEE 802.11 DCF helps in the discovery of the causes of many of these problems, and may even suggest possible solutions (Lin and Wong 2006). In order to better understand the performance model of IEEE 802.11 DCF, the critical challenges can be summarised in the following research questions:

How do we evaluate the performance model? How can we enhance the effectiveness of IEEE 802.11 DCF?

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These questions can be divided into a multiple sub-questions related to our main objective as follows:

What is the difference between the busy probability and the collision probability in the transmission mechanism?

Do we need to consider the fact that the busy probability is different from the collision probability in the analytical model? Why?

How can a model that considers the difference between the busy probability and the collision probability help to guarantee the QoS in IEEE 802.11 DCF?

How can the performance modelling and the analysis of IEEE 802.11 DCF help in discovering the inherent cause or causes of the many problems that are related to the system's performance?

1.4 Aims

The aim of this research is to investigate and enhance the performance modelling of IEEE 802.11 DCF under saturated and non-saturated traffic load conditions in order to improve the performance metrics of QoS.

The first part of this thesis deals with the accuracy of the performance model of IEEE 802.11 DCF. In this part, the scenario is studied in which every station in the network always has a packet to transmit. This scenario is known as the saturated traffic load conditions. In addition, the architecture and the mechanisms of IEEE 802.11 are investigated in order to discover points of weakness. This review suggests that most

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of the previous research studies have not considered the main difference between the busy probability and the collision probability in analytical models. Some of these studies considered both probabilities to be the same or ignored the busy probability and considered only the collision probability, which is not a justified assumption. In this thesis, a new analytical model based on the difference between the probabilities is proposed. The simulation of the proposed model demonstrates that there is a significant change on the throughput performance results, when the difference between the busy probability and the collision probability is considered. Furthermore, the difference between probabilities is employed to propose an accurate analytical model for estimating the MAC layer packet delay distribution of IEEE 802.11 DCF.

The second part of this thesis deals with the enhancement of the performance model of IEEE 802.11 DCF. In this part, the non-saturated traffic load conditions scenario is considered, and then an investigation is conducted into how the backoff algorithm deals with the dynamic traffic loads. The thesis presents a new backoff algorithm that can deal with dynamic traffic loads more efficiently. This new algorithm provides a better transmission medium utilisation and reduces the average transmission packet delay in comparison with other related algorithms.

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1.5 Objectives

The objectives of this research are:

- To identify and investigate issues related to the performance evaluation system of IEEE 802.11 DCF in terms of throughput and delay under saturated and non-saturated traffic load conditions.
- To develop the analytical model for computing a packet transmission probability under saturated traffic loads.
- To evaluate the saturation throughput performance of IEEE 802.11 DCF.
- To estimate the MAC layer packet delays distribution of IEEE 802.11 DCF under saturated traffic load conditions.
- To enhance the system performance for IEEE 802.11 DCF in terms of throughput and delay under non-saturated traffic load conditions.

1.6 Contributions

To achieve the above objectives, the research develops new analytical models and backoff algorithm to evaluate and enhance the system performance for IEEE 802.11 DCF. The accuracy of the proposed models and algorithm are validated through MATLAB simulation experiments. In addition, Maple software has been used to undertake calculation of certain equations. The original contributions of this research are summarised as follows:

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- New analytical models to compute a packet transmission probability and estimate the MAC layer packet delay distribution for IEEE 802.11 DCF are proposed under saturated traffic load conditions. In addition, the proposed models are used to investigate the impact of considering the differences between the busy probability and the collision probability on the performance system in terms of throughput and delay.
- New performance evaluation models for IEEE 802.11 DCF are proposed under saturated traffic load conditions. The performance results highlight the importance of considering the differences between the busy probability and the collision probability in transmission mechanism for the accurate evaluation of the system performance model in IEEE 802.11 DCF.
- A novel backoff algorithm for contention window-based IEEE 802.11 DCF is proposed. The algorithm is proposed to enhance the performance metrics of QoS for IEEE 802.11 DCF in terms of throughput and delay under non-saturated traffic load conditions.
- The system throughput for the proposed algorithm and other related algorithms are evaluated under non-saturated traffic load conditions. The throughput results have been investigated under different contention window sizes. The traffic parameters used in the validations are based on the EPA model in the work of Wang et al. (2009). Results of extensive simulation experiments show that the proposed algorithm yields better performance throughput than other related backoff algorithms.

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- The average transmission packet delay for the proposed algorithm and other related algorithms are calculated under non-saturated traffic load conditions. The numerical results demonstrate that the proposed algorithm can maintain the average transmission packet delay at low value in comparison with other related backoff algorithms.

1.7 Thesis Organisation

This thesis is divided into seven chapters. In order to show how this thesis is organised, the plan and structure are presented below as a diagram in Figure 1.1.

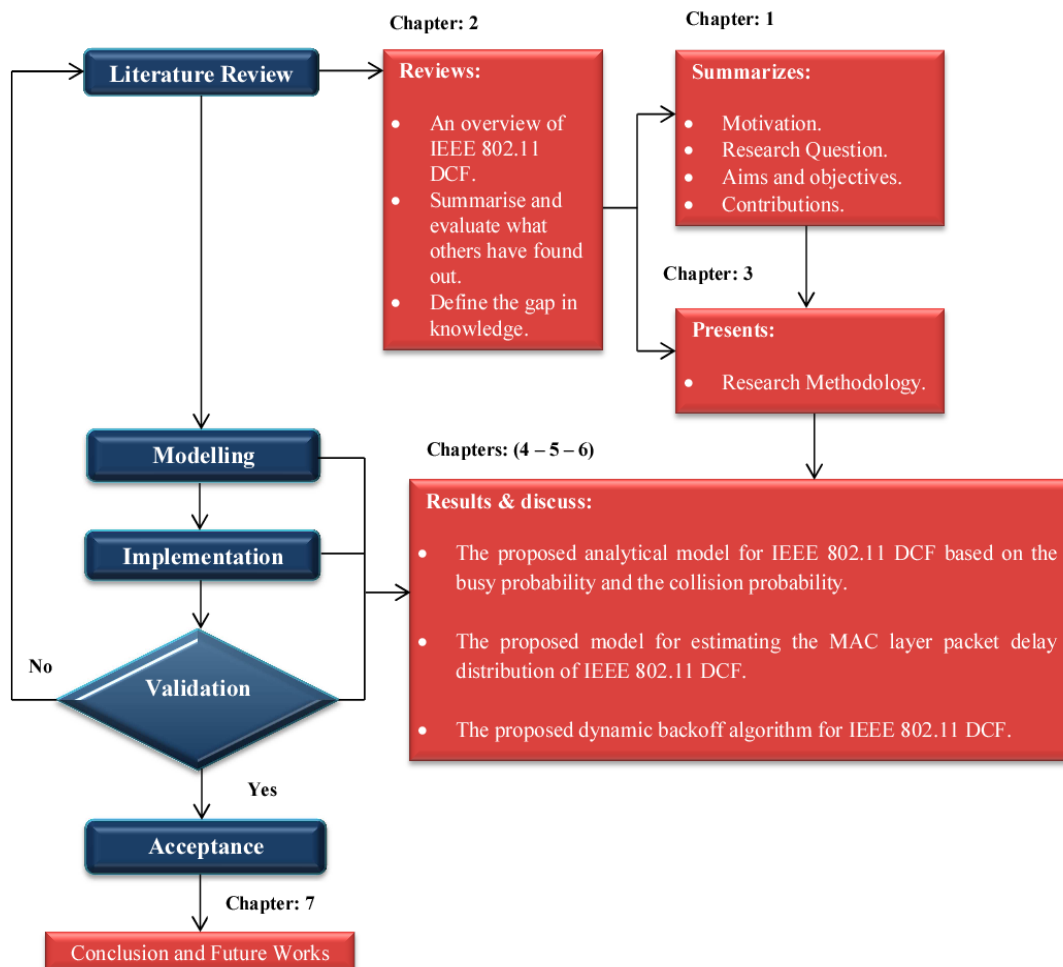


Figure 1.1: Thesis plan and structure

Chapter 1 : Introduction

In the following chapter, the rest of this thesis is organised as follows:

Chapter 2: This chapter presents an overview and a comprehensive review of the literature. It presents a background of IEEE 802.11, its architecture and its mechanisms. Then, the chapter introduces and evaluates some related research about the performance modelling and QoS of IEEE 802.11DCF. Finally, it presents the problem statement and provides answers to some of the research questions.

Chapter 3: This chapter presents the research methodology considered in this thesis. The chapter includes a discussion of the research design, research approach, justification, modelling methods, simulation environment and software tools used for implementation and validation.

Chapter 4: This chapter presents the new performance analytical model of IEEE 802.11 DCF based on the difference between the busy probability and collision probability in backoff mechanism. It presents the modelling, numerical results, simulation results and discussion.

Chapter 5: This chapter presents an accurate estimation way of the medium access control layer packet delay distribution for IEEE 802.11 DCF. It presents the modelling, numerical results, simulation results and discussion.

Chapter 6: This chapter presents the new backoff algorithm for contention window-based wireless networks. It presents the mechanism of the proposed algorithm, performance evaluation system in terms of throughput and Average packet transmission delay. Finally, this chapter discusses the performance results in comparison with other related algorithms.

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Chapter 7: This chapter presents the conclusion of this thesis. It presents the contribution that the thesis has made to develop the existing knowledge. It also discusses the limitations of the research work. Furthermore, future work is highlighted within this chapter.

Overview and Literature Review

2.1 Introduction

The technologies of WLANs operate using radio frequencies and data transmissions. Therefore, the IEEE 802.11 standard is built on two specifications layers known as the PHY layer and the MAC layer. The PHY layer deals with transmitting bits over a communication transmission medium while the MAC layer interacts with the PHY layer to provide multiple access. Moreover, the reliability and the delivery of data are based on the MAC layer. This is because the MAC layer plays an important role in accessing the transmission medium, but still presents many challenges related to QoS. In order to understand and evaluate the performance modelling of IEEE 802.11 DCF, the details regarding the MAC layer will be carefully studied. It is important to know the functionalities of the MAC layer to improve the performance model of IEEE 802.11

Chapter 2 : Overview and Literature Review

DCF. However, as mentioned in the first chapter, the focus of this thesis will be on the basic access mechanism for IEEE 802.11 MAC - DCF. Therefore, in this chapter the components of DCF such as architectures, functions, and mechanisms will be described. Then, previous work related to performance modelling and enhancement of IEEE 802.11 DCF will be discussed.

2.2 Overview of IEEE 802.11 DCF

Typically, WLAN equipment supports only the DCF due to the complexity of implementing the PCF such as WLAN routers (Ming et al. 2008). Thus, in this thesis the details of the PCF are not examined in detail, but the focus will be on the DCF. The DCF defines the basic access mechanism of IEEE 802.11 (Vassis and Kormentzas 2005). It is developed to support multiple accesses and asynchronous data flow using carrier sense multiple access with collision avoidance (CSMA/CA) scheme with binary exponential backoff (BEB) algorithm. However, the LAN can detect the collisions using carrier sense multiple accesses with collision detection (CSMA/CD) scheme, but this technique is not possible for WLAN due to wireless environment. This is the reason the DCF is based on CSMA/CA scheme rather than CSMA/CD scheme. The CSMA/CA scheme allows stations to listen before transmitting, which is known as listen before talk (LBT) mechanism (Ming et al. 2008). Therefore, this scheme enables many stations to transmit over the same transmission medium. Moreover, the CSMA/CA scheme can help stations to detect the collision and then improve the transmission medium utilization. This is why the CSMA/CA scheme plays a major role in developing the standard of IEEE 802.11 such as IEEE 802.11e.

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2.2.1 Carrier Sense Multiple Access with Collision Avoidance Scheme

The CSMA/CA scheme specifies two types of access methods. The basic access method is known as a two-way handshake mechanism, and an optional access method is known as a four-way handshake mechanism (Roshan 2003). The two-way handshake mechanism plays a major role in avoiding the collision risk using an acknowledgment (ACK) frame technique as shown in Figure 2.1. An ACK frame is used to confirm that the data has been successfully received. In this scenario, the transmitter station sends the data and waits for an amount of time known as the short inter frame space (SIFS) duration.

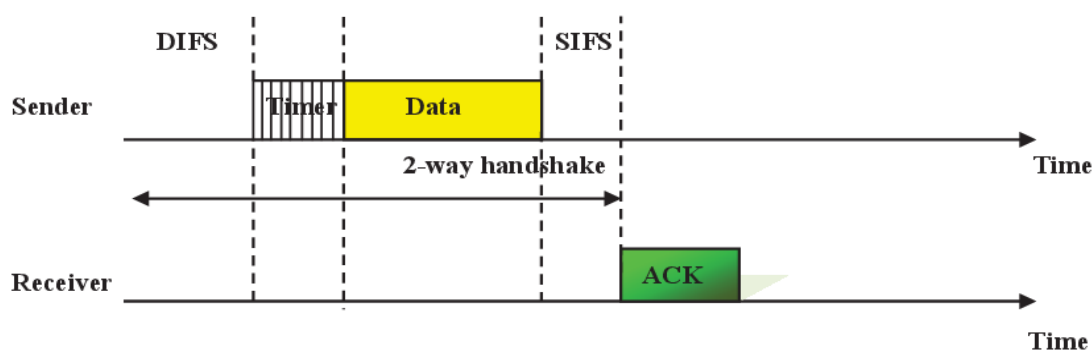


Figure 2.1: Two - way HandShake mechanism (Data / ACK)

If the transmitter station does not receive the ACK within SIFS duration, it will assume that there is a collision or data lost (Chatzimisios et al. 2005). Thus, the two-way handshake mechanism (DATA/ACK) is suitable for small data packets because it is based on short interval time. However, the hidden station problem cannot be detected using DATA/ACK and also the large data packet may lead to a collision risk. For these reasons, the CSMA/CA mechanism specifies the four-way handshake as an optional mechanism. In this scenario, the transmitter station can reduce the risk of collision using

Chapter 2 : Overview and Literature Review

request to send/clear to send (RTS/CTS) packets as shown in Figure 2.2. In this way, the transmitter station can reserve the transmission medium by sending the RTS packet to receiver side. If the transmission medium is free, the receiver will confirm the reservation by replying the CTS packet to the sender station (Ming et al. 2008).

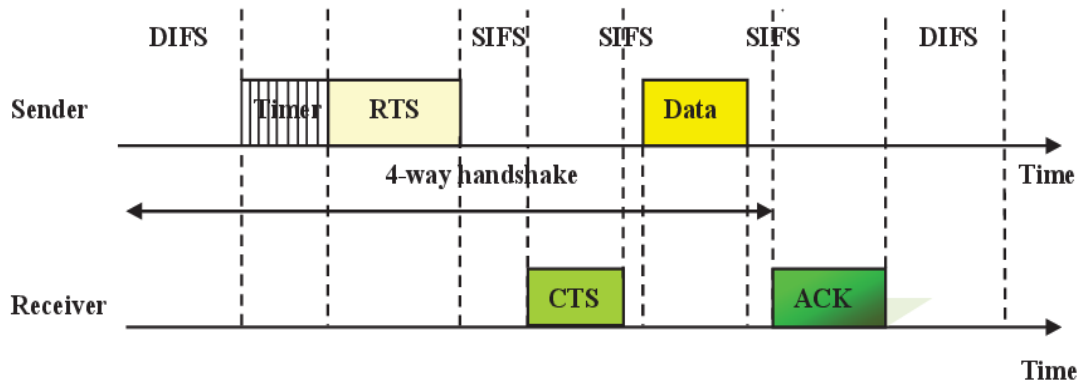


Figure 2.2: Four - way Handshake mechanism (RTS / CTS)

As a result, the four-way handshake mechanism RTS/CTS can reduce the probability of collision when transmitting long packets. Moreover, the RTS/CTS mechanism can deal with hidden station problems. This is because the four-way handshake mechanism enables the transmitter station to reserve the transmission medium before transmitting.

2.2.2 Binary Exponential Backoff Scheme

The IEEE 802.11 DCF standard is a completely distributed scheme; whenever more than one station attempts to access the transmission medium simultaneously, it will lead to a collision. However, if the collided stations attempt to access the transmission medium again, the transmission packets will collide as the multiple stations are synchronised in time (Gangrade et al. 2013). Therefore, multiple stations must be organised into time slots. To organise multiple stations temporally, a backoff scheme is

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generated such as the BEB algorithm. In DCF, the transmitter station first listens to the transmission medium until it becomes idle for a specific amount of time, called distribution inter frame space (DIFS) duration (Roshan 2003). After that, the station generates the backoff timer by following a backoff algorithm. The time value is defined as the contention window (CW). In the standard algorithm (BEB), the backoff timer will set between zero and CW_{\max} . If the transmission medium is still idle, the backoff timer will decrease to zero and then the station can transmit. Otherwise, the transmission medium becomes busy during the back-off timer process, and then the station would freeze the backoff timer until the transmission medium becomes idle again. After each successful transmission, the CW will reset to zero. In cases when the transmitter station does not receive an ACK after SIFS duration, it will execute as when a collision has occurred, and the CW will be doubled size in value as shown in Figure 2.3. Therefore, the CW will continue to double until it is equal to CW_{\max} or by obtaining the successful transmission (Gangrade et al. 2013).

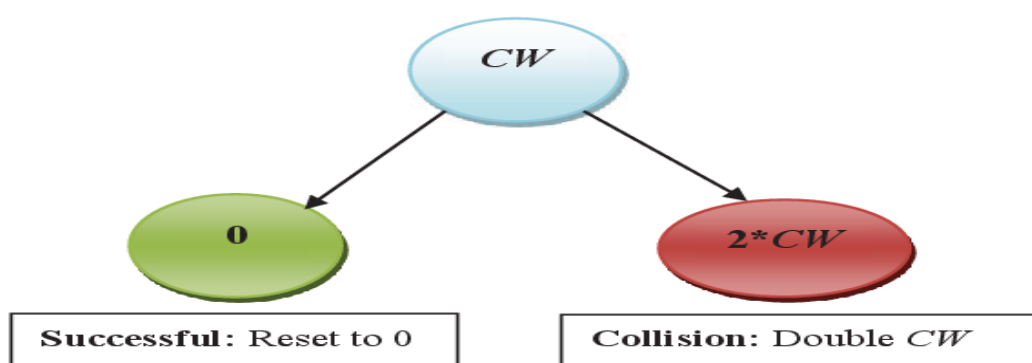


Figure 2.3: CW process in BEB scheme

However, the collision probability will lead to unsuccessful transmission and then decrease the throughput. Therefore, improving the backoff algorithm will help to avoid

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throughput degradation and high delay transmission. This is why many researchers pay great attention to improving the backoff algorithm or may even propose a new backoff algorithm.

2.3 Literature Review

This literature review serves three main purposes. It discusses and evaluates what others have done and discovered regarding performance modelling, the behaviour of MAC layer packet delay, and methods of backoff schemes. The literature review aims to define the gap in knowledge in order to reduce it or suggest possible solutions.

2.3.1 Related Work on the Analytical Modelling of IEEE 802.11 DCF

The famous performance analytical model for IEEE 802.11 DCF under saturated traffic load conditions is the model of Bianchi work in 2000. Bianchi represented the behaviour of a single station using a two-dimensional Markov chain analysis model, which is a suitable way to represent a series of transitions between different states such as the behaviour of IEEE 802.11 DCF. Consequently, many pieces of research work are based on this model. However, Bianchi (2000) provided the analysis for saturation throughput performance based on conditional collision probability. This model neglected the frozen period. Thus, the model assumed the busy probability and the collision probability are the same. Therefore, Taher et al. (2011) argued that the assumption of considering the channel busy probability and the collision probability as

Chapter 2 : Overview and Literature Review

the same is not a justified assumption. This is because the busy probability and the collision probability are a different event and mechanism.

There are alternative approaches to proposing or extending the analytical model of IEEE 802.11. For example, in the work of Wang et al. (2009), the authors proposed a new analytical performance model under more flexible traffic sources using equilibrium point analysis (EPA). This analysis method is applicable in order to propose the analytical performance model for IEEE 802.11 DCF based on various traffic loads. It is a suitable method to evaluate the system throughput under different parameter settings. However, this model represented the transmission medium mechanism in idle state, transmission state and collision state. In this case, the authors did not take into account the mechanism for the busy probability. Dong and Varaiya (2005) proposed the performance analytical model for IEEE 802.11 DCF using virtual slot time under saturated traffic load conditions. The authors used virtual slot to represent transmission medium activity, which can represent transmission error. However, this method is a similar mechanism to an analysis model using two-dimensional Markov chain. The method is based on the collision probability and the error transmission probability but without any mention of the busy probability. Besides these, many researchers have extended Bianchi's model in order to improve the performance model of IEEE 802.11 DCF. However, Bianchi's model has some limitations that must be investigated, such as an idle channel assumption (no errors and no hidden station exist), single-hop case, infinite packet retransmissions assumption, saturated traffic loads assumption, and performance analytical model based only on collision probability. Therefore, Vishnevsky and Lyakhov (2002) extended Bianchi's model to include the channel noise. Hou et al. (2003) also extended Bianchi's model from the single-hop case to the multi-

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hop case. The authors have taken into account the hidden station problem by assuming an average number of hidden stations occur for each station.

Ergen et al. (2005) proposed a new performance analytical model for IEEE 802.11a under non-saturated traffic load conditions. In this model the busy probability and the collision probability are assumed to be the same. Malone et al. (2007) extended Bianchi's model to non-saturated traffic load conditions. The change was made by adding a new state to represent the post backoff, which was not taken into account in Bianchi's model. However, Malone's model is based on the collision probability and idle probability. Therefore, Malone's model did not consider the busy probability because it is extended the Bianchi model in terms of traffic load conditions only.

On the other hand, many researchers pay great attention to the enhancement of the IEEE 802.11 standard. For example, in the work of Lin and Wong (2006), the authors laboured on an enhancement distributed channel access (EDCA) under saturated traffic load conditions. The authors proposed a new performance analytical model for IEEE 802.11e using mean value analysis (MVA). This method provides less computation overhead than the multi-dimensional Markov chain method. Hui and Devetsikiotis (2004) proposed a unified performance analytical model for IEEE802.11e-EDCA. In this work, the Markov chain analysis is based on Bianchi's model (Bianchi 2000), and the MVA, which is based on Tay's model (Tay and Chua 2001), are combined into one model. The authors proposed a unified performance analytical model to reduce the complexity for applying and understanding the model.

Most of the above models extended Bianchi's model. In this case, the models did not take into account the busy probability in analytical model. Some of the performance

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analytical models considered the busy probability and the collision probability to be the same, which is not a justified assumption (Alkadeki et al. 2013a, Alkadeki et al. 2013b).

2.3.2 Related Work on the Behavior of the MAC Layer Packet Delay

As mentioned in the previous section, most of the popular work for studying the behaviour of a single-hop case and performance for wireless network is based on the Markov chain analysis model. Therefore, Bianchi (2000) proposed a good evaluation performance model for IEEE 802.11 DCF under saturated traffic loads. However, network standard are based on several layers. Thus, the delay will occur on different layers such as MAC layer and upper layer. Wu et al. (2002) extended the Bianchi model by considering a maximum retry limit. In this model the DCF scheme is also modified to new scheme called DCF+, which can enhance the performance for transmission control protocol (TCP). This means that the authors worked on the MAC layer to improve the performance analysis model and the transport layer to support the transmission of packets over WLANs (Alkadeki et al. 2013c). He and Nahrstedt (2006) investigated the delay control problem over the upper layer to improve the QoS. This work showed that the upper layer could not provide delay support without the MAC layer service.

On the other hand, there is a lot of research work focused on the MAC layer delay rather than the transport layer. For example, based on Markov chain analysis model, Chatzimisios et al. (2003) worked on the MAC layer to develop Wu's performance analysis model, by taking into account packet retry limits under saturated traffic load conditions. This work showed that the model considering the packets retry limits would

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provide better results than the model without considering the packets retry limits. Furthermore, Vukovic and Smavatkul (2004) enhanced Bianchi's performance analytical model from a two-dimensional Markov chain to a one dimensional Markov chain. Moreover, in this model, the authors calculated the average packet delay by reducing Wu's performance analytical model from a two-dimensional Markov chain to a one dimensional Markov chain. However, one dimensional Markov chain is a good idea for a simple calculation but it is not suitable for large networks (Alkadeki et al. 2013c). Therefore, Raptis et al. (2005) proposed a new performance analytical model to calculate the average packet delay of IEEE 802.11 DCF. In addition, the authors claimed that their model provides better accuracy than Vukovic's model in (Vukovic and Smavatkul 2004). Raptis et al. (2009) developed the delay model for IEEE 802.11 DCF under saturated traffic loads. The authors considered the most likely delay events, such as average packet delay, average packet drop time, packet delay jitter and packet delay distribution. However, the authors followed the same discrete time Markov chain in Wu's model, which extended the Bianchi model. Thus, the delay model did not account for the difference between the busy probability and the collision probability.

Some research work has paid attention to predicting real time. For example, Qi et al. (2009) used multiplayer games to estimate the performance of IEEE 802.11 infrastructure WLAN. The authors derived the delay, jitter, and throughput as a number of clients. Ivanov et al. (2011) proposed estimation method for packet service time distribution under saturated traffic loads. This model represented the behaviour of MAC layer delay as a terminating renewal process, which is based on successful transmission. In this model the authors did not take into account the busy probability.

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Most existing models focused on estimation of the average MAC layer packet delay but the packet delay distribution is still unsolved (Ivanov et al. 2011). In addition, most existing models do not take into account the difference between the busy probability and the collision probability. This is the reason much of the research work did not account for the busy probability.

2.3.3 Related Work on the Methods of Backoff Algorithms

As mentioned in Section 2.2.2, the backoff algorithm for IEEE 802.11 is very important for controlling channel access to maximize throughput and fairness (Cho and Jiang 2015). There are several methods for extending or proposing backoff algorithms. Most of these are based on modifying the backoff parameters such as CW size and backoff stage (m), which is why much research has focused on modifying the CW size during the execution of the backoff algorithm to improve the performance of the IEEE 802.11 DCF. Therefore, an appropriate CW size leads to an improvement in the system throughput by reducing the probability of collisions. However, some of the methods do not account for dynamic traffic loads. For example, according to research work in (Bharghavan et al. 1994), the authors proposed a new backoff algorithm, called the multiplicative increase and linear decrease (MILD) algorithm. Their work focused on modifying the CW size to $CW \times 1.5$ rather than doubling it after every unsuccessful transmission. Moreover, CW size is decremented by one after every successful transmission rather than resetting it to zero. However, decreasing the CW size gradually helps avoid any degradation in performance. Therefore, the MILD algorithm is better than the BEB algorithm over large networks. Deng et al. (2004) extended the MILD

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algorithm by creating a new algorithm called the linear increase linear decrease (LILD) algorithm. However, the authors applied $CW + CW_{\min}$ as the size rather than multiplying by 1.5 to avoid the problem of slow linear change. Therefore, the LILD algorithm provides good quality performance over large networks. In other research (Song et al. 2003), the authors proposed a new backoff algorithm, called the exponential increase exponential decrease (EIED) algorithm. This algorithm is based on increasing and decreasing the CW size exponentially. Vitsas et al. (2005) proposed a new algorithm called the double increment double decrement (DIDD) algorithm. This algorithm is based on doubling the CW size after every unsuccessful transmission, in the same way as the BEB algorithm, but using $CW/2$ as the size after every successful transmission. The DIDD algorithm generates a better result than the other algorithms mentioned above. In addition, improving the BEB algorithm is still an active research topic. Therefore, Cheng et al. (2014) recently evaluated the performance of BEB as a poor algorithm due to a number of collisions and CW restoration after every successful transmission. This study is devoted to improve collision avoidance under saturated traffic loads.

However, the above algorithms do not consider dynamic traffic loads. There are other interesting directions that can be taken. For example, according to the research in (Lin et al. 2008), the authors focused on channel traffic loads, and proposed a new algorithm called the exponential linear backoff algorithm (ELBA). ELBA combines both exponential and linear algorithms depending on traffic loads and provides better system throughput than the BEB, EIED, and LILD algorithms. Liang et al. (2008) used pause count backoff for monitoring channel traffic loads. This algorithm aims to set an appropriate CW size based on estimation results. Hai-Xia and Gang (2009) proposed an

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adaptive backoff algorithm based on the trade-off of efficiency and fairness for ad hoc networks. This work is based on a fair schedule to control the increase and decrease in *CW* size depending on the channel situation (idle or busy). Fu et al. (2009) considered dynamic traffic loads by proposing an algorithm based on monitoring the channel before data transmission. In this algorithm, each station can record the number of busy slots by opening an observation window. Thus, the sender can calculate a dynamic priority and *CW* size according to the number of successful transmissions. In (Balador and Movaghar 2010, Balador et al. 2012), the authors monitored the channel traffic loads by using a channel state (CS) vector, and proposed a new algorithm called the dynamic deterministic contention window control algorithm. This algorithm is based on monitoring the channel traffic load conditions by checking the CS. However, selecting the optimum *CW* size based on different traffic load conditions using the CS vector is difficult.

Overall, the majority of research work has paid great attention to improving the performance of a saturated system without accounting for non-saturated traffic load conditions. Therefore, creating a new backoff algorithm under non-saturated traffic load conditions is the objective of this thesis.

2.4 Problem Statement

In order to understand the difference between the busy probability and the collision probability in transmission mechanism, the MAC layer mechanism of IEEE 802.11 DCF has been investigated. However, the transmission mechanism is based on CSMA/CA scheme and BEB algorithm. Thus, first the transmitter station senses the transmission medium. If the transmission medium is idle for DIFS duration, the transmitter station will set backoff timer between zero and CW . After that, the backoff timer starts decrementing when the transmission medium is still idle. The backoff timer continues decrementing until zero and then the transmitter station transmits the packet. In the event that the transmission medium becomes busy while the backoff timer is decrementing, then the backoff timer will be frozen until the channel becomes idle again. This frozen period in the performance model is known as busy probability as shown in Figure 2.4. On the other hand, the transmitter station can detect the packet which has been received successfully using the two-way handshake mechanism. Specifically, the transmitter station waits for SIFS duration to confirm that the packet has been received correctly by receiving the ACK frame. In case the transmitter station does not receive the ACK frame, it will assume that the data has been lost or collided. This event in the performance model is known as collision probability. The mechanism for the collision probability, as shown in Figure 2.5, is different from the busy probability. This is because in a collision mechanism, the transmitter station retransmits the packet by setting a new backoff timer such as double the CW and incrementing the backoff stage in BEB scheme. A summarised comparative study of the main differences between the busy probability and the collision probability is illustrated in Table 2-1.

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Events	Busy mechanism	Collision mechanism
Duration	It detects after DIFS period when the transmitter station senses the channel is busy.	It detects after SIFS period when the transmitter station does not receive the ACK frame.
Procedure	Freezes the backoff timer until the channel becomes idle again.	Retransmits packet by setting a new backoff timer and incrementing the backoff stage to the next stage.
Reason	The transmission medium is busy from another transmitter station or collision.	Packet is lost or has collided because it crashed with another packet or any other reason.
Ending	When the transmission medium becomes idle again.	When the transmitter station has received the ACK frame to ensure that the receiver station has received frame successfully.
Mechanism	Listen before transmit (LBT).	Two-way handshake (Data / ACK).

Table 2-1: Difference between the busy probability and the collision probability

Based on the difference between the busy probability and the collision probability, a new analytical model is proposed to compute a packet transmission probability (τ) for IEEE 802.11 DCF under saturated traffic load conditions. After calculating τ , the saturated throughput simulation results are evaluated in extensive comparison with original model such as Bianchi's model. The comparison of throughput performance shows that the difference between probabilities must be taken into account in the analytical model. This is because the proposed model proves that the busy probability

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acts on the throughput performance, which means that the difference between the busy probability and the collision probability must be considered in order to achieve the most accurate prediction of performance evaluation. This leads to the investigation of the effect of the busy probability on estimation of delay distribution, which is important to enhance the QoS in IEEE 802.11 DCF. Therefore, an accurate way to estimate the MAC layer packet delay distribution for IEEE 802.11 DCF is proposed. This research work demonstrates that the analytical model including the difference between the busy probability and the collision probability agrees strongly with wireless network behaviour simulation. Therefore, this model provides a prediction of high quality compared with other related previous work.

On the other hand, investigating the analysis of IEEE 802.11 DCF has helped to discover the limitations of the performance model such as non-saturated traffic load conditions and delay. Indeed, typical WLAN traffic load conditions are not saturated conditions. Therefore, this research work pays close attention to the saturated and the non-saturated traffic load conditions. In order to enhance the system throughput and the average transmission delay, a new backoff algorithm under non-saturated traffic load conditions is proposed. This algorithm presents better performance results than other related backoff algorithms.

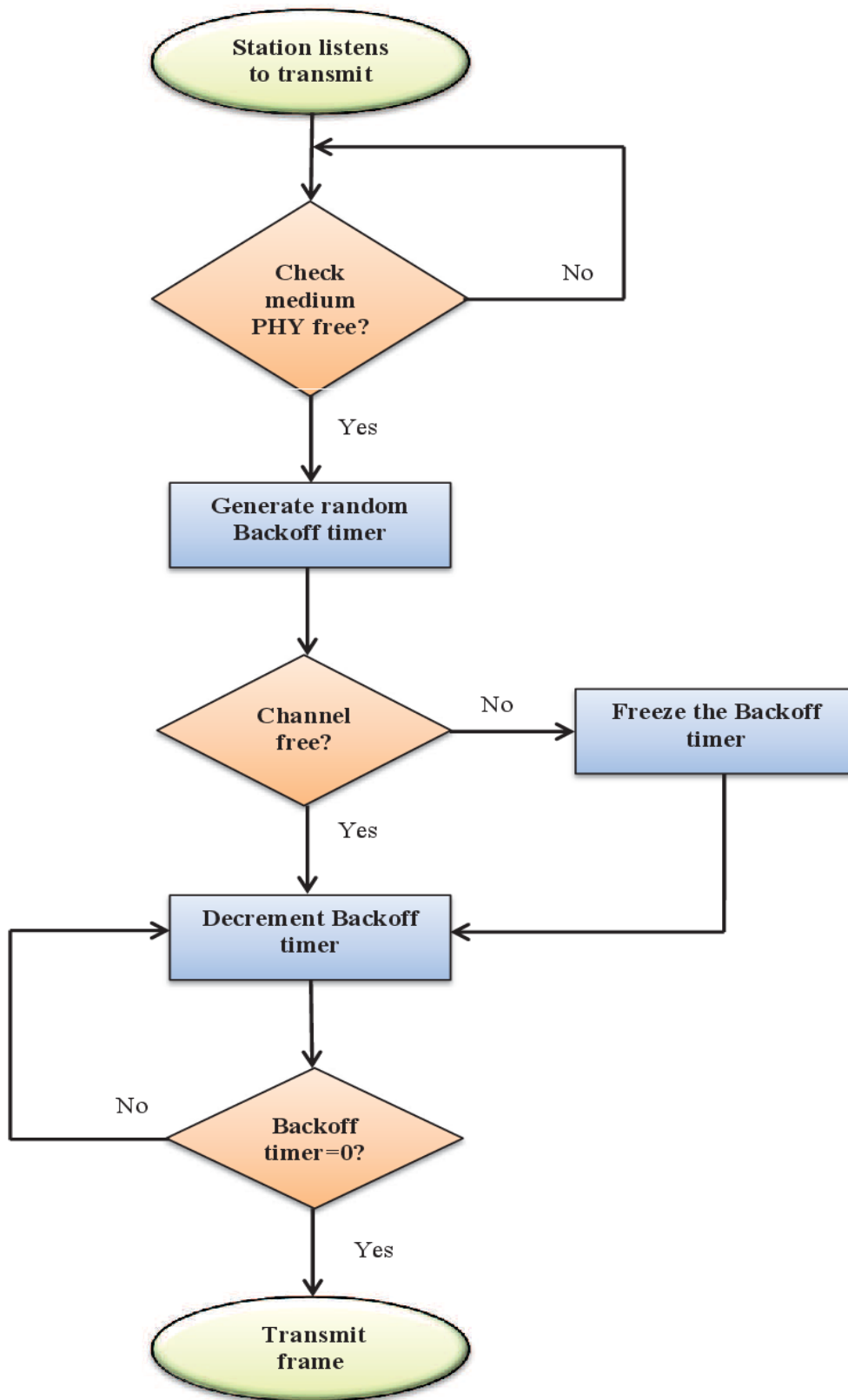


Figure 2.4: Busy mechanism of IEEE 802.11 DCF

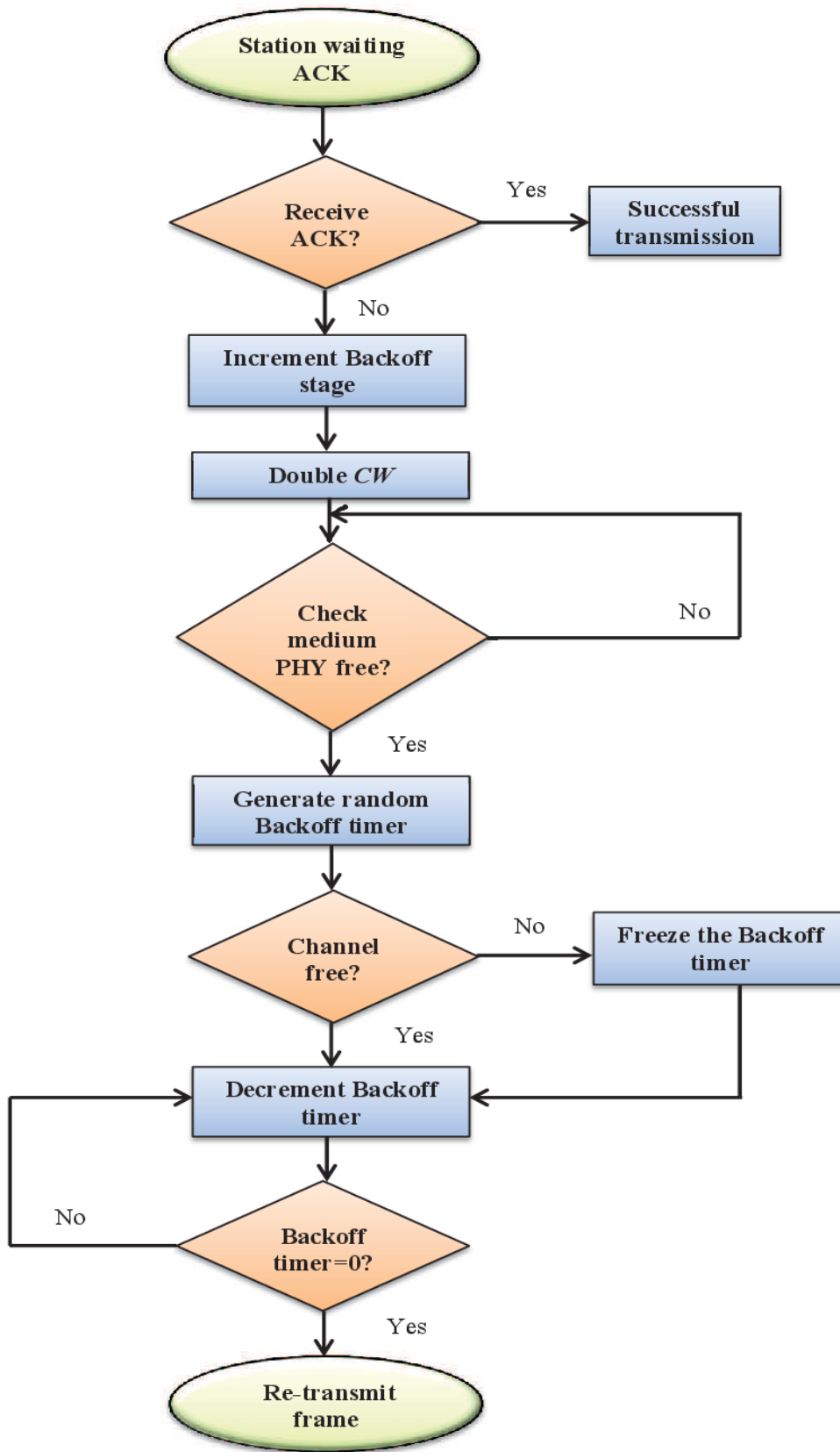


Figure 2.5: Collision mechanism of IEEE 802.11 DCF

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2.5 Summary

The chapter is divided into two parts. The first part reviews the basic components of the IEEE 802.11 DCF. It describes the components and functions of IEEE 802.11 DCF such as CSMA/CA, two-way and four-way hand shake. The procedure for transmission such as standard algorithm (BEB) is also explained. The second part reviews what other research work has been conducted with reference to what has been discovered regarding the performance modelling and enhancement of IEEE 802.11 DCF. It then considers and specifies the gaps in current knowledge.

As can be seen from the CSMA/CA scheme with BEB for IEEE 802.11 DCF, and the literature review, there is a difference between the busy probability and the collision probability. However, the literature review illustrated that much research work did not take into account the main difference between the busy probability and the collision probability in analytical models of IEEE 802.11 DCF. Therefore, some research work considered the busy probability and the collision probability to be the same. Others ignore the busy probability and considered only the collision probability, which is not a justified assumption. The difference between the busy probability and the collision probability must be considered in the performance modelling and enhancement of IEEE 802.11 DCF, because each probability will cause different delays during the transmission process.

This thesis considers the difference between the busy probability and the collision probability to propose a new analytical model for calculating a packet transmission probability (τ), and also to evaluate the performance model of IEEE 802.11 DCF. Moreover, the difference between the busy probability and the collision probability are

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employed to propose an accurate estimation method of the MAC layer packet delay distribution for IEEE 802.11 DCF.

The literature review also showed that the backoff algorithm for IEEE 802.11 is very important in controlling system throughput over contention window-based wireless networks. Additionally, the literature review illustrated that much research work has not accounted for non-saturated traffic load conditions. This provides the rationale for proposing a new backoff algorithm aiming to reduce the time delay, which leads to improvement of the system throughput. Specifically, proposing and implementing the new backoff algorithm under non-saturated traffic load conditions is considered through the research work. The following chapter will outline the details about the research methodology approach.

Research Methodology

3.1 Research Strategy

The research strategy is important in defining the process for answering the research questions and meeting the objective of the study. To add clarity to the thesis, this chapter will illustrate the research life cycle to ensure there is an understanding of how this piece of work will be designed and implemented.

3.1.1 Research Design

Research design is the process of collecting, analysing, interpreting, and reporting data in research studies (Creswell et al. 2011). In order to design an action plan, the modified Waterfall model has been used to define the research work life cycle. This helps to

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manage the process of the research work as shown in Figure 3.1. Therefore, the research work has the following stages, which were executed in order:

- **Literature Review:**

Presenting an overview of IEEE 802.11 DCF and related research work, including a detailed examination of the gaps in knowledge.

- **Modelling:**

Constructing and designing the proposed research work. The proposed research work is constructed from the summary of the above stage. A mathematical concept and language are used to propose and design this research work.

- **Implementation:**

Coding and running the above stage. A software program is used to implement the proposed research work.

- **Validation:**

Testing and demonstrating the proposed research work and comparing it with other related work. A software program is used also to make sure that the proposed research work has achieved the objective.

- **Acceptance:**

Evaluating and concluding the results. This is the final stage of the research work. In this stage, assurance will be sought that the proposed model has been completed with the desired results. Otherwise, it will be necessary to refer back to previous stages to improve the results.

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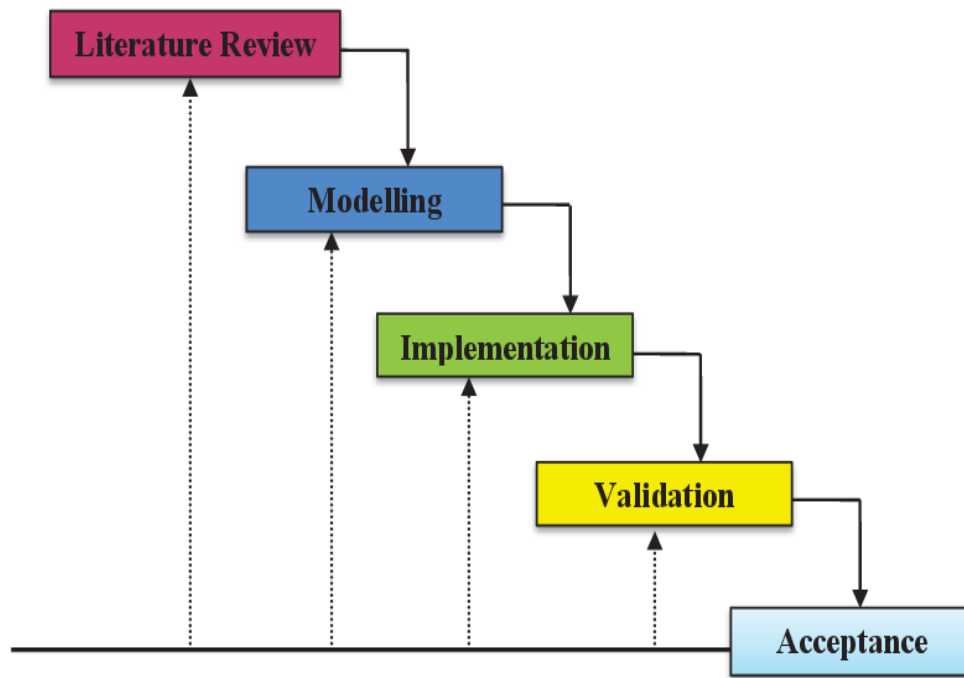


Figure 3.1: Research life cycle

3.1.2 Research Approach

According to the research design, the quantitative approach has been selected since the information collected through the literature review is translated into mathematical model. This approach is related to the numerical technique, which is the nature of mathematical modelling. Hence, the quantitative approach (scientific method) is a suitable approach in this situation for obtaining data and summarising the research information (Creswell 2003).

3.2 Justification

As discussed in the literature review in the previous chapter, most existing models for IEEE 802.11 DCF did not take into account the difference between the busy probability and the collision probability, which will lead to the ignoring of the busy probability in the analytical model of IEEE 802.11 DCF. To overcome this weakness, this research work has been started by studying the main difference between the busy probability and the collision probability in the transmission mechanism of IEEE 802.11 DCF. Then it proposes a new analytical model to compute a packet transmission probability for IEEE 802.11 DCF. This proposed model extends the work of Bianchi (2000), which is based on the collision probability only. The extension will lead to the production of a new performance evaluation model based on the busy probability and the collision probability.

However, when consideration is given to the busy probability and the collision probability into the analytical model, it is possible to observe something new based on a significant change on the saturation throughput performance results compared with Bianchi's model. This study shows that the busy probability acts on the saturation throughput performance in the same way as any other probability. For this reason, the busy probability is also taken into account to propose an accurate model to estimate the MAC layer packet delay distribution for the single hop of WLANs. The performance results show that the model provides prediction of high quality where the analytical model has a good agreement with IEEE 802.11 DCF behaviour simulation under saturated traffic load conditions.

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On the other hand, a great deal of attention is also paid to the improvement of the system performance for IEEE 802.11 DCF under non-saturated traffic load conditions. Therefore, a new backoff algorithm based on non-saturated traffic load conditions is proposed. Extensive simulation experiments show that the proposed algorithm provides better throughput performance and reduces the average transmission packet delay when compared with two other related backoff algorithms. The rest of this chapter will present the research life cycle with more details.

3.3 Modelling

This section presents the fundamental method and techniques to develop the analytical model and the backoff algorithm. According to the research life cycle, literature review, mathematical concepts and language are used to propose and develop the performance model of IEEE 802.11 DCF. The mathematical model describes the behaviour of a system before using the software tools for implementation and validation the proposed research work as shown in Figure 3.2.

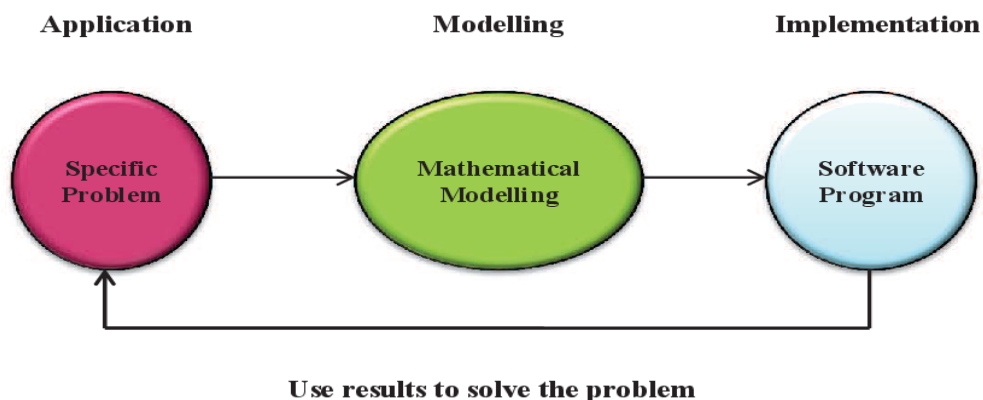


Figure 3.2: Research framework

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Based on a quantitative approach, the information collected through the literature review requires translating into numeric information. Therefore, it is important to select a suitable method to design the proposed model, as explained in the subsections below.

3.3.1 Modelling Method for Analysing IEEE 802.11 DCF

Throughout the literature review, the performance analytical model of IEEE 802.11 DCF was analysed in several ways, for example, Markov chain analysis model in one-dimensional, two-dimensional or multi-dimensional (Bianchi 2000, Vukovic and Smavatkul 2004, Taher et al. 2011, Tse et al. 2013, Kristic et al. 2013, Hoang et al. 2014, Swain et al. 2015), EPA model (Wang et al. 2009), mean value analysis (Lin and Wong 2006) and virtual slot time (Dong and Varaiya 2005). In this research, the two-dimensional Markov chain analysis model has been used, which is a convenient way to represent a series of transitions between different states for the behaviour of IEEE 802.11 DCF.

This model is divided into two parts. First, the bi-dimensional Markov chain analysis model is used to describe the behaviour of a single station. Single station behaviour is represented by two-dimensional stochastic processes $(s(t), b(t))$ with the discrete-time Markov chain. The current size of CW is represented by $s(t)$, and the current value of the backoff timer is represented by $b(t)$. According to the binary exponential backoff algorithm, the current size of CW is represented by $CW=2^i CW$, where $i \in (0, m)$ and m is represented a maximum backoff stage. The backoff timer is represented by k , where $k \in (0, W_i-1)$. Therefore, $(s(t), b(t))$ can be modelled by a two-dimensional Markov chain analysis model as shown in Figure 3.3. In addition, the packet transmission probability

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(τ) is calculated based on the difference between the busy probability and the collision probability.

Second, the saturated throughput is evaluated in terms of τ . This facilitates the investigation of the impact of considering the differences between the busy probability and the collision probability on the performance system. This model provides an accurate prediction for system throughput, which can be a fundamental base for improving the performance model of IEEE 802.11 DCF.

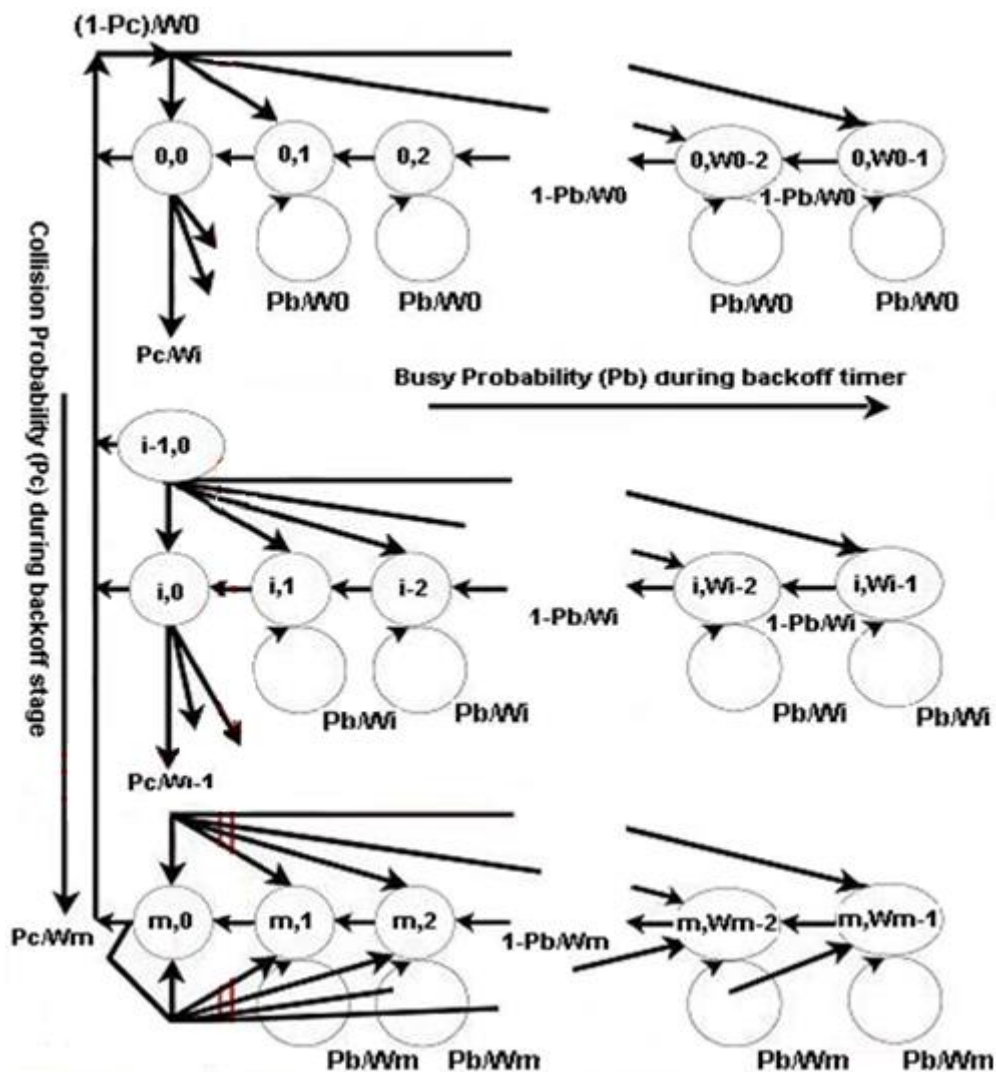


Figure 3.3: Markov chain for representing the proposed model

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3.3.2 Modelling Method for Estimating the MAC Layer Packet Delay Distribution

Besides the two-dimensional Markov chain analysis model, terminating renewal processes theory (Feller et al. 1971) and previous related work of Ivanov et al. (2011) are used to propose an accurate analytical model for estimating the MAC layer packet delay distribution of IEEE 802.11 DCF under saturated traffic load conditions. The total delay obtained by a packet can be presented as follows:

$$\text{Total Delay} = \text{Delay on Upper Layers (above MAC)} + \text{Delay on MAC Layer}$$

In this study, the delay on the MAC layer only has been considered. For this reason, it is assumed that packets are not sent from the upper layers until the channel is free. Therefore, the MAC layer packet delay can be considered a terminating renewal process, which terminates with each successful transmission. This time delay includes the duration of a successful transmission and the duration of non-transmission. In this thesis, the MAC layer packet delay is represented as sequence of discrete random variables. These random variables represent the number of collision or frozen period, which are terminated by successful transmission as shown in Figure 3.4.

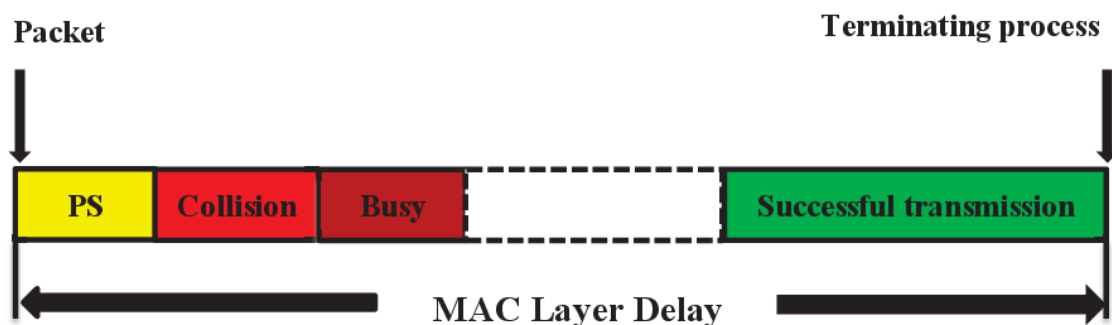


Figure 3.4: Discrete time sequence

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3.3.3 Modelling Method for Analysing the Proposed Backoff Algorithm

In order to run the proposed algorithm under non-saturated traffic load conditions, the EPA model is used. The EPA model provides a very convenient way to evaluate the system performance under non-saturated traffic load conditions (Wang et al. 2009).

In the EPA model, if there are a large number of nodes or high collision rate, the transmission probability of node R_i at any state of node i is calculated as

$$R_i = \frac{1}{2^i CW_{min}}$$

Throughput of the BEB algorithm under the EPA model can be calculated as

$$E[S(x)] = x_e^T,$$

where: $S(x)$ is the conditional throughput in state x .

However, the proposed algorithm adaptively changes the CW size with respect to the collision rate or the transmitting nodes. Therefore, the proposed algorithm under the EPA model affects the transmission probability of node R_i at any state of node i as

$$R_i = \frac{1}{CW_i}$$

As a result of using the EPA model, the traffic load behaviour will follow Poisson distribution with rate time/packets. Therefore, the performance system of the proposed algorithm can be investigated under various traffic load conditions.

3.4 Implemented Research Option

This section presents the tools used in implementing this research work. Typically, the choice of research implementation depends on the availability of requirements. There are two ways to obtain research findings:

- Hardware option.
- Software option.

However, due to the complexity and expense of implementing a hardware experiment, a software experiment is considered a more suitable option to do the research work. The software program is widely used and well recognized in engineering research.

Consequently, modelling and simulation have become well-known methods to gain information about the behaviour of the proposed model without actually testing it in real life. For example, if we wanted to propose a new performance model for WLANs, we would be able to use suitable software to create a computer simulation of the proposed model. Then, we can evaluate the performance model without the need to use hardware.

In this thesis, the throughput and the average transmission packet delay are evaluated without using any hardware tools. This is why a software option is selected to implement the research work, which is more convenient and cheaper than hardware tools. MATLAB software is used as the developing, implementing and validation tool. MATLAB (Matrix Laboratory) is a widely used tool in the engineering community specifically suitable for mathematical manipulation, data analysis and simulation.

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Given that this research work is based on a mathematical model, data analysis and simulation. Thus, MATLAB is a suitable tool for conducting this research work and it is used on multipurpose schemes as follows:

- To check and prove that the total probability for the proposed models is equal to one.
- To implement the new analytical proposed model to compute a packet transmission probability for IEEE 802.11 DCF under saturated traffic load conditions.
- To implement the new performance evaluation model for IEEE 802.11 DCF under saturated traffic load conditions.
- To validate the accuracy and compare the saturated throughput results of the proposed model with other related models.
- To implement the new analytical model for estimating the MAC layer packet delay distribution of IEEE 802.11 DCF under saturated traffic load conditions.
- To validate the accuracy and compare the delay distribution results of the proposed model with WLANs behaviour simulation results.
- To implement the new backoff algorithm for contention window-based IEEE 802.11 DCF under non-saturated traffic load conditions.

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- To test the throughput performance for the proposed backoff algorithm under non-saturated traffic loads and compare the system throughput results with other related algorithms.
- To calculate the average transmission packet delay for the proposed backoff algorithm under non-saturated traffic loads and compare the results with other related algorithms.

Besides MATLAB software, Maple software is also used to undertake calculation of certain equations such as polynomial equations. Maple software is a simpler and faster tool to solve equation problems. This is the reason Maple software is used in some cases of calculation equations.

3.5 Simulation Study

This section presents the simulation environment and assumptions used in this research work. The accuracy of the proposed analytical models and algorithm has been validated through extensive MATLAB simulation experiments. All stations are considered stationary and operate according to the standard IEEE 802.11 DCF based MAC protocol (IEEE 1999) using 1 Mbit/s basic rate (physical slot time = $50 \mu s$, SIFS = $28 \mu s$, DIFS = $128 \mu s$) with a data frame payload size of 8184 bits. Remaining parameters are summarised in Tables 4-2, 5-1 and 6-1.

Two scenarios of traffic load conditions are simulated. Therefore, both of saturated and non-saturated traffic load conditions are considered. Each of them assumes a fixed

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number of stations and a fixed data packet length. In addition, every station is able to communicate with each other and thus there are no hidden terminals in simulation experiments. In this way, the network topology is considered a single-hop ad hoc wireless network with n stations, where the stations communicate directly without the use of a router and access point.

The entire simulations are executed in a sequential process and re-defined according to the demand, as shown in Figure 3.5. Therefore, all the results obtained in the simulation experiments should present a significant improvement compared with other related work.

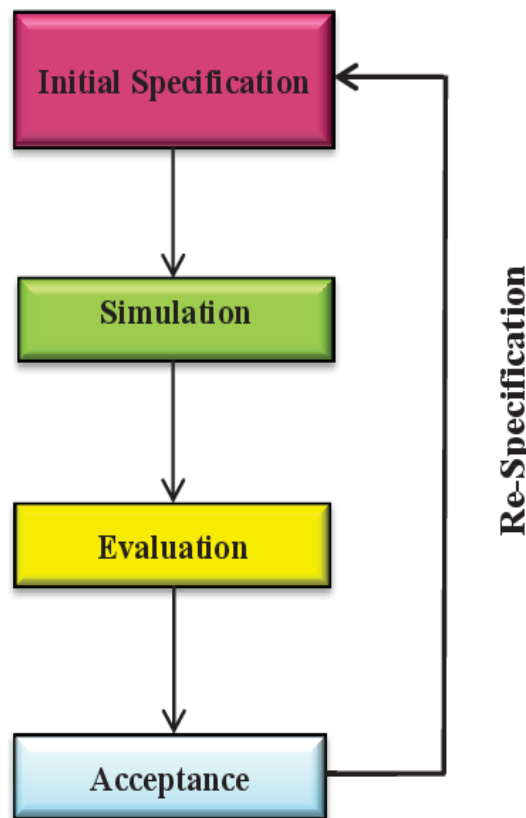


Figure 3.5: Simulation process management

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3.6 Summary

This chapter presents the research life cycle, which is a sequence of design processes. Each stage is based on the outcome of the previous stage. Based on the nature of the research work, the quantitative approach has been considered. The research methods involved in this chapter include the Markov chain analysis model, terminating renewal processes theory, and EPA model. In addition, the implementation tools and simulation environment have concluded through this chapter. The following chapter will deal with the proposed analytical model, numerical results, simulation results and validation.

Performance Analysis of IEEE 802.11 DCF based on the Busy Probability and the Collision Probability

4.1 Performance Modelling

In this section, modelling techniques are presented and the issues related to the new proposed model of IEEE 802.11 DCF are discussed. In particular, a new analytical model is proposed for computing a packet transmission probability (τ). Then, the system throughput is evaluated in terms of τ under saturated traffic load conditions.

Chapter 4 : Performance Analysis of IEEE 802.11 DCF based on the Busy Probability and the Collision Probability

4.1.1 Analytical Model

As mentioned in the Methodology Chapter, a two-dimensional Markov chain analysis model is the modelling method. This method has been used to extend Bianchi's model in terms of a packet transmission probability (τ). The Bianchi model assumed that the τ depends on the collision probability only, which is not a justified assumption. This limitation has been removed in this research work in order to propose an accurate analytical model for IEEE 802.11 DCF. The key difference between this model and the Markov chain model of Bianchi's work (2000) is that a new probability (p_b) is introduced. The busy probability (p_b) is introduced using a stationary distribution ($b_{i,k}$), where k must be greater than zero. This is because if $k = 0$, then a transmission has occurred. In this case, the proposed model considers the busy probability (p_b) and the collision probability (p_c) to be two independent events during the MAC transmission mechanism as shown in Figure 4.1. The collision event occurs when multiple stations start transmissions simultaneously. While the busy event is considered if the channel is sensed as busy due to a transmission from another station.

Chapter 4 : Performance Analysis of IEEE 802.11 DCF based on the Busy Probability and the Collision Probability

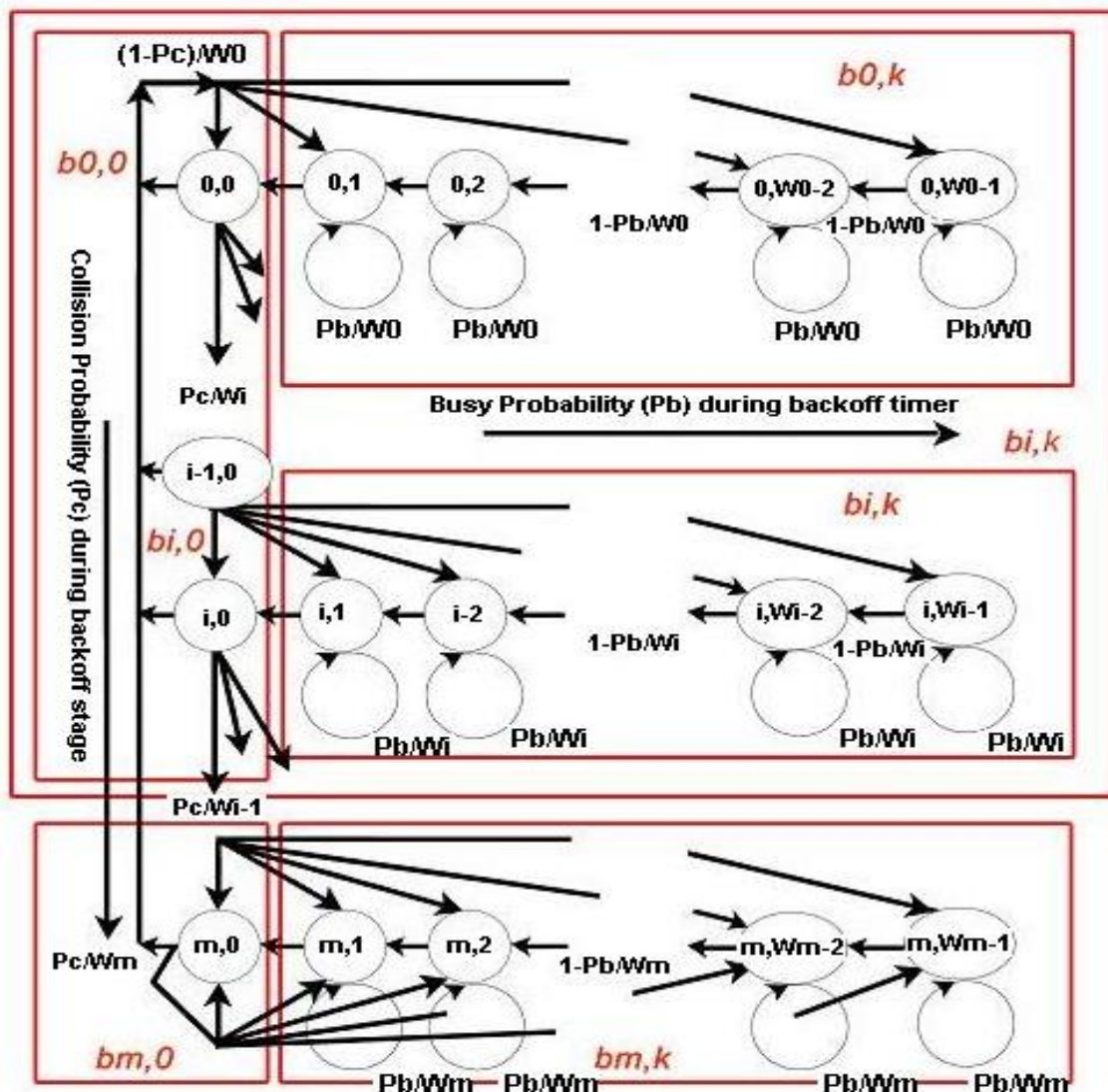


Figure 4.1: State transition diagram of the proposed analytical model

As can be seen from Figure 4.1, the two-dimensional stochastic processes $(s(t), b(t))$ will be analysed with the discrete-time Markov chain denoted by (i, k) . For convenience, the same channel assumptions of Bianchi (2000) are used. Therefore, it is assumed that the wireless channel is idle and saturated conditions with fixed number n of stations.

Chapter 4 : Performance Analysis of IEEE 802.11 DCF based on the Busy Probability and the Collision Probability

This Markov chain model represents the transmission mechanism of IEEE 802.11 DCF in five transition probability states. These transition probabilities are represented, respectively:

- **Idle state:** The backoff timer is decremented at the beginning of each slot time when the channel sensed idle (Bianchi 2000).
- **Successful transmission state:** The sender station has received an ACK and the backoff timer of the new packet starts from the backoff stage= 0 (Bianchi 2000).
- **Busy state:** The channel is busy and the backoff timer of the sender station is frozen at $k > 0$ (Alkadeki et al. 2013a).
- **Collision state at i stag:** Unsuccessful transmission and collision occurred at the backoff stage i and the packet requires retransmitting at new backoff stage (Bianchi 2000).
- **Collision state at m stag:** Unsuccessful transmission and collision occurred at the maximum backoff stage (m), which will lead to drop the packet (Bianchi 2000).

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The above accounts are in discrete-time whose nonzero transition probabilities as described in Table 4-1 below.

Account	Equation	Conditional
1. Idle state (Bianchi 2000)	$P [(i,k) (i,k+1)] = 1-p_b / W_i$	$k \in (0, W_i-2),$ $i \in (0, m).$
2. Successful transmission state (Bianchi 2000)	$P [(0,k) (i,0)] = (1-p_c) / W_0$	$k \in (0, W_0-1),$ $i \in (0, m)$
3. Busy state (Alkadeki et al. 2013a)	$P [(i,k) (i,k)] = p_b / W_i$	$k \in (1, W_i-1),$ $i \in (0, m)$
4. Collision state at i stag (Bianchi 2000)	$P [(i,k) (i-1,0)] = p_c / W_i$	$k \in (0, W_i-1),$ $i \in (1, m)$
5. Collision state at m stag (Bianchi 2000)	$P [(m,k) (m,0)] = p_c / W_m$	$k \in (0, W_m-1),$ $i = m$

Table 4-1: Transition probabilities account

In this case, the stationary distribution is denoted as:

$$b_{i,k} = \lim_{t \rightarrow \infty} P\{s(t) = i, b(t) = k\},$$

$$\text{where: } P (i_1, k_1 | i_0, k_0) := P(s_{t+1} = i_1, b_{t+1} = k_1 | s_t = i_0, b_t = k_0).$$

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Satisfy the forward Kolmogorov equation:

$$b_{i,k} = \sum_{j=0}^m \sum_{\ell=0}^{W_j-1} P(i,k | j,\ell) b_{j,\ell}, \quad \forall k \in (0, W_i - 1), i \in (0, m),$$

where: $P(i,k | j,\ell) := P(s_{t+1}=i, b_{t+1}=k | s_t=j, b_t=\ell)$ are the transition probabilities.

4.1.2 Packet Transmission Probability

As mentioned above, the discrete-time Markov chain process was denoted by (i,k) . Therefore, the behavior of single station can be divided into several states as shown in Figure 4.1.

$(b_{0,k}, b_{i,0}, b_{i,k}, b_{m,0}, b_{m,k}, b_{0,0})$

As a result of deriving the formulae for these states, τ can be computed.

For the network depicted in the model diagram in Figure 4.1, the following equation can be derived:

$$b_{i,W_i-1} = b_{i,W_i-1} \frac{P_b}{W_i} + b_{i-1,0} \frac{P_c}{W_i}, \quad \forall i \in (1, m-1) \quad (4.1)$$

From (1), (3), and (4) respectively in Table 4-1, the probability for transmission can be derived, collision probability and busy probability in one equation:

$$b_{i,k} = b_{i,k} \frac{P_b}{W_i} + b_{i,k+1} \left(1 - \frac{P_b}{W_i}\right) + b_{i-1,0} \frac{P_c}{W_i}, \quad \forall k \in (1, W_i - 2), i \in (1, m-1) \quad (4.2)$$

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Equation (4.2) can be considered as the following:

$$b_{i,k} = b_{i,k+1} + b_{i-1,0} \frac{\frac{P_c}{W_i}}{1 - \frac{P_b}{W_i}}$$

With considering the Contention Window (W) through the above equation, then

$$b_{i,k} = b_{i,W_i-1} + (W_i - 1 - k)b_{i-1,0} \frac{\frac{P_c}{W_i}}{1 - \frac{P_b}{W_i}}$$

Equation (4.1) can be considered as follows:

$$b_{i,W_i-1} = b_{i-1,0} \frac{\frac{P_c}{W_i}}{1 - \frac{P_b}{W_i}}$$

On the other hand,

$$b_{i,k} = b_{i-1,0} (W_i - k) \frac{\frac{P_c}{W_i}}{1 - \frac{P_b}{W_i}}, \forall k \in (1, W_i - 1), i \in (1, m - 1) \quad (4.3)$$

Further, from a zero stage in the model diagram in Figure 4.1, the backoff procedure can be considered as follows:

$$b_{0,k} = b_{0,k} \frac{P_b}{W_0} + b_{0,k+1} \left(1 - \frac{P_b}{W_0}\right) + \frac{1 - P_c}{W_0} \sum_{j=0}^m b_{j,0}, \forall k \in (0, W_0 - 2) \quad (4.4)$$

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And

$$b_{0,W_0-1} = b_{0,W_0-1} \frac{P_b}{W_0} + \frac{1-P_c}{W_0} \sum_{j=0}^m b_{j,0} \quad (4.5)$$

Equation (4.4) can be defined as follows:

$$b_{0,k} = b_{0,k+1} + b_{i-1,0} \frac{\frac{(1-p_c)}{W_0}}{1 - \frac{P_b}{W_0}} \sum_{j=0}^m b_{j,0}$$

$$\text{Consequently, } b_{0,k} = b_{0,W_0-1} + (W_0 - 1 - k) \frac{\frac{(1-p_c)}{W_0}}{1 - \frac{P_b}{W_0}} \sum_{j=0}^m b_{j,0}$$

$$\text{From the equation (4.5), } b_{0,W_0-1} = \frac{\frac{(1-p_c)}{W_0}}{1 - \frac{P_b}{W_0}} \sum_{j=0}^m b_{j,0}$$

As can be seen from Figure 4.1, the backoff counter direction (k) was represented horizontally, and the backoff stage direction (i) was represented vertically. Therefore, the stationary probability ($b_{i,k}$) represents all possible states, which can be obtained by deriving the formulae from the analytical model as the following:

$$b_{0,k} = (W_0 - k) \frac{\frac{(1-p_c)}{W_0}}{1 - \frac{P_b}{W_0}} \sum_{j=0}^m b_{j,0}, \quad \forall k \in (1, W_0 - 1) \quad (4.6)$$

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$$b_{0,0} = b_{0,1} \left(1 - \frac{P_b}{W_0}\right) + \frac{1 - P_c}{W_0} \sum_{j=0}^m b_{j,0} \quad (4.7)$$

$$b_{i,0} = b_{i,1} \left(1 - \frac{P_b}{W_i}\right) + b_{i-1,0} \frac{P_c}{W_i}, \quad \forall i \in (1, m-1) \quad (4.8)$$

Where $k = 1$, then:

$$b_{0,0} = (W_0 - 1) \frac{1 - P_c}{W_0} \sum_{j=0}^m b_{j,0} + \frac{1 - P_c}{W_0} \sum_{j=0}^m b_{j,0} = (1 - P_c) \sum_{j=0}^m b_{j,0}$$

Therefore,

$$\sum_{j=0}^m b_{j,0} = b_{0,0} \frac{1}{1 - P_c} \quad (4.9)$$

In this case, the mathematical equations for all the parts in the model diagram can be derived. First, the equation (4.6) can be considered as follows:

$$b_{0,k} = b_{0,0} \frac{1}{1 - \frac{P_b}{W_0}} (1 - k/W_0), \quad \forall k \in (1, W_0 - 1) \quad (4.10)$$

However, the equation (4.3), where $k = 1$

$$b_{i,1} = b_{i-1,0} (W_i - 1) \frac{\frac{P_c}{W_i}}{1 - \frac{P_b}{W_i}}$$

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From the equation(4.8), $b_{i,0}$ can be considered as follows:

$$b_{i,0} = b_{i-1,0} (W_i - 1) \frac{P_c}{W_i} + b_{i-1,0} \frac{P_c}{W_i} = P_c b_{i-1,0}$$

Second, $b_{i,0}$ can be computed as follows:

$$b_{i,0} = P_c^i b_{0,0}, \quad \forall i \in (0, m-1) \quad (4.11)$$

Third, $b_{i,k}$ can be computed from the equation(4.3) as follows:

$$b_{i,k} = b_{0,0} P_c^{i-1} (W_i - k) \frac{\frac{P_c}{W_i}}{1 - \frac{P_b}{W_i}} = b_{0,0} \frac{P_c^i}{1 - \frac{P_b}{W_i}} (1 - k / W_i), \quad \forall k \in (1, W_i - 1), i \in (1, m-1) \quad (4.12)$$

When (i) achieve the final backoff stage (m), as a consequence:

$$b_{m,k} = b_{m,k} \frac{P_b}{W_m} + b_{m,k+1} (1 - \frac{P_b}{W_m}) + b_{m-1,0} \frac{P_c}{W_m} + b_{m,0} \frac{P_c}{W_m}, \quad \forall k \in (1, W_m - 2) \quad (4.13)$$

$$b_{m,W_m-1} = b_{m-1,0} \frac{P_c}{W_m} + b_{m,W_m-1} \frac{P_b}{W_m} + b_{m,0} \frac{P_c}{W_m} \quad (4.14)$$

$$b_{m,0} = b_{m-1,0} \frac{P_c}{W_m} + b_{m,1} (1 - \frac{P_b}{W_m}) + b_{m,0} \frac{P_c}{W_m} \quad (4.15)$$

$$b_{m-1,0} = P_c^{m-1} b_{0,0}$$

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Same as the equation (4.11), however the equation (4.13) can be denoted as follows:

$$b_{m,k} = b_{m,k+1} + \frac{1}{1 - \frac{P_b}{W_m}} (b_{0,0} \frac{P_c^m}{W_m} + b_{m,0} \frac{P_c}{W_m})$$

As a result of considering W in the equation instead of k ,

$$b_{m,k} = b_{m,W_m-1} + (W_m - 1 - k) \frac{1}{1 - \frac{P_b}{W_m}} (b_{0,0} \frac{P_c^m}{W_m} + b_{m,0} \frac{P_c}{W_m}), \text{ and the equation (4.14) can be}$$

considered as follows:

$$b_{m,W_m-1} = \frac{1}{1 - \frac{P_b}{W_m}} (b_{0,0} \frac{P_c^m}{W_m} + b_{m,0} \frac{P_c}{W_m})$$

$$b_{m,k} = (W_m - 1) \frac{1}{1 - \frac{P_b}{W_m}} (b_{0,0} \frac{P_c^m}{W_m} + b_{m,0} \frac{P_c}{W_m}), \quad \forall k \in (1, W_m - 1) \quad (4.16)$$

While the backoff counter $k = 1$, then the equation (4.16) can be represented as follows:

$$b_{m,1} = (W_m - 1) \frac{1}{1 - \frac{P_b}{W_m}} (b_{0,0} \frac{P_c^m}{W_m} + b_{m,0} \frac{P_c}{W_m})$$

And from the equation(4.15), can be represented as follows:

$$\begin{aligned} b_{m,0} &= b_{0,0} \frac{P_c^m}{W_m} + b_{m,1} (1 - \frac{P_b}{W_m}) + b_{m,0} \frac{P_c}{W_m} \\ &= b_{0,0} \frac{P_c^m}{W_m} + (W_m - 1) (b_{0,0} \frac{P_c^m}{W_m} + b_{m,0} \frac{P_c}{W_m}) + b_{m,0} \frac{P_c}{W_m} \end{aligned}$$

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$$= b_{0,0}p_c^m + b_{m,0}p_c$$

Fourth, $b_{m,0}$ can be computed as follows:

$$b_{m,0} = b_{0,0} \frac{p_c^m}{1 - p_c} \quad (4.17)$$

Fifth, from the equation(4.16), $b_{m,k}$ can be computed as follows:

$$b_{m,k} = b_{0,0} (1 - k/W_m) \frac{1}{1 - \frac{p_b}{W_m}} \frac{p_c^m}{1 - p_c}, \quad \forall k \in (1, W_m - 1) \quad (4.18)$$

The only unknown quantity is the stationary probability ($b_{0,0}$), which can be found from the normalization condition as follows:

$$\begin{aligned} 1 &= \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} \\ &= \sum_{k=1}^{W_0-1} b_{0,k} + \sum_{i=1}^{m-1} \sum_{k=1}^{W_i-1} b_{i,k} + \sum_{i=0}^{m-1} b_{i,0} + b_{m,0} + \sum_{k=1}^{W_m-1} b_{m,k} \\ &= b_{0,0} \left(\sum_{k=1}^{W_0-1} \frac{1}{1 - \frac{p_b}{W_0}} (1 - k/W_0) + \sum_{i=0}^{m-1} p_c^i + \sum_{i=1}^{m-1} \sum_{k=1}^{W_i-1} \frac{p_c^i}{1 - \frac{p_b}{W_i}} (1 - k/W_i) + \frac{p_c^m}{1 - p_c} + \sum_{k=1}^{W_m-1} (1 - k/W_m) \frac{1}{1 - \frac{p_b}{W_m}} \frac{p_c^m}{1 - p_c} \right) \end{aligned}$$

Where the equations (4.10), (4.11), (4.12), (4.17) and (4.18) have been used,

$$\sum_{k=1}^{W_i-1} (1 - k/W_i) = W_i - 1 - \frac{1}{W_i} \sum_{k=1}^{W_i-1} k = W_i - 1 - \frac{1}{W_i} \frac{(W_i - 1)W_i}{2} = \frac{W_i - 1}{2}$$

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Finally, $b_{0,0}$ can be computed based on the busy probability (p_b), and the collision probability(p_c) as follows:

$$b_{0,0} = \left(\sum_{i=0}^{m-1} p_c^i + \sum_{i=0}^{m-1} \frac{p_c^i}{1 - p_b/W_i} \frac{W_i - 1}{2} + \frac{p_c^m}{1 - p_c} + \frac{1}{1 - p_b/W_m} \frac{p_c^m}{1 - p_c} \frac{W_m - 1}{2} \right)^{-1}$$

Once $b_{0,0}$ is found, all the stationary probabilities are obtained through equations (4.10), (4.11), (4.12), (4.17), and (4.18). Therefore, the probability that a station is in states with zero backoff timer can be computed from the following formula:

$$\begin{aligned} \tau &= \sum_{i=0}^m b_{i,0} \\ &= b_{0,0} \left(\sum_{i=0}^{m-1} p_c^i + \frac{p_c^m}{1 - p_c} \right) = b_{0,0} \left(\frac{1 - p_c^m}{1 - p_c} + \frac{p_c^m}{1 - p_c} \right) = b_{0,0} \frac{1}{1 - p_c}. \end{aligned}$$

4.1.3 Saturated Throughput

The throughput is a very important parameter for evaluating the system performance of IEEE 802.11 (Gupta and Rai 2013). However, the transmission packet probability (τ) plays a major role in the throughput calculation. Thus, the throughput is expressed in terms of τ by analysing the events that occur in an average slot. In this case, the obtained value of τ from the above-proposed analytical model is used to evaluate the system throughput. The same expression for throughput can be used as in Bianchi (2000). Therefore, the saturated throughput will be calculated in the same way for Bianchi's model by the following ratio:

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$$S = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr} (1 - P_s) T_c}, \quad (4.19)$$

where the required time to transmit payload bits successfully is defined by:

- Transmission probability (P_{tr}) in a slot is calculated by:

$$P_{tr} = 1 - (1 - \tau)^n, \quad (4.20)$$

- Successful transmission probability (P_s) is calculated by:

$$P_s = \frac{n \tau \cdot (1 - \tau)^{n-1}}{1 - (1 - \tau)^n}, \quad (4.21)$$

where (n) is the total number of stations. Besides these probabilities, there is a collision time (T_c) and a successful transmission time (T_s) taken into throughput calculation account denoted by:

$$T_c^{bas} = H + E[P^*] + DIFS + \sigma \quad (4.22)$$

$$T_s^{bas} = H + E[P] + SIFS + \sigma + ACK + DIFS + \sigma \quad (4.23)$$

Based on the assumption of all packets having the same fixed size, the average of packet payload size can be considered the same as:

$$E[P^*] = E[P],$$

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where $E [P^*]$ is the average of the longest packet payload involved in a collision probability (Bianchi 2000).

Therefore, once the τ is obtained from the previous section, the equations (4.20), (4.21), (4.22) and (4.23) can be calculated. Then the equation (4.19) can be obtained, which will enable the evaluation of the throughput performance of IEEE 802.11 DCF under saturated traffic load conditions.

4.2 Performance Evaluation

In this section, both numerical and simulation results of the proposed analytical model are presented. In addition, the accuracy of the proposed model is investigated. Furthermore, the comparison between the proposed model simulation results and Bianchi's model simulation results are presented.

4.2.1 Analytical Results

The proposed analytical model is carried out using MATLAB programming language. The analysis calculation is implemented based on the system parameters for the basic access mechanism in bits, and in $50 \mu s$ slot time units as described in Table 4-2.

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Table 4-2: System parameter settings for the analysis of IEEE 802.11 DCF under saturated conditions (Bianchi 2000)

First, the τ is calculated from the above analytical model based on the difference between the busy probability and the collision probability in transmission mechanism. However, the probability theory identified that all probabilities must be less than or equal to one. Therefore, random values between (0, 1) can be used to represent the busy probability (p_b) and the collision probability (p_c) as shown in Table 4-3. Then the obtained τ can be used to obtain and evaluate the system throughput by solving the equation (4.19).

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p_b	p_c	τ	Throughput: ($W = 32, m = 3$)			
			$n = 10$	$n = 20$	$n = 30$	$n = 50$
0.8	0.2	0.0457	0.72	0.66	0.64	0.6
0.7	0.3	0.0381	0.75	0.69	0.66	0.62
0.6	0.4	0.0309	0.76	0.71	0.68	0.63
0.5	0.3	0.0382	0.74	0.7	0.66	0.61
0.4	0.2	0.0435	0.738	0.68	0.65	0.6
0.3	0.2	0.0462	0.71	0.65	0.63	0.58
0.2	0.1	0.0538	0.7	0.61	0.59	0.57
p_b	p_c	τ	Throughput: ($W = 32, m = 5$)			
			$n=10$	$n=20$	$n=30$	$n=50$
0.8	0.2	0.0451	0.73	0.67	0.66	0.61
0.7	0.3	0.0358	0.76	0.72	0.69	0.64
0.6	0.4	0.0261	0.78	0.74	0.7	0.66
0.5	0.3	0.0360	0.75	0.71	0.67	0.62
0.4	0.2	0.0455	0.74	0.70	0.66	0.6
0.3	0.2	0.0456	0.72	0.68	0.64	0.69
0.2	0.1	0.0538	0.7	0.61	0.59	0.57

Table 4-3: Numerical results of saturated throughput based on different values of the busy probability and the collision probability

As can be seen from Table 4-3, the numerical results have shown that the saturated throughput (S) depends on the number of stations in the ad hoc wireless network, which is the same as Bianchi's model. The results show that a large number of stations will

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produce lower throughput and vice versa. In addition, this research work shows that the Bianchi model and other related models agree strongly about the relationship between the throughput and the number of stations, but it is also observed that the busy probability causes changes in the throughput. This is because the busy probability added a time delay when the channel becomes busy. This duration of time will affect the throughput result and performance evaluation model of IEEE 802.11 DCF. Therefore, it is necessary to consider the difference between the busy probability and the collision probability in the transmission mechanism through an analytical model.

4.2.2 Model Validation

This subsection first investigates the accuracy of the proposed analytical model through extensive MATLAB simulation experiments and then uses the proposed model to evaluate the saturated throughput of IEEE 802.11 DCF in comparison with Bianchi's model. The section is implemented into three scenarios in the following subsections.

4.2.2.1 Mathematical Model Validation

As previously mentioned, the probability theory states that all probabilities must be less than or equal to one. Therefore, MATLAB program is used to check the accuracy of the proposed analytical model. This check is obtained by confirming that the total calculation of transmission probabilities packet is equal to one. The confirmation was achieved by proving the equation (4.24).

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$$\sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} = 1 \quad (4.24)$$

After confirming that the total of stationary probabilities is equal to one, the modelling implementation and simulation can be completed as described in the following sections.

4.2.2.2 Analytical and Simulation Results Comparisons

The accuracy of the proposed model is validated through the extensive comparison of the analytical performance results with those obtained from MATLAB simulation experiment. The simulation experiment is implemented over the same parameters and assumption for the analytical model and Bianchi's model as described in Table 4.2. Therefore, the idle channel, finite number of stations and saturated traffic load conditions are taken into account. However, Bianchi's model was based on the collision probability only. Thus, the proposed model is built on the busy probability and the collision probability. In the simulation experiment, the busy probability is a constant value of EIFS duration as described in Table 4-2. This duration is the time delay in seconds which a station will face in case of busy channel.

Figure 4.2 presents a good agreement between the analytical results and corresponding simulation results specifically at values ($p_b = 0.4$, $p_c = 0.2$), where $W = 32$ and $m = 3$ as illustrated in Table 4-3. The gap between simulation and analytical model can be justified by the difference between simulation environment and model assumption. In

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addition, the performance results show that the system throughput depends on the busy probability, the collision probability, and the number of stations.

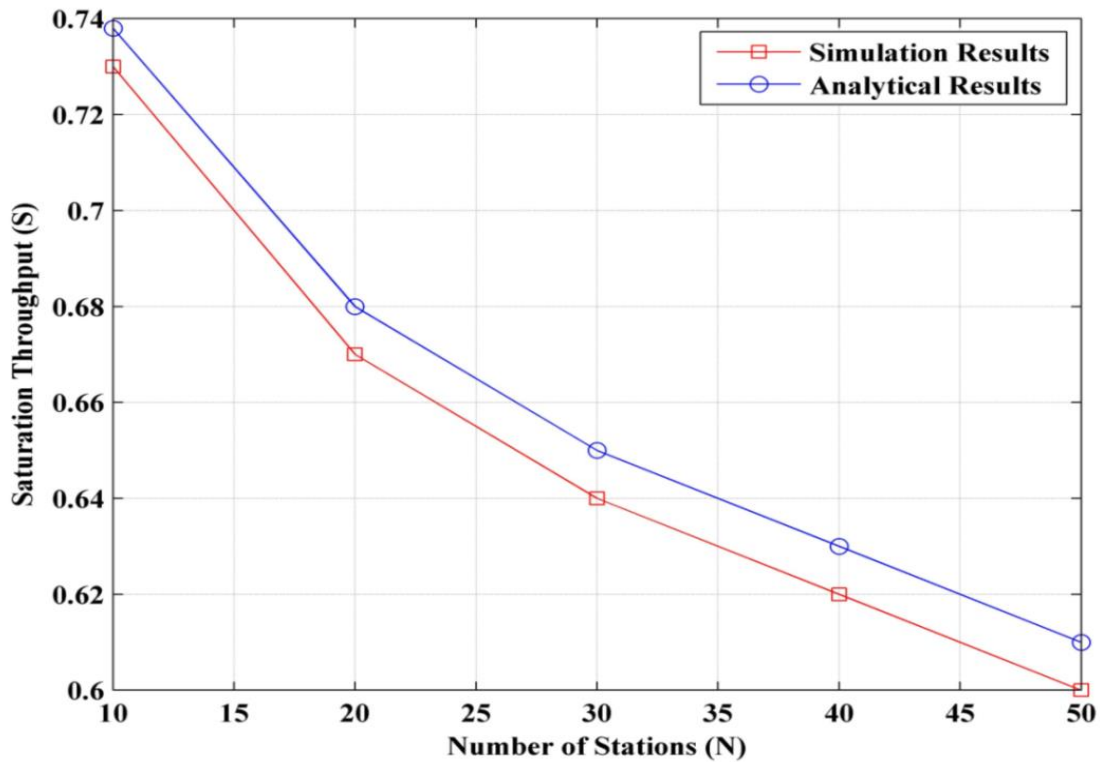


Figure 4.2: Analytical performance results versus simulation performance results, where: ($m = 3$, $W = 32$, $n = 50$)

4.2.2.3 Performance Comparisons

The performance of the proposed model is compared with Bianchi's model in terms of throughput under saturated traffic load conditions. Both models are simulated for 10 and 50 stationary nodes, respectively. The system parameters for both the models simulation have been set as illustrated in Table 4-2. In order to prove that the busy probability affects the throughput performance, the simulation results of the proposed model are then compared with Bianchi's model simulation results, as shown in Figure 4.3.

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Figure 4.3 demonstrates that the proposed model performs much better over large networks as compared to Bianchi's model. On the other hand, Bianchi's model performs better over small networks. However, adding the busy probability will result in enough waiting time for transmission stations. This enables stations to avoid the collision probability over large networks, which can lead to increasing the system throughput. On the other hand, the busy probability will lead to delay over a small network, which will decrease the system throughput. This observation emphasises the importance of taking into account the difference between the busy probability and the collision probability. The comparison of the performance results shows that the busy probability must not be ignored, nor be assumed the same as the collision probability. Therefore, it is necessary to take all the possible events for the transmission mechanism in order to accurately evaluate the IEEE 802.11 DCF standard.

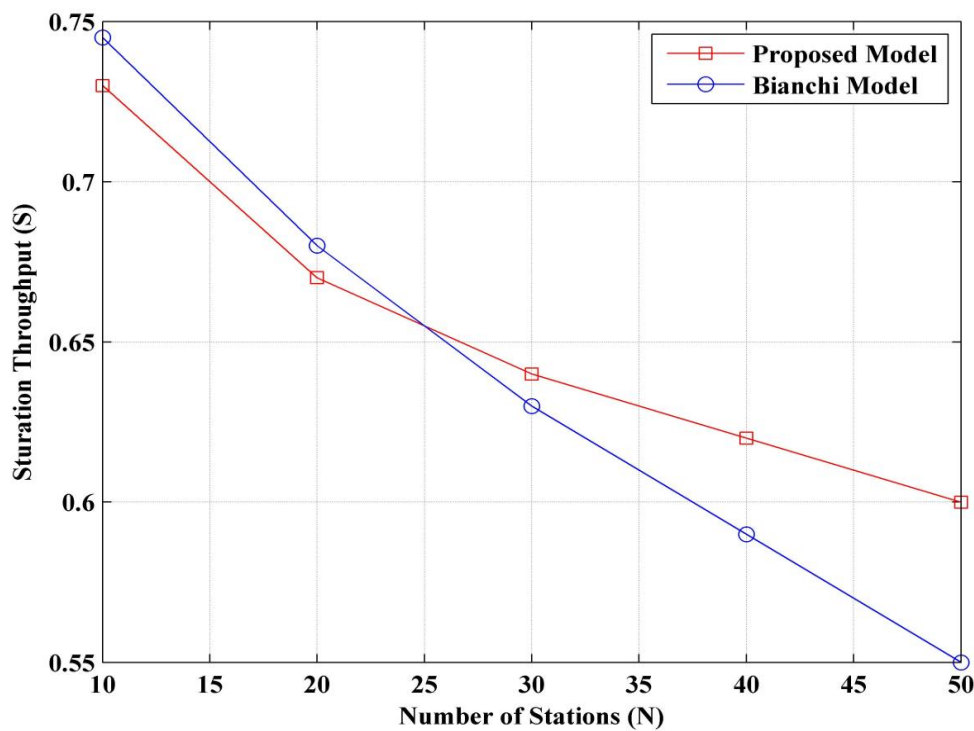


Figure 4.3: Performance comparison between the proposed model and Bianchi's model, where: ($m = 3$, $W = 32$, $n = 50$)

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4.3 Summary

In this chapter, the performance of IEEE 802.11 DCF under saturated traffic load conditions has been studied. In particular, the impact of adding the busy probability in the analytical model of IEEE 802.11 DCF has been evaluated. Using the difference between the busy probability and the collision probability, a new analytical model for computation of the packet transmission probability (τ) has been proposed. The accuracy of the analytical model has been validated through MATLAB programming language by proving the total probability is equal to one.

The motivation of this chapter was to prove that the difference between the busy probability and the collision probability affects the performance of IEEE 802.11 DCF. Therefore, it is important to consider the difference between both probabilities through the analytical model. This helps in achieving the most accurate prediction of the performance evaluation model of IEEE 802.11 DCF.

Furthermore, the chapter also discussed the saturated throughput based on calculating τ from the proposed model. The experiment was implemented under the same parameters and assumptions for Bianchi's model. It was demonstrated that the proposed model performance works well over a large network by comparing it with Bianchi's model. This is because the busy probability can reduce the number of the collision probabilities over a large network, which will lead to increasing the system throughput. It proved that the difference between the busy probability and the collision probability must be taken into account through the analytical model.

Chapter 4 : Performance Analysis of IEEE 802.11 DCF based on the Busy Probability and the Collision Probability

Finally, the accuracy of the performance evaluation model has been validated through the MATLAB simulation experiment, and the performance results were then compared with those achieved by an analytical model and Bianchi's model. The above research work has been published in an international conference paper (Alkadeki et al. 2013a) and in Dline journal (Alkadeki et al. 2013b). The following chapter will discuss the estimation method of the MAC layer packet delay distribution for IEEE 802.11 DCF under saturated conditions based on considering the difference between the busy probability and the collision probability in transmission mechanism.

Estimation of the MAC Layer Packet Delay Distribution for IEEE 802.11 DCF

5.1 Performance Modelling

In this section, the events of the MAC layer during the backoff transmission mechanism of IEEE 802.11 DCF are presented. The Markov analysis model is used to present the difference of time delays. The analytical model for estimating the MAC layer packet delay distribution for IEEE 802.11 DCF is proposed. The proposed model takes into account the renewal process theory and the difference between the busy probability and the collision probability in transmission mechanism.

Chapter 5 : Estimation of the MAC Layer Packet Delay Distribution for IEEE 802.11 DCF

5.1.1 Transmission Mechanism in MAC – DCF

As mentioned in the previous chapter, there are five transition probabilities according to the possible events during the backoff transmission mechanism of IEEE 802.11 DCF. These events are represented using the Markov analysis model as shown in Figure 5.1.

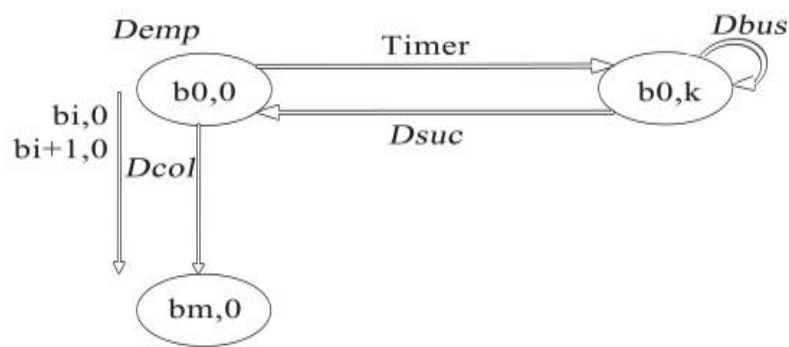


Figure 5.1: Time events during the backoff mechanism in IEEE 802.11 DCF represented by bi-dimensional Markov analysis model

As can be seen from Figure 5.1, the total time is regarded as a sequence of intervals of empty delay time (D_{Emp}), successful delay time (D_{Suc}), busy delay time (D_{Bus}), and collision delay time (D_{Col}).

Consequently, the discrete time delays are calculated using the following equations:

$$D_{Emp} = 50 \mu s \quad (5.1)$$

$$D_{Suc} = RTS + SIFS + CTS + SIFS + H + E [P] + SIFS + ACK + DIFS \quad (5.2)$$

$$D_{Col} = RTS + DIFS \quad (5.3)$$

$$D_{Bus} = DIFS + SIFS + ACK \quad (5.4)$$

Chapter 5 : Estimation of the MAC Layer Packet Delay Distribution for IEEE 802.11 DCF

5.1.2 Analytical Model for the MAC Layer Packet Delay Distribution

The network in this study has 20-30 stationary nodes; each node is equally likely to transmit. This uniform distribution was considered because the time was very short. Therefore, this proposed model is based on two probabilities to represent the behaviour of the model for each state. These probabilities were represented by the probability of the sender station attempting a transmission (τ_{tr}), and the probability of one neighbour station attempting a transmission (τ_{nb}). In this case, the following possible different probability events have been considered and calculated by the equations (5.5), (5.6), (5.7), (5.8), and (5.9):

$$P_{Emp} = (1 - \tau_{tr}) \cdot (1 - \tau_{nb})^{n-1}, \quad (5.5)$$

$$P_{Suc} = (n - 1) \cdot \tau_{nb} \cdot (1 - \tau_{tr}) \cdot (1 - \tau_{nb})^{n-2}, \quad (5.6)$$

$$P_{Own} = \tau_{tr} \cdot (1 - \tau_{nb})^{n-1}, \quad (5.7)$$

$$P_{Col} = \tau_{tr} \cdot (n - 1) \cdot \tau_{nb} \cdot (1 - \tau_{nb})^{n-2}, \quad (5.8)$$

$$P_{Bus} = 1 - P_{Emp} - P_{Own} - P_{Suc} - P_{Col}, \quad (5.9)$$

where:

- P_{Emp} : Idle state (no transmission packet attempts).
- P_{Suc} : One of neighbour's attempting to transmit packet.
- P_{Own} : The sender station attempting to transmit packet.
- P_{Col} : Packet transmission simultaneous attempt.
- P_{Bus} : Channel busy by packet transmission or packet collision.

Chapter 5 : Estimation of the MAC Layer Packet Delay Distribution for IEEE 802.11 DCF

As mentioned in Methodology Chapter, the MAC layer packet delay was represented as sequence of discrete random variables and terminated by each successful transmission as shown in the equation (5.10).

$$S_n = T_1 + T_2 + T_3 + \dots + T_n + D_{suc}, \quad (5.10)$$

where T_i represented the discrete random variable for time delay in seconds when a station will face in case of a collision or frozen period (Alkadeki et al. 2013c). All T_i have the same improper probability distribution function (F) and probability density function (f). In addition, the D_{Emp} , D_{Suc} , D_{Col} , D_{Bus} are the random variables whose corresponding probability density functions are P_{Emp} , P_{Suc} , P_{Col} , P_{Bus} which are obtained from the equations (5.5), (5.6), (5.8) and (5.9). Therefore,

$$P_{Emp} = f(D_{Emp})$$

$$P_{Suc} = f(D_{Suc})$$

$$P_{Col} = f(D_{Col})$$

$$P_{Bus} = f(D_{Bus})$$

However, P_{Emp} , P_{Suc} , P_{Col} , P_{Bus} present the probabilities of the slots or transmission attempts in which a station will not transmit. Therefore, probability distribution function (F) will be equal to one if (P_{Own}) is added to it.

F defines in this research work as follows:

$$F(\infty) = 1 - P_{Own}$$

Chapter 5 : Estimation of the MAC Layer Packet Delay Distribution for IEEE 802.11 DCF

From the theory of probability and stochastic, it is known that the f can be obtained by taking the derivation of F . On the other hand, F can be obtained by integrating the f . However, from the renewal process theory (Feller et al., 1971), if the basic renewal equation is compared with the equation (5.11):

$$\int_0^{\infty} e^{x.y} . F(dy) = 1 \quad (5.11)$$

It is known that the transform variable or the Laplace transform variable can be represented by x . Therefore, the equation (5.12) can be derived by obtaining the value of x . Then the process terminates after a time value t as follows:

$$P(M > t) \approx \frac{1 - F(\infty)}{X . \mu} . e^{-x.t}, \quad (5.12)$$

where:

$$\mu = \int_0^{\infty} y . e^{x.y} . F(dy) \quad (5.13)$$

The equation (5.11) and the equation (5.13) can be considered as the following:

$$P_{Emp} . e^{x.D_{Emp}} + P_{Suc} . e^{x.D_{Suc}} + P_{Col} . e^{x.D_{Col}} + P_{Bus} . e^{x.D_{Bus}} = 1 \quad (5.14)$$

$$D_{Emp} . P_{Emp} . e^{x.D_{Emp}} + D_{Suc} . P_{Suc} . e^{x.D_{Suc}} + D_{Col} . P_{Col} . e^{x.D_{Col}} + D_{Bus} . P_{Bus} . e^{x.D_{Bus}} = \mu \quad (5.15)$$

As a result of obtaining x value from the equation (5.14) and μ value from the equation (5.15), the estimation of the equation (5.12) can be done. Therefore, the MAC layer packet delay distribution for IEEE 802.11 DCF can be estimated from the equation

Chapter 5 : Estimation of the MAC Layer Packet Delay Distribution for IEEE 802.11 DCF

(5.16) and the equation (5.17) by obtaining the value of probability ($P \{M>t\}$) as follows:

$$P \{d \in [a; b]\} = P \{M > a\} - P\{M > b\} \quad (5.16)$$

$$P \{d \in [0; c]\} = 1 - P\{M > c\} \quad (5.17)$$

Equations (5.16) and (5.17) represent the MAC layer delay distribution (d) as a histogram, which are based on estimating the equation (5.12) after the service time value (t -ms).

5.2 Performance Evaluation

In this section, the performance results of the proposed model are compared with wireless network behaviour simulation experiment. In addition, the performance results of the proposed model will be compared with previous related research work of Ivanov et al. (2011).

5.2.1 Numerical Results

The time delays were calculated with the help of equations (5.1), (5.2), (5.3), and (5.4) and the values given in Table 5-1 are illustrated in Table 5-2.

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Table 5-1: System parameter settings for the proposed model based on theory of terminating renewal processes (Ivanov et al. 2011)

Therefore, the time delay values are as follows:

D_{Emp}	D_{Suc}	D_{Col}	D_{Bus}
50 μs	9412 μs	478 μs	456 μs

Table 5-2: Time delay values

Chapter 5 : Estimation of the MAC Layer Packet Delay Distribution for IEEE 802.11 DCF

5.2.1.1 Numerical Results over 20 Nodes

The probabilities were calculated with the help of equations (5.6), (5.7), (5.8), and (5.9) where $n = 20$. Therefore, the values of probability were obtained as illustrated in Table 5-3.

P_{Emp}	P_{Suc}	P_{Col}	P_{Bus}	P_{Own}
0.3585	0.3585	0.0189	0.2453	0.0189

Table 5-3: Probability values over $n = 20$

To obtain the real value of x it is necessary to calculate the roots of the equation (5.14). This can be done easily, by converting it into polynomial equation and then a real root is obtained using Maple software as shown in the equation (5.18) and the equation (5.19). Therefore, by substituting $e^{X.50.10^{-6}} = t$, and solving the equation (5.14) as follows:

$$0.3585t + 0.2453t^9 + 0.0189t^{10} + 0.3585t^{188} = 1 \quad (5.18)$$

$$0.3585t + 0.2453t^9 + 0.0189t^{10} + 0.3585t^{188} - 1 = 0 \quad (5.19)$$

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This equation has 188 possible solutions. Therefore, Maple program will be used for the numerical calculations to find the roots of the equation (5.19). The real root for t was obtained = 1.000261721(Alkadeki et al. 2013c). However, $t = e^{X.50.10^{-6}}$ then,

$$1.000261721 = e^{X.50.10^{-6}}$$

$$\ln(1.000261721) = x.50.10^{-6}$$

$$x = 5.234$$

Therefore, by obtaining x value then the value for μ can be obtained by the equation (5.15). Finally, the values for x and μ have been used to solve the equation (5.12) during the interval service time between 0 and 200 ms . Figure 5.2 presents the results between the probability distribution and time interval as a histogram.

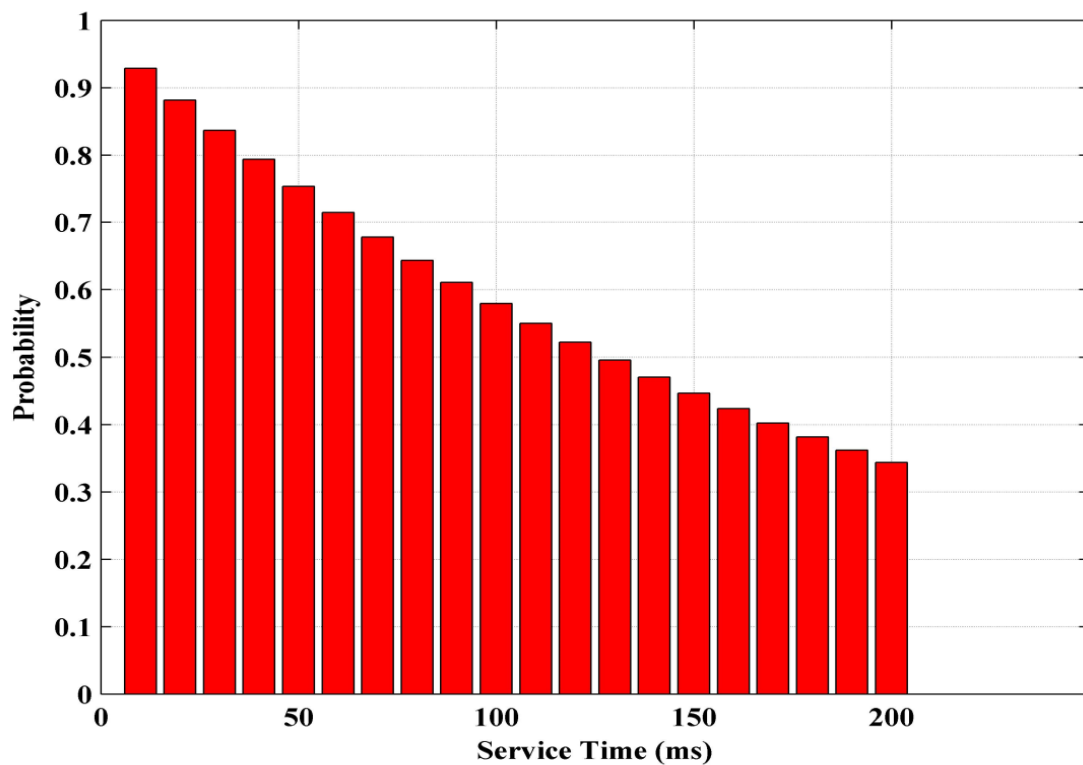


Figure 5.2: Performance results of the proposed model over $n = 20$

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5.2.1.2 Numerical Results over 30 Nodes

The calculation process is the same as the previous section. Therefore, the probabilities were calculated with the help of equations (5.6), (5.7), (5.8), and (5.9) where $n = 30$.

The probabilities values were obtained as illustrated in Table 5-4:

P_{Emp}	P_{Suc}	P_{Col}	P_{Bus}	P_{Own}
0.3617	0.3617	0.0125	0.2517	0.0125

Table 5-4: Probability values over $n = 30$

To obtain the real value of x it is necessary to calculate the roots of the equation (5.14). This can be done easily, by converting it into polynomial equation and then a real root is obtained using Maple software as shown in the equation (5.20) and the equation (5.21).

Therefore, by substituting $e^{X.50.10^{-6}} = t$, and solving the equation (5.14) as follows:

$$0.3617t + 0.2517t^9 + 0.0125t^{10} + 0.3617t^{188} = 1 \quad (5.20)$$

$$0.3617t + 0.2517t^9 + 0.0125t^{10} + 0.3617t^{188} - 1 = 0 \quad (5.21)$$

This equation also has 188 possible solutions. Therefore, Maple program will be used for the numerical calculations to find the roots of the equation (5.21). However,

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$t = e^{x.50.10^{-6}}$. Therefore, the value of x can be obtained using Maple program as follows, $x = 3.5$.

In addition, by obtaining x value then the value for μ can be obtained by the equation (5.15). Finally, the values for x and μ have been used to solve the equation (5.12) during the interval service time between 0 and 200 ms. Figure 5.3 presents the results between the probability distribution and time interval as a histogram.

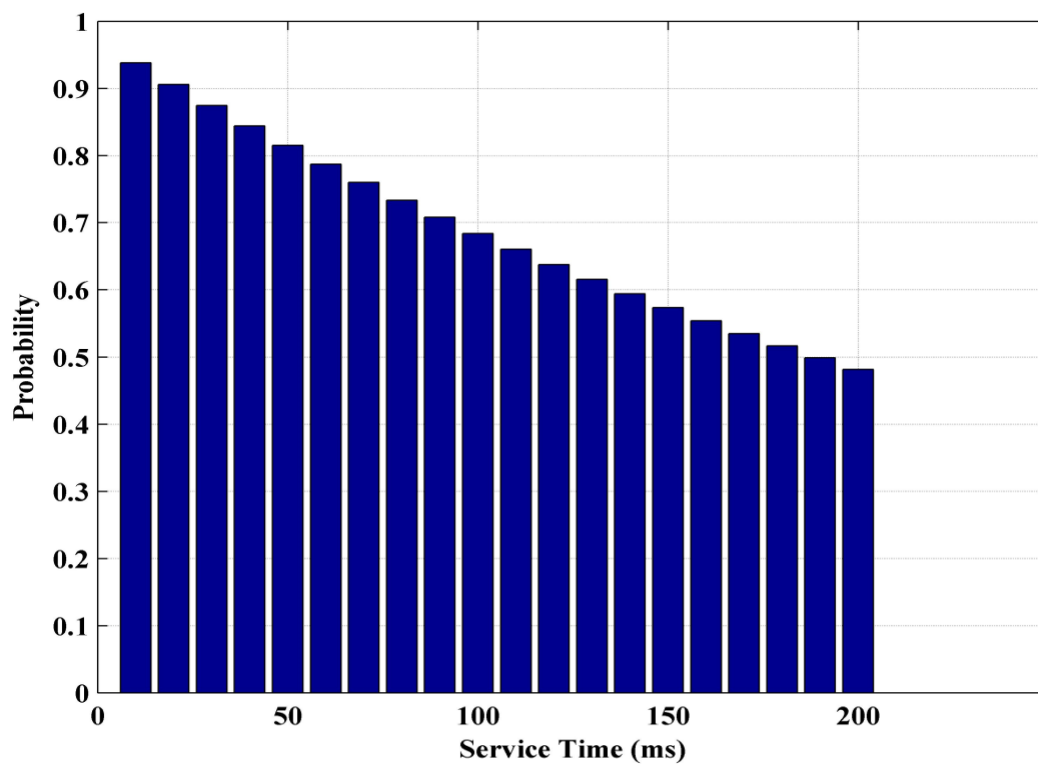


Figure 5.3: Performance results of the proposed model over $n = 30$

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5.2.2 Model Validation

In this section, the performance results of the proposed analytical model are compared with the wireless network behaviour based on the work of Bianchi (2000). Furthermore, the performance results are also compared with the previous related work of Ivanov et al. (2011). In this case, the same system parameters and assumptions have been used as in the previous related work for τ_{tr} and τ_{nb} ; both are considered the same as τ value in the work of Bianchi (2000) as follows:

$$P = 1 - (1 - \tau)^{n-1}, \quad (5.22)$$

$$\tau = \frac{2}{1 + CW + P \cdot CW \cdot \sum_{i=0}^{m-1} 2^i P^i}, \quad (5.23)$$

where CW is the minimum contention window, and m represents the maximum backoff stage.

The system parameters used for both the proposed analytical model and the simulation experiments are illustrated in Table 5-1. Figures 5.4 and 5.5 present the knowledge of the possible estimation for packet delay distribution using Equation (5.16) and Equation (5.17). Each station requires $8200 \mu s$ to transmit 8184 bits of data packet length through a 1 Mbps wireless channel. A MATLAB simulation experiment runs models 20 minutes of work of a real wireless network, and all results are averaged over 20 iterations.

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As can be seen from the figures, the analytical results closely match those obtained from the simulation experiments of the behaviour of IEEE 802.11 DCF standard, which validates the accuracy of the proposed model. These results present the packet delay right tail distribution function (RTDF), where $(RTDF(x) = P(X > x))$ for $x \in \mathcal{R}$ probability that packet delay exceeds x). In these experiments, the errors do not exceed 0.0082 for networks of 20 nodes and 0.0025 for networks of 30 nodes.

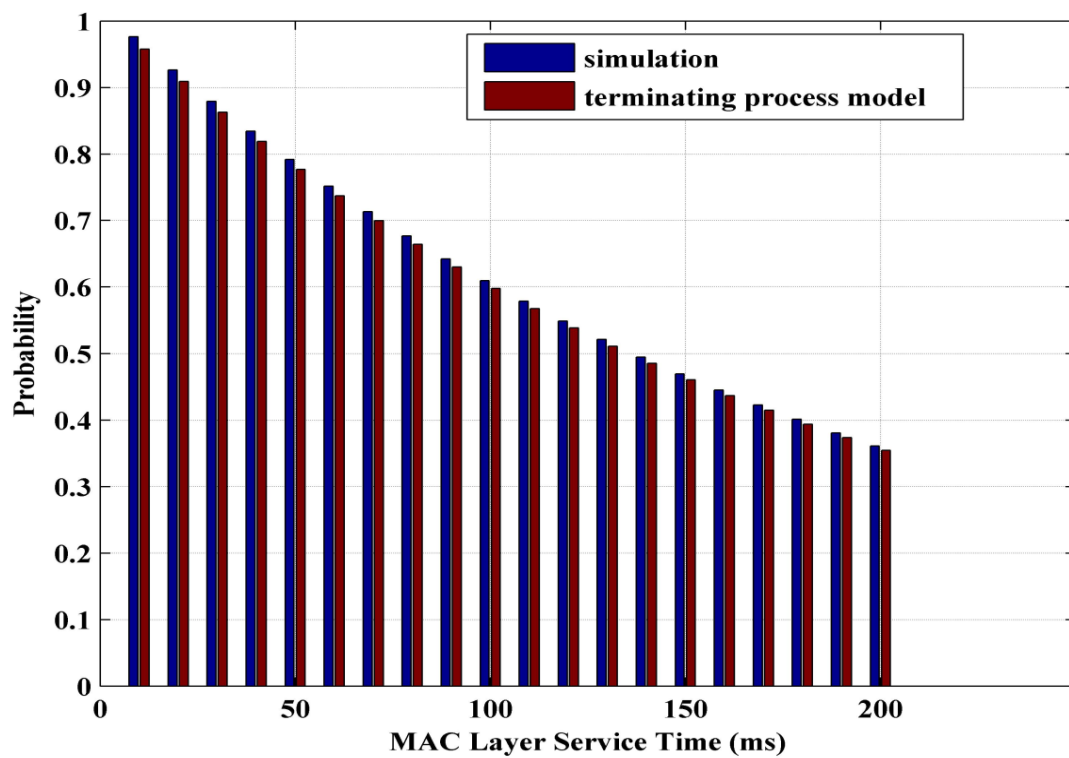


Figure 5.4: Performance comparison between the proposed model and IEEE 802.11 DCF simulation over $n = 20$

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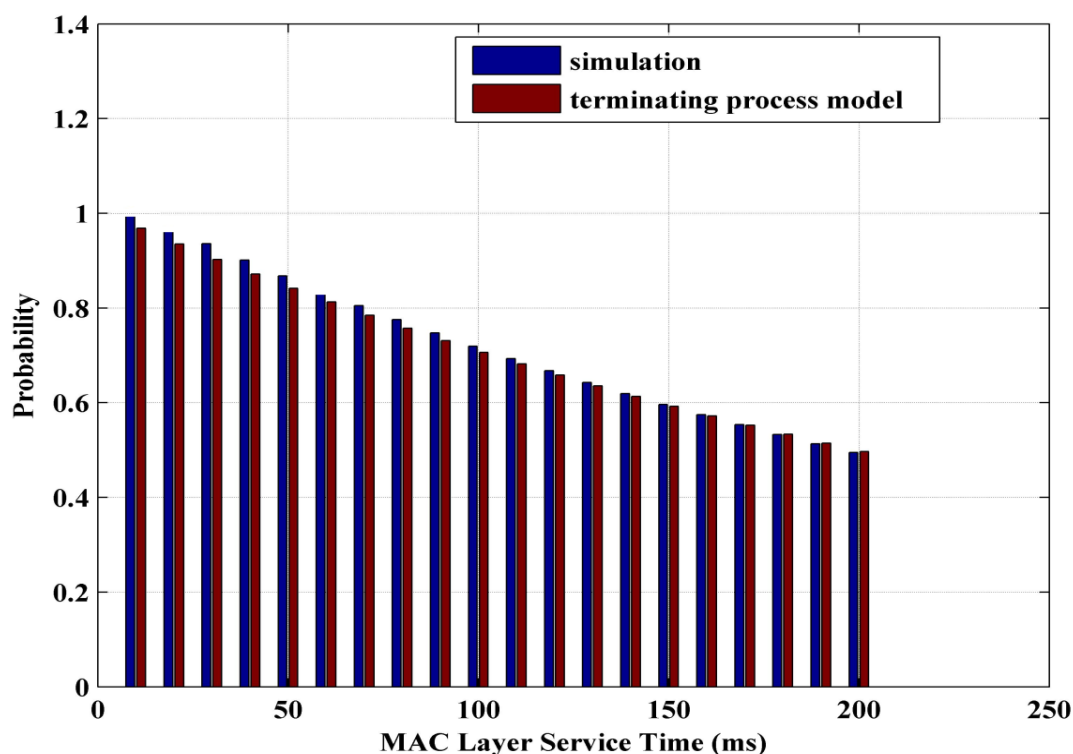


Figure 5.5: Performance comparison between the proposed model and IEEE 802.11 DCF simulation over $n = 30$

Table 5-5 demonstrates that the proposed model can achieve better accuracy than the previous work of Ivanov et al. (2011), where the errors were 0.0332 for networks of 20 nodes and 0.0235 for networks of 30 nodes. On the other hand, the proposed model and the previous work of Ivanov et al. (2011) agree strongly about the effects for D_{Emp} , D_{Col} and D_{Bus} are minor in comparison to that of D_{Suc} . Furthermore, the proposed analytical model provides an accurate method for estimating the MAC layer packet delay distribution.

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Network Nodes (n)	Error Comparison under 200 ms	
	Proposed Model	Previous Model
20	0.0082	0.0332
30	0.0025	0.0235

Table 5-5: Performance comparison between the proposed model and previous model

5.3 Summary

In this chapter, the packet delay distribution based on the MAC layer has been studied. However, the MAC layer provides a way for channel access. Therefore, several events can happen during the channel access and may cause delay during transmission. In this study, the terminating renewal process theory for modelling the MAC layer packet delay distribution of IEEE 802.11 DCF was used. In addition, the proposed solution considered the difference between the busy probability and the collision probability, which will lead to improvement of the accuracy for estimating the MAC layer packet delay distribution for single-hop wireless network.

The motivation of this chapter was to prove that the model considering the difference between the busy probability and the collision probability can help to guarantee an accurate analytical model for estimating the MAC layer packet delay distribution of IEEE 802.11 DCF. However, the delay is a very important parameter to guarantee the

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QoS. Consequently, the proposed model may enable the capture of the behaviour of the MAC layer packet delay distribution of IEEE 802.11 DCF, which can support the QoS of IEEE 802.11 DCF standard.

The simulation results showed that the proposed analytical model provides a good agreement with IEEE 802.11 DCF behaviour simulation experiment. Furthermore, the proposed model provides prediction of high quality as expected. The above research work has been published in (Alkadeki et al. 2013c). The following chapter will present the performance enhancement of IEEE 802.11 DCF by proposing a new backoff algorithm under non-saturated traffic load conditions.

Improving Performance of IEEE 802.11 DCF by a Dynamic Control Backoff Algorithm under Unsaturated Traffic Loads

6.1 Backoff Strategy

In this section, the proposed algorithm is discussed in detail. The discussion starts by describing the principle behind the proposed algorithm in terms of mechanism and traffic load conditions.

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6.1.1 Principle of the Proposed Algorithm

As mentioned in the previous literature review (Chapter 2), most existing models do not consider traffic loads under non-saturated conditions, and thus do not take into account practical network operation. In this section, a new backoff algorithm is proposed, called the dynamic control backoff time algorithm (DCBTA). The DCBTA is implemented under non-saturated traffic loads using the equilibrium point analysis (EPA) model in the work of Wang et al. (2009). This is because the EPA model provides a very convenient way to evaluate the system performance under non-saturated traffic loads. Therefore, the presentation of the DCBTA algorithm under more flexible traffic sources is enabled. Furthermore, it is possible to investigate the network traffic load conditions under a different number of stations.

In the DCBTA, channel conditions are checked by a CW threshold ($CW_{Threshold}$). The $CW_{Threshold}$ value serves as a reference point for the collision rate. Therefore, $CW_{Threshold}$ plays a major role in the proposed algorithm as illustrated in Figure 6.1. The $CW_{Threshold}$ value is dependent on the maximum contention window size (CW_{max}), where the value of $CW_{Threshold}$ is equal to half that of CW_{max} . For example, the value of CW_{max} in (Wang et al. 2009) was selected to be 1024. In this case, the value of $CW_{Threshold}$ is set to 512.

Figure 6.1 shows that the proposed algorithm enables the detection of heavy or light traffic load using the $CW_{Threshold}$ value. After every unsuccessful transmission, if the CW size is smaller than the $CW_{Threshold}$ value, that is, a light traffic load, the CW size is doubled as ($2 \times CW$) similar to the BEB algorithm. Conversely, if the CW size is greater than $CW_{Threshold}$, that is, a heavy traffic load, the CW size is doubled and incremented by two as ($2 \times CW + 2$). Adding two to double the CW size leads to a decrease in the

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collision probability, thus increasing system throughput. A summary of this discussion is given below:

- **Light traffic load:**

If ($CW_i \leq CW_{Threshold}$)

Successful transmission: $CW_i = CW_{i-1} - 1$;

Else ($CW_i = CW_{i-1} \times 2$).

- **Heavy traffic load:**

If ($CW_i > CW_{Threshold}$)

Successful transmission: $CW_i = CW_{i-1} - 2$;

Else ($CW_i = CW_{i-1} \times 2 + 2$).

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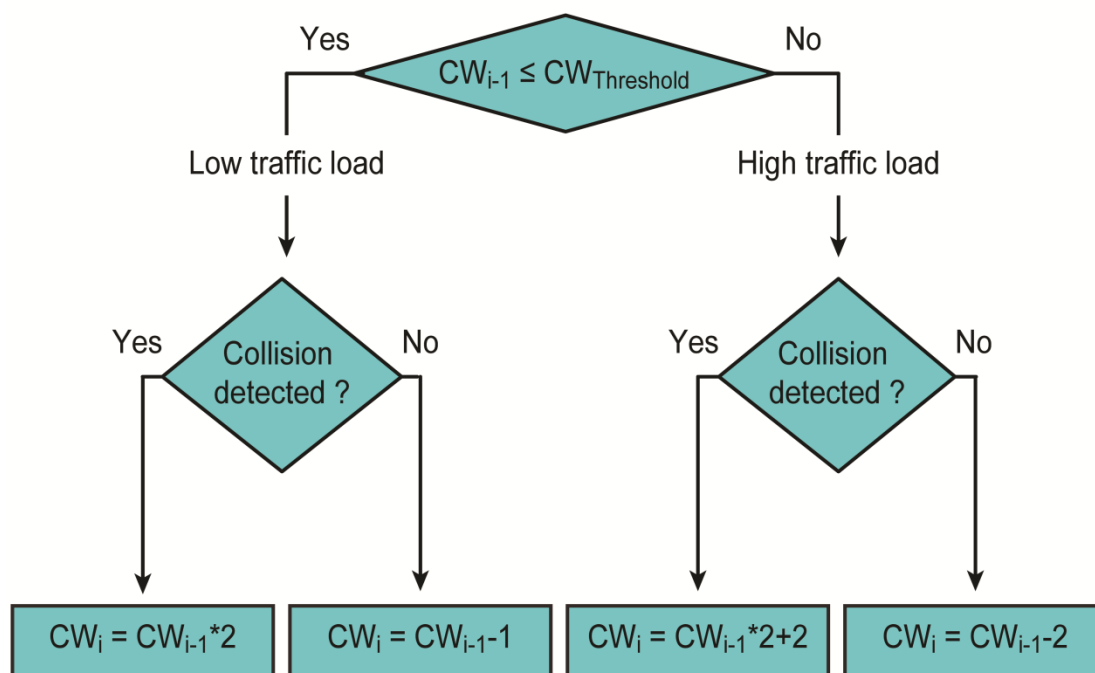


Figure 6.1: Underlying mechanism of the proposed algorithm (DCBTA)

6.1.2 DCBTA under EPA Model

As mentioned in the Methodology Chapter, the traffic load generated by each station follows the Poisson distribution with rate $t/\text{packets}$. Thus, the packet transmission probability (R) plays a pivotal role in the EPA model mechanism. In networks with a large number of nodes or a high collision rate, the proposed algorithm results in a very low probability of transmission. In this case, the CW size increases to more than the threshold size, resulting in a high traffic load. The throughput formula is the same, where R_i is calculated as follows:

$$R_i = \frac{1}{2^i CW_{min} + 2}$$

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Otherwise, the value of CW_i decreases to less than or equal to the threshold value, resulting in a low traffic load. Then, R_i is calculated in the same way as the BEB algorithm under the EPA model. In the case of successful transmission, the CW_i size decreases gradually to avoid performance degradation. However, if the CW_i size is less than or equal to $CW_{Threshold}$, the CW size for the next stage CW_{i+1} is decremented by one as follows:

$$CW_i = CW_{i-1} - 1$$

If CW_i is greater than $CW_{Threshold}$, CW_{i+1} is decremented by two as follows:

$$CW_i = CW_{i-1} - 2$$

6.2 Performance Evaluation

In this section, the proposed backoff algorithm is compared with related algorithms in terms of throughput and average packet transmission delay. The comparative evaluation of backoff algorithms is carried out using MATLAB simulation experiments.

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6.2.1 Simulation Settings

The proposed and related algorithms are implemented based on the EPA model assumption in the work of Wang et al. (2009). Therefore, there are no hidden terminals and system performance can be investigated under more flexible traffic sources with fixed packet length. The different system parameters used in the simulation experiments are summarised in Table 6-1.

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Table 6-1: System parameter settings for the performance evaluation of the proposed algorithm (Wang et al. 2009)

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6.2.2 Comparison of Throughput

System performance of the proposed algorithm (DCBTA) is compared with that of the BEB algorithm under non-saturated traffic load conditions in the work of Wang et al. (2009). In addition, the performance of DCBTA is compared with other related algorithms, such as ELBA in the work of Lin et al. (2008). ELBA combines both exponential and linear algorithms, which is why it was selected for comparison with the proposed algorithm. The number of nodes is set to 50; the maximum number of backoff stages equals six. Figure 6.2 illustrates the throughput performance for DCBTA compared with the BEB algorithm and ELBA under various traffic load conditions. The results show that the throughput performance of DCBTA is better than that of the BEB algorithm and ELBA under various traffic loads.

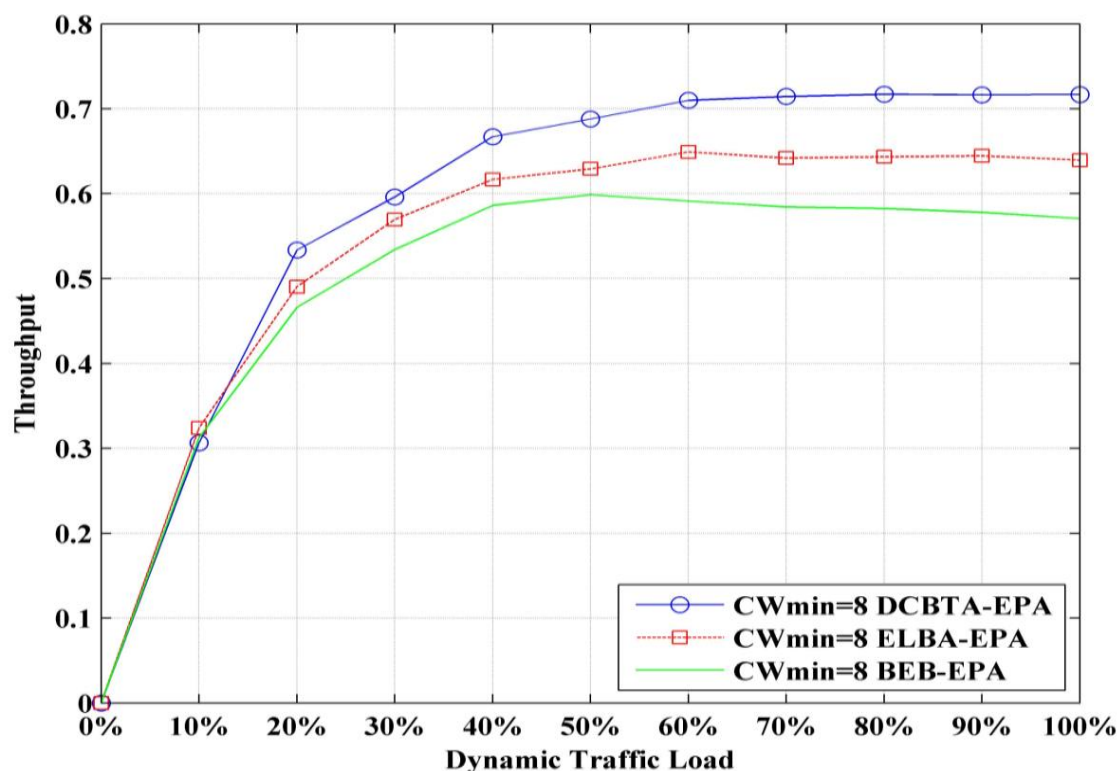


Figure 6.2: Non-saturated throughput comparison of the proposed algorithm and various related backoff algorithms, where ($CW_{min} = 8$, $m = 6$)

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To investigate the impact of using different CW_{min} size, Figure 6.3 plots the throughput performance for DCBTA, BEB, and ELBA with a varying size of 8, 16, and 32 CW_{min} . The throughput increases when CW_{min} increases, since increasing CW_{min} contributes to collision avoidance. Moreover, system throughput depends on the incoming data (Alam et al. 2013). Therefore, the throughput result is equal to the increase in the incoming traffic data rates if the traffic load is low. Otherwise, throughput becomes saturated if the amount of data is sufficiently high. Hence, the system performance strongly depends on system parameters, such as CW_{min} and m .

Figure 6.3 clearly shows that DCBTA provides better throughput results than BEB and ELBA with different CW_{min} size under various offered loads. The DCBTA allows the stations to adjust CW value appropriately according to the traffic load variation within the network. This means that the DCBTA mechanism can reduce the number of collisions, which will lead to increased system throughput. In addition, the performance results show that DCBTA has lower performance degradation than BEB and ELBA. The reason for this is that the CW size decreases gradually after every successful transmission.

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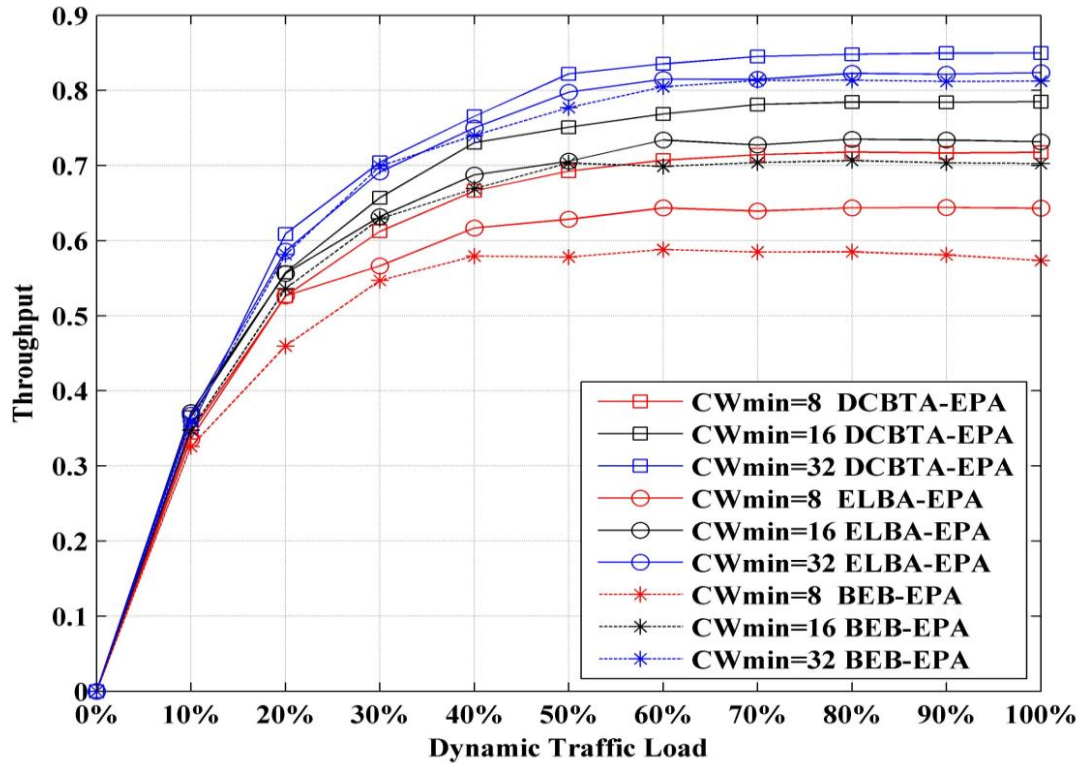


Figure 6.3: Non-saturated throughput comparison of the proposed algorithm and various related backoff algorithms with varying CW_{min} (8, 16, 32), $m = 6$

6.2.3 Comparison of Delay

In the work of Wang (2009), the EPA model represented the MAC channel in idle, transmission, and collision states under varying traffic load conditions. The MAC channel was proposed as a multi-dimensional discrete-time Markov chain analysis model. Therefore, the delay can be represented as a sequence of discrete-time delays as follows:

$$\text{Average Transmission Delay} = \text{Total Delay} / \text{Total number of Transmissions},$$

where:

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- Total Delay = Total Transmission Time + Total Time Delay in the Collision + Backoff Time + Empty Slot.
- Total Transmission Time = Transmission Time of single Packet * Total number of Transmissions.
- Transmission Time of single Packet = RTS + SIFS + CTS + SIFS + Data + SIFS + ACK + DIFS.
- Total Time Delay in the Collision = Delay Time of single Collision * Total number of Collision.
- Delay Time of Single Collision = RTS + DIFS.

Average packet transmission delays for the BEB algorithm, ELBA, and DCBTA are calculated over 100 stationary nodes. For further investigation, the performance of algorithms is also examined under different CW_{min} values of 32, 64, and 128. All the assumptions and system parameters related to this experiment are the same as in the previous section. Figure 6.4, Figure 6.5, and Figure 6.6 show the delay comparison of the BEB, ELBA, and DCBTA algorithms under the EPA unsaturated model. The increment in CW size in the BEB and ELBA algorithms results in greater delay compared to that of the DCBTA algorithm. This means that the DCBTA mechanism produces a small delay by reducing a collision rate. Actually, when there is a high offered traffic load, the CW size should be kept large to avoid frequent collision. Moreover, DCBTA reduces CW size more slowly after successful transmission in

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order to avoid the collision probability. For these reasons, it can clearly be seen that the proposed algorithm has a smaller average transmission delay than that of the BEB and ELBA algorithms, as shown in the figures below.

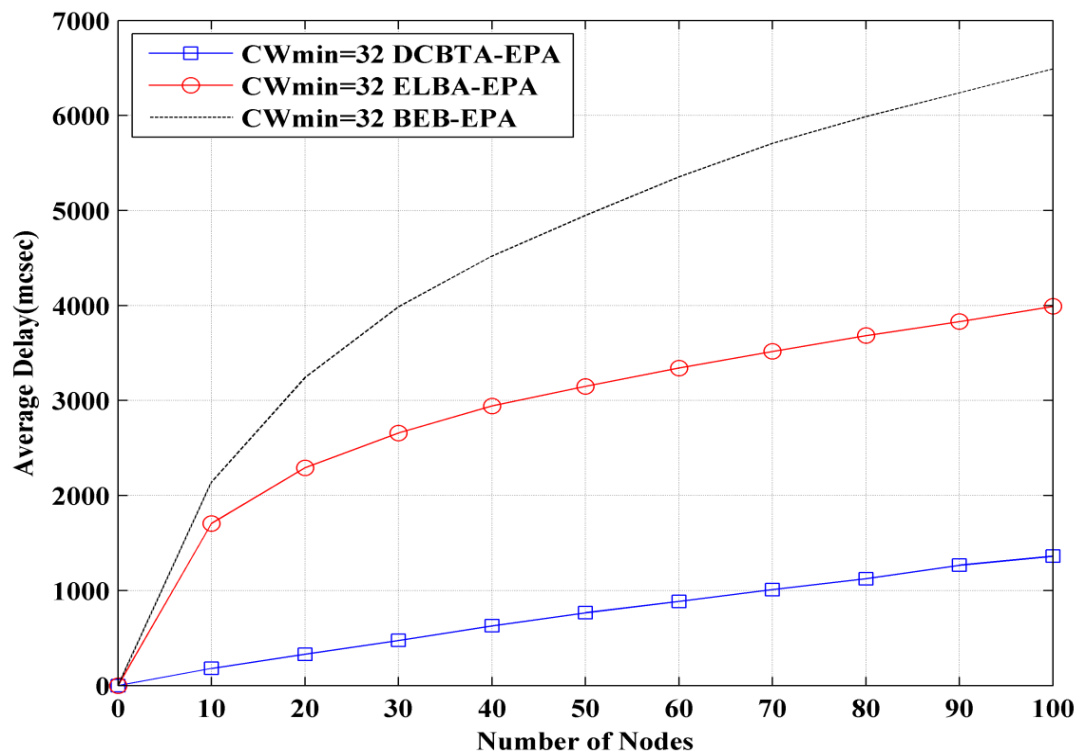


Figure 6.4: Average packet transmission delay with $CW_{min} = 32$, $m = 6$

Chapter 6 : Improving Performance of IEEE 802.11 DCF by a Dynamic Control Backoff Algorithm under Unsaturated Traffic Loads

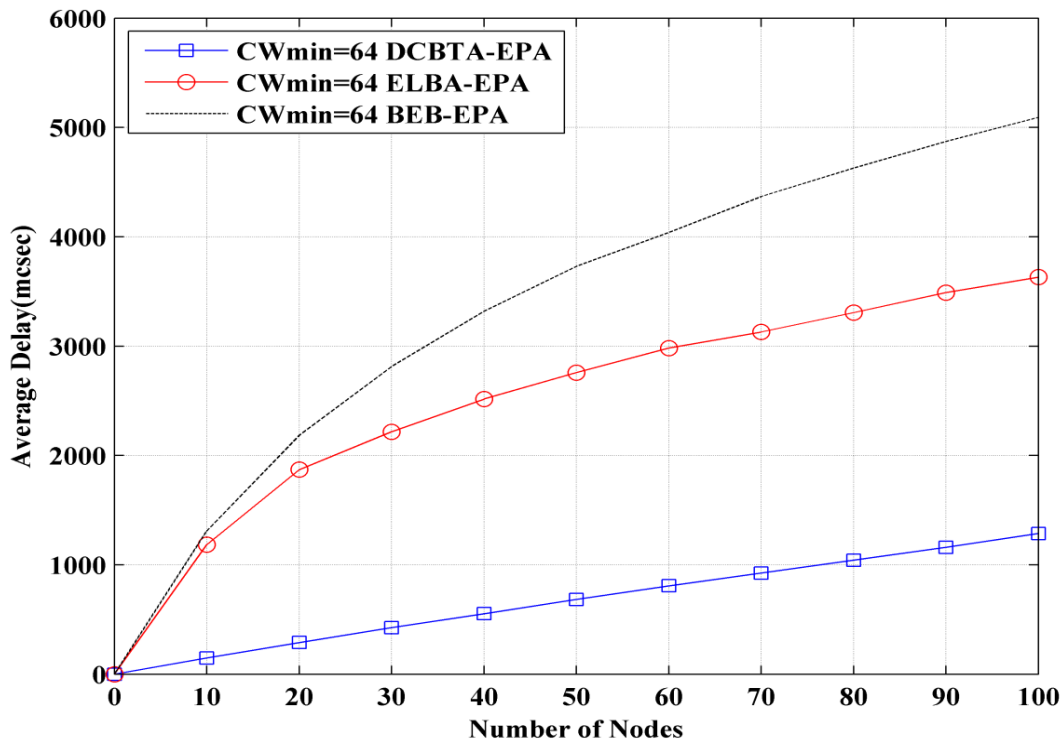


Figure 6.5: Average packet transmission delay with $CW_{min} = 64$, $m = 6$

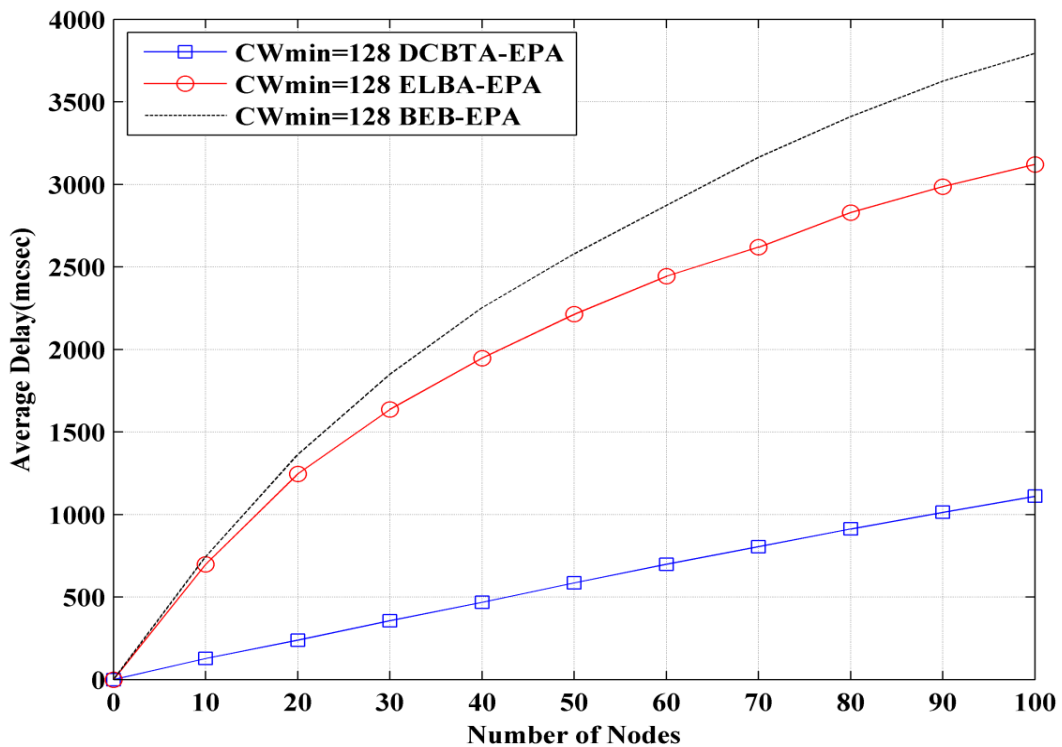


Figure 6.6: Average packet transmission delay with $CW_{min} = 128$, $m = 6$

Chapter 6 : Improving Performance of IEEE 802.11 DCF by a Dynamic Control Backoff Algorithm under Unsaturated Traffic Loads

6.3 Summary

In this chapter, a new backoff algorithm under non-saturated traffic load conditions was proposed to represent actual network situations. A suitable model was selected to evaluate system performance under non-saturated traffic loads such as the EPA model.

The motivation of this chapter was to enhance the performance of the IEEE 802.11 DCF under non-saturated traffic load conditions in terms of system throughput and time delay. To realize this, a new backoff algorithm was proposed and then integrated with the EPA model.

The simulation results showed that the proposed algorithm (DCBTA) improves the system throughput compared with BEB algorithm and ELBA algorithm. In addition, simulation results show that the proposed algorithm (DCBTA) presents better system throughput than the BEB algorithm and ELBA. In addition, calculation of the average packet transmission delay for each algorithm shows that the DCBTA provides a better time delay than the BEB algorithm and ELBA. This is because the DCBTA decreases the time delay, which leads to an increase in system throughput. However, throughput and delay are both relevant for QoS. Therefore, the proposed algorithm may help to enhance QoS of the IEEE 802.11 DCF. To support QoS, a possible further extension of the DCBTA would be to consider the optimum threshold for *CW* size. The above research work has been submitted to Ad hoc and Sensor Wireless Networks journal for publication. The following chapter will conclude the research work and discuss the possible future work.

Conclusions and Further Work

This research work has provided very important theoretical and experimental evidence in the performance modelling and enhancement of IEEE 802.11 DCF. The research work involved three main tasks. The first task was focused on the performance evaluation model of IEEE 802.11 DCF, and the second task was to propose an accurate analytical model for estimating the MAC layer packet delay distribution for IEEE 802.11 DCF. Finally, the third task was to enhance the system performance of IEEE 802.11 DCF in terms of throughput and delay. The scenarios of saturated and non-saturated traffic load conditions have been taken into account throughout this research work.

As a result, this chapter discusses the research objectives which have been met and concludes the research work undertaken in this thesis. This chapter also provides the possible direction for future work.

Chapter 7 : Conclusion and Further Work

7.1 Major Contributions

The main achievements in this research work are summarised as follows:

- A new analytical model has been developed for computing a packet transmission probability of IEEE 802.11 DCF under saturated traffic load conditions. The differences between the busy probability and the collision probability have been taken into account through the analytical model. The analytical results demonstrated that the total of stationary probability of the developed model has proved it is equal to one and then the formula for computing the packet transmission probability has been derived.
- The developed model has been used to evaluate the system throughput of IEEE 802.11 DCF under saturated traffic load conditions. The throughput results have highlighted the importance of taking into account the differences between the busy probability and the collision probability in transmission mechanism for the accurate evaluation of the system performance model in IEEE 802.11 DCF. The accuracy of the proposed model is validated through the extensive experiment comparison of the analytical performance results with those obtained from simulation experiments and original performance model.
- An accurate analytical model for estimating the MAC layer packet delay distribution for IEEE 802.11 DCF has been developed under saturated traffic load conditions. This model was developed based on the differences between the busy probability and the collision probability in transmission mechanism.

Chapter 7 : Conclusion and Further Work

The results have demonstrated that the developed analytical model has presented a good agreement with IEEE 802.11 DCF simulation. Furthermore, the developed analytical model has demonstrated better accuracy results than previous related work of Ivanov et al. (2011).

- A novel backoff algorithm for IEEE 802.11 DCF has been proposed under non-saturated traffic load conditions. The algorithm is proposed to enhance both delay and throughput performance of IEEE 802.11 DCF. In particular, the EPA model is used to demonstrate the algorithm under non-saturated traffic load conditions. The extensive simulation experiments have demonstrated that the proposed algorithm delivered better system performance than other related algorithms.

The simulation experiments and validation of the above proposed models and algorithm have been carried out using MATLAB. In addition, Maple has been used to undertake calculation of certain equations such as polynomial equations and exponential equations.

7.2 Limitations of the Research Work

The thesis mainly aimed to investigate and enhance the performance modelling of IEEE 802.11 DCF. Although this research work has achieved its aims and main objectives, the limitations of this research work are detailed below:

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- **Length of data packets:**

In this research work, the data frame payload size has been considered a fixed size. This is because the research work has paid great attention to the impact of the probabilities according to the possible events during the backoff transmission mechanism of IEEE 802.11 DCF. In addition, the system parameter settings which were used to propose the models or algorithm assumed that the packet length of data frame payload to be fixed. For example, the proposed algorithm implemented under EPA model, which is an analytical tool, used a fixed data packet length.

- **Hidden nodes:**

This research work is based on IEEE 802.11 DCF single-hop WLANs. In this case, all stations can communicate with each other directly. Therefore, the hidden nodes were ignored in this thesis. This is because the problem of hidden nodes is well-known in multi-hop rather than single-hop WLANs. In addition, the system parameter settings that were used to propose the models or algorithm assumed that the channel is in an idle condition (i.e. no hidden nodes).

- **System parameters:**

The system parameters adopted in this research work have followed the IEEE 802.11 standard (IEEE 1999), such as the work in (Bianchi 2000, Wang et al. 2009, Ivanov et al. 2011). These system values were used to perform experiments in terms of modelling and validation. This is because most existing models are based on those parameters. Therefore, those parameters have been used in order to compare the proposed model with other related

Chapter 7 : Conclusion and Further Work

models. However, recently the timeslots of realistic system parameters are five times shorter than those parameters. Thus, realistic parameters should be considered in future work.

7.3 Conclusion

This thesis has presented a number of contributions to the field of WLANs performance modelling, especially to the enhancement of the performance modelling of IEEE 802.11 DCF. As stated in Section 7.1, the aims and objectives of this research work have been met successfully. In this research work, a two-dimensional Markov chain analysis model was selected to analyse the behaviour of a single station, as the backoff timer and the backoff stage can be very clearly represented. In order to investigate the impact of considering the difference between the busy probability and the collision probability on the system performance, a new analytical model for computing a packet transmission probability of IEEE 802.11 DCF has been proposed. Most existing work for analytical model ignores the busy probability that can lead to inaccurate results of the system performance. Thus, the proposed model has used to evaluate the saturated throughput of IEEE 802.11 DCF. The performance results highlight the importance of taking into account the differences between the busy probability and the collision probability in transmission mechanism for an accurate evaluation performance model.

Furthermore, the differences between the busy probability and the collision probability in the transmission mechanism have been used to propose an accurate analytical model for estimating the MAC layer packet delay distribution of IEEE

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802.11 DCF. The terminating renewal process theory has been used in order to represent the MAC layer packet delay as sequence of discrete random variables terminated by successful transmission. The packet delay right tail distribution function results of the proposed model demonstrate a good agreement with the wireless network behaviour simulation. Therefore, the proposed model presents an accurate method for estimating the MAC layer packet delay distribution for IEEE 802.11 DCF.

This research work has also highlighted other issues relating to the enhancement of the system performance for IEEE 802.11 DCF. A review of the analysis of IEEE 802.11 DCF has led to the proposal of a new backoff algorithm in order to enhance the system performance by reducing the delay through the transmission mechanism. In addition, most existing models are based on saturated traffic load conditions which are not a new representation of network conditions. Therefore, the new backoff algorithm has been implemented under various traffic load conditions, which are a real representation of actual network conditions. In particular working environments, the EPA model is used to implement the algorithm under non-saturated traffic load conditions. The performance results have shown that the proposed algorithm offers better system performance than other related algorithms. Moreover, the extensive simulation experiments have demonstrated that the proposed algorithm can work very well under non-saturated traffic load conditions.

However, this research work has paid great attention to the enhancement of the system performance in terms of throughput and delay, which are both relevant for the QoS. Therefore, this research work can lead to the improvement of the QoS in IEEE 802.11 DCF.

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7.4 Future Work

This research work has produced several interesting ideas, which can be used to extend the proposed models and algorithm or may even recommend possible developments in WLANs, as follows:

- The performance modelling and the analysis of IEEE 802.11 DCF have presented very important theoretical and practical works in the design and enhancement of WLANs. Based on analytical modelling development, this research work has proved that there is a significant difference between the busy probability and the collision probability, especially in term of transmission mechanism. This difference can be taken into account to investigate and propose:
 - Analytical model under non-saturated traffic loads.
 - Delay model.
 - Packet delay and transmission energy analysis.
 - Energy consumption model.
 - Guarantee the QoS for real time application in WLANs.
- This research work has paid great attention to the behavior of the single station, which is enabled us to capture and investigate the behavior of the MAC in terms of the system throughput and the access delay. Therefore, this research work has proposed an accurate analytical model for estimating the

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MAC layer packet delay distribution for IEEE 802.11 DCF single-hop network. However, the MAC protocol design presents more challenge to multi-hop than single-hop WLANs (Hoang et al. 2014, Sanada et al. 2015). Consequently, possible further work will seek to obtain the packet delay distribution over multi-hop wireless networks.

- The proposed algorithm is based on using the $CW_{Threshold}$. The size for the $CW_{Threshold}$ is dependent on the CW_{max} , where the value of $CW_{Threshold}$ size equals the half value of the CW_{max} size. Possible further work of the proposed algorithm can be done to take into account the optimum threshold of the CW size.

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Appendix-A

Appendix A: Project Management

A.1 Organization of the Study

As mentioned in the previous Methodology Chapter, the research life cycle was conducted in five stages. Each stage led to the production of a specific chapter or more.

These stages can be summarised as follows:

- **Literature Review:**

The data collection from the literature review was used to inform and propose the research questions, the research approach and define the gap in knowledge.

The information obtained throughout the literature review has also informed the chapters, namely Chapter 1, Chapter 2 and Chapter 3.

- **Modelling:**

The practical research work was started by a mathematical modelling design to enhance the gap in knowledge of IEEE 802.11 DCF. Therefore, this stage is covered in detail through results and discussion chapters, specifically Chapter 4, Chapter 5 and Chapter 6.

- **Implementation:**

The proposed works were implemented through this stage using software. The implementation stage is referred to and discussed throughout the results and discussion chapters, namely, Chapter 4, Chapter 5 and Chapter 6.

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- **Validation:**

The aforementioned implementation stage was validated through this step by comparing the analytical results with the simulation results, or by comparing with other related work. If the result showed good progress in improving the gap in knowledge, then the research work would be accepted it. Otherwise, the previous stages would be necessary to investigate again. Therefore, this stage is also included in the result and discussion chapters, namely Chapter 4, Chapter 5 and Chapter 6.

- **Acceptance:**

The previous stages are discussed in detail in Conclusion Chapter.

In order to implement the above stages, the research work was conducted in four phases respectively as the following:

- Phase 1.
- Phase 2.
- Phase 3.
- Writing up Stage.

In each phase the data were collected through literature review, modelling and experiments. A specific plan of research work and time management had been assigned to each phase, in order to achieve the objective of this research work and complete the overall thesis by the specified time.

Appendix-A

A.1.1 Phase 1

In the first phase the study was focused on producing the literature review in order to detect the point of weakness in IEEE 802.11 DCF. The collected data were used to propose the project plan, research questions and methods to enhance the performance model of IEEE 802.11 DCF. The following activities were implemented during the first phase:

- **Research Planning:**

This is very important stage in which to organise and document the research work. A good plan will lead to a guarantee of the time management schedule for the completion of overall research work, quality work and documentation. Therefore, the plan had been prepared during the beginning of study to ensure achievement of the objectives within an agreed period of time. A Gantt chart was used to manage the plan and show the research tasks schedule.

- **Initial Literature Review Preparation:**

Throughout this stage the previous works relating to the performance modelling and enhancement of IEEE 802.11 DCF were analysed and evaluated. The literature review and the initial research questions were drafted.

- **Methodology:**

The methodology approach was selected based on a review of the information collected from the literature review and checked against the research questions. The literature review confirmed that the best way to undertake this research work would be through the use of a quantitative approach. This is because the

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best way to approach enhancement of the performance models of WLANs is by using mathematical modelling and computational program.

- **Data Collection:**

Through this stage the data were collected from the literature review and supervisor team discussion.

- **Data Analysis:**

The data collection was used to understand and identify the idea to enhance the point of weakness in IEEE 802.11 DCF. The research questions relevant to the objectives were asked and confirmed based on the data collected and analysed.

- **Implementation:**

After the data had been analysed were used to implement the research work. This stage was divided into two parts:

- Modelling.
- Programming.

Throughout Phase 1, modelling and calculations were done. Also in this phase, the performance modelling of IEEE 802.11 DCF was implemented based on the difference between the busy probability and the collision probability in transmission mechanism. The Markov chain analysis model was used for modelling purpose. Then the MATLAB program was used to prove the total of stationary probabilities is equal to one.

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- **Final Phase Preparation:**

At the end of each phase, progress was checked by the progress review panel members (PRP 1). In addition, the presentation and the research plan were presented during the end of the phase.

A.1.2 Phase 2

In the second phase the study had completed the previous work by proposing model validation as the following:

- The analytical performance results were proposed and compared with the proposed model simulation results using MATLAB.
- The performance model was also evaluated and compared with other related model using MATLAB.

In addition, an accurate way for estimating the MAC layer packet delay distribution of IEEE 802.11 DCF was proposed using the Markov chain analysis model and terminating renewal processes theory. Maple program was used to undertake some calculation of the equations. Then the MATLAB was used to implement and validate the proposed model as the following:

- The proposed analytical model results were implemented and compared with the behavior of IEEE 802.11 DCF.
- The performance model was evaluated by comparing with other related model such as work of Ivanov (2011).

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Finally, phase completion was achieved by presenting overall progress to, and passing, PRP 2.

A.1.3 Phase 3

In the third phase the study was focused on publishing the previous works. Therefore, a conference paper was created and published through presentation the paper at the International Conference on Networking Applications 2013. In addition, a poster was created and presented through the university symposium. Finally, throughout this phase, two papers were drafted and published in international journals.

Furthermore, the study in Phase 1 and Phase 2 were focused on the performance model of IEEE 802.11 DCF under saturated traffic load conditions. Therefore, the study in Phase 3 paid attention to studying the performance model of IEEE 802.11 DCF under non-saturated traffic load conditions. A new backoff algorithm for IEEE 802.11 DCF under non-saturated traffic load conditions was proposed. The proposed algorithm was implemented and compared with other related algorithms in terms of throughput and average packet transmission delay using MATLAB. Finally, phase completion was completed by presenting overall progress to, and passing, PRP 3.

A.1.4 Writing up

This is the final stage for completion and documentation this research work. All the previous works were drafted and summarised as shown in Figure A.1. In addition, the proposed backoff algorithm was drafted and submitted to journal for publication.

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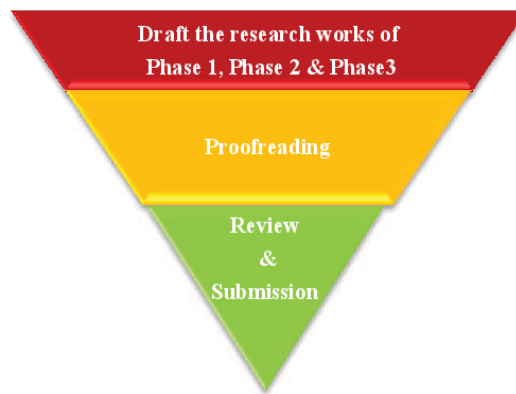


Figure A.1: Writing up process

A.2 Project Timelines

A Gantt chart was used to present the schedule and progress of the research work. All activities and time duration were listed and shown using the Gantt chart. Therefore, the research planning is described within the following subsections.

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A.2.1 Gantt Chart for Phase 1

The following Gantt chart shows the different activities with starting and ending date during the Phase 1:

Tasks	Activities	2011 - 2012											
		J U N	J U L	A U G	S E P	O C T	N O V	D E C	J A N	F E B	M A R	A P R	
1.	Research preparation, planning and Draft literature review.	■											
2.	Attend Module M001 DCR and specific module credits APLeD (45 credits).					■							
3.	Choosing methodology and MATLAB practice.					■							
4.	Data collection and data analysis. Research questions confirmation.						■						
5.	Modelling proposal for packet transmission probability of IEEE 802.11 DCF.							■					
6.	Prove the total stationary probabilities in the proposed model are equal to one.										■		
7.	PRP 1 examination and Phase 1 completion.											■	

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A.2.2 Gantt Chart for Phase 2

The following Gantt chart shows the different activities with starting and ending date during the Phase 2:

Tasks	Activities	2012 - 2013											
		M A Y	J U N	J U L	A U G	S E P	O C T	N O V	D E C	J A N	F E B	M A R	A P R
1.	Analytical proposed model calculation.												
2.	Model simulation.												
3.	Model validation.												
4.	Model evaluation.												
5.	Draft a conference paper.												
6.	Modelling proposal for estimating the MAC layer packet delay distribution for IEEE 802.11 DCF.												
7.	Model simulation.												
8.	Model evaluation and validation.												
9.	PRP 2 examination and Phase 2 completion.												

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A.2.3 Gantt Chart for Phase 3

The following Gantt chart shows the different activities with starting and ending date during the Phase 3:

Tasks	Activities	2013 – 2014											
		M A Y	J U N	J U L	A U G	S E P	O C T	N O V	D E C	J A N	F E B	M A R	A P R
1.	Draft a journal paper 1.												
2.	Draft a journal paper 2.												
3.	EPA model implementation												
4.	Attend an international conference.												
5.	Algorithm proposal for contention window-based IEEE 802.11 DCF.												
6.	Throughput evaluation.												
7.	Delay evaluation.												
8.	PRP 3 examination and Phase 3 completion.												

Appendix-A

A.2.4 Gantt Chart for Writing up

The following Gantt chart shows the different activities with starting and ending date during the Writing up stage:

Tasks	Activities	2014 – 2015											
		M A Y	J U N	J U L	A U G	S E P	O C T	N O V	D E C	J A N	F E B	M A R	
1.	Draft a journal paper 3.	■	■										
2.	Draft chapter 1 and revision.			■									
3.	Draft chapter 2 and revision.				■								
4.	Draft chapter 3 and revision.					■							
5.	Draft chapter 4 and revision.						■						
6.	Draft chapter 5 and revision.							■					
7.	Draft chapter 6 and revision.								■				
8.	Draft chapter 7 and appendix..									■			
9.	Thesis proofreading and references revision.										■		
10.	Revision of thesis and submission											■	

Appendix-A

A.3 Development Activities

Besides the above research activities, other activities were undertaken during the study to ensure the quality of the research work. These included the following activities:

- **Meetings with Supervisory Team:**

A very essential activity to discuss the research work progress or any other issue related to the study. Regular meeting provided a good opportunity for proposing the development plan, problem discussion and reviewing the progress.

- **Seminars and Conferences:**

Attending seminars and/or conferences provided a good opportunity for developing of research skills, updating knowledge and for learning from other people experiences. Therefore, many seminars and conferences were attended during the study, for example:

- World Congress on Multimedia and Computer Science (WCMCS) in 2013 in Tunisia.
- International Conference on e - Business Engineering (ICEBE) in 2013 in UK.
- Research Symposium was held in university in 2014.
- Many local seminars were held in university.

Appendix-A

- **Workshop Attended:**

Attending workshops were very useful to gain the necessary knowledge, research skills and techniques. Different workshops attended during the study included:

- Planning and Drafting your Thesis.
- Ref Works.
- Preparing for your PRP.
- MATLAB for Data Analysis and Advanced Symbolic and Numerical Modelling.
- How to Write a Successful Journal Paper.
- Getting Published.
- Creating a Scientific Poster.
- Time Management and Motivation.
- Preparing for Viva.

Appendix-A

A.4 Summary

In this chapter, the project activities, schedule and planning have been presented. As can be seen from the above description, the research life cycle has been implemented into three phases and documented in the writing up stage. However, the research work is based on modelling and computational program. Therefore, the quantitative approach has been assigned for analysing and summarising data. In order to manage and plan the research work, the Gantt chart has been used to ensure the research stayed on track and achieved the main objectives at specified time. Moreover, many other development activities were taken into account to ensure the quality of the research work.

Appendix-B

Appendix B: Codes for the Proposed Performance Analysis of IEEE 802.11 DCF based on the Busy Probability and the Collision Probability

B.1 Introduction

As mentioned in the Methodology Chapter, MATLAB was used to implement and validate this research work. Appendix B presents the codes that were used to propose and implement the tasks in Chapter 4.

B.2 Analytical Model

Based on the probability theory, the total probability must be less than or equal to one. Therefore, this section presents the analytical model and codes that were used to prove that the total stationary probabilities were equal to one for the proposed model. In addition, the calculation of the packet transmission probability (τ) is presented. Then, τ can be used to evaluate the saturated throughput (S) based on different values of the busy probability (p_b) and the collision probability (p_c).

Appendix-B

```
%.....  
% Analytical model program  
%.....  
  
% clean up the workspace  
clc  
clear all  
close all  
  
% max backoff stage (m) & contention window (W)  
m=3;  
W = 32;  
  
% collision probability ( $p_c$ ) & busy probability ( $p_b$ ), where the probability values are  
random between (0, 1) for example:  
 $p_c = 0.2$ ;  
 $p_b = 0.4$ ;  
  
% allocate the output array  
b = [];  
  
% calculate  $b_{\{0,0\}}$   
% as the MATLAB counted from one, therefore  $b_{\{0,0\}}$  is replaced by  $b_{\{1,1\}}$   
 $W_m = W * 2^m$ ;  
 $b_{(1,1)} = p_c^m / (1-p_c) + 1 / (1-p_b/W_m) * p_c^m / (1-p_c) * (W_m-1) / 2$ ;  
for i = 0:m-1  
     $W_i = W * 2^i$ ;  
     $b_{(1,1)} = b_{(1,1)} + p_c^i + p_c^i / (1-p_b/W_i) * (W_i-1) / 2$ ;  
end  
 $b_{(1,1)} = 1/b_{(1,1)}$ ;
```

Appendix-B

% fill in $b_{\{0,k\}}$ (equation (4.10))

$W_0 = W;$

for $k = 1:W_0-1$

$b_{(1,k+1)} = b_{(1,1)} / (1-p_b/W_0)^*(1-k/W_0);$

end

% fill in $b_{\{i,0\}}$ (equation (4.11))

for $i=1:m-1$

$b_{(i+1,1)} = p_c^i * b_{(1,1)};$

end

% fill in $b_{\{i,k\}}$ (eq. (4.12))

for $i = 1:m-1$

$W_i = W * 2^i;$

for $k = 1:W_i-1$

$b_{(i+1,k+1)} = b_{(1,1)} * p_c^i / (1-p_b/W_i)^*(1-k/W_i);$

end

end

% fill in $b_{\{m,0\}}$ (equation (4.17))

$b_{(m+1,1)} = b_{(1,1)} * p_c^m / (1-p_c);$

% fill in $b_{\{m,k\}}$ (equation (4.18))

for $k = 1:W_m-1$

$b_{(m+1,k+1)} = b_{(1,1)} * (1-k/W_m) / (1-p_b/W_m)^* p_c^m / (1-p_c);$

end

% print the total of probabilities

```
fprintf(' The total probability mass is %f\n ', sum(sum(b)));
```

% MATLAB Result

```
>Result: The total probability mass is 1.000000
```

Appendix-B

% packet transmission probability calculation

$$\tau = b_{(1,1)}/(1-p_c);$$

%.....

% Performance evaluation

%.....

% the obtained value of τ from the above analytical model was used to evaluate the following formula for saturated throughput

$$S = \frac{P_s P_{tr} E[P]}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr} (1 - P_s) T_c}$$

% therefore, defines the parameters as follows:

% number of station

n = [10:10:50];

T_s=8982;

T_c=8713;

EP =8184; % data packet size

$\sigma = 1$; % propagation delay in μs

$\tau_length=length(\tau)$;

for ii=1:1: τ_length

for jj=1:1:5

% transmission probability calculation

$$P_{tr}(ii,jj) = 1-(1-\tau(ii)).^n(jj);$$

% successful transmission probability calculation

$$P_s(ii,jj) = n(jj)*\tau(ii).*(1-\tau(ii)).^(n(jj)-1) / P_{tr}(ii,jj);$$

% saturated throughput calculation

$$S(ii,jj)=P_s(ii,jj).*P_{tr}(ii,jj).*EP/((1-P_{tr}(ii,jj))*\sigma+P_{tr}(ii,jj).*P_s(ii,jj).*T_s+P_{tr}(ii,jj).*(1-P_s(ii,jj)).*T_c);$$

Appendix-B

```
    end
end

% plot the results (Throughput evaluation (S) versus number of stations)
Plot(n, S, '-*');
Xlabel ('Number of Stations (N)');
Ylabel ('Saturation Throughput (S)');
Title ('Performance Evaluation');
grid on;
```

B.3 Model Simulation

This section presents the simulation proposed model.

```
%.....
% main program for model simulation
%.....

% clean up the workspace
clc
clear all
close all

% define the parameters for main program
couter_w = 1;
for w = 32
for t = 1:1:5
n = 10*t; % number of stations which want to transmit
m = 3;
w1 = w*ones (1,n); % contention window
```

Appendix-B

```
m1 = zeros (1,n);
delay_back_off = 0;

% sense channel
% delay
back_off_timer = randi ((w-1),1,n);
new_back_off_timer = back_off_timer;
collision_detection_time = zeros(2,n);
collision_detection_time(1,:) = back_off_timer;
collision_time = zeros(1,n);
transmission_detection = zeros(1,n);
freezed_time = zeros(1,n);
for loop = 1:1:20000
[new_back_off_timer,delay_back_off,freezed_time] = back_off_timer_decrement(
new_back_off_timer,n,delay_back_off,freezed_time );
[new_back_off_timer,m1,w1,back_off_timer,collision_time,collision_detection_time,tra
nsmission_detection]
= check_collision_transmission ( new_back_off_timer,n,w1,m1,m,w,
back_off_timer, collision_detection_time,collision_time,transmission_detection);
end

used_time = sum( transmission_detection )*8184;
total_time = 200;
% saturated throughput calculation
% then the results can be compared with the above analytical results and also with
Bianchi's model simulation.
Throughput (couter_w,t) = used_time / total_time;
end
couter_w = couter_w+1;
end
```


Appendix-B

```
% number of station (50)
```

```
Stations = 10:10:50
```

```
plot (stations,throughput (1,:),'-bs')
```

```
hold on
```

```
Xlabel ('Number of Stations (N)');
```

```
Ylabel (' Saturation Throughput (S)');
```

```
hleg1 = legend ('m=3 w=32');
```

```
%.....
```

```
% check collision transmission ( $p_c$ )
```

```
%.....
```

```
Function[new_back_off_timer,m1,w1,back_off_timer,collision_time,collision_detection  
_time,transmission_detection ] = check_collision_transmission
```

```
(new_back_off_timer,n,w1,m1,m,w,back_off_timer,collision_detection_time,collision_t  
ime,transmission_detection)
```

```
[a,b] = sort (new_back_off_timer);
```

```
for i=1:1:n
```

```
    if (a(i)==0)
```

```
        j=i;
```

```
    end
```

```
end
```

```
if (j>1)
```

```
    for i=1:1:j
```

```
        m1(b(i))=m1(b(i))+1;
```

```
    if (m1(b(i))==m+1)
```

```
        m1(b(i))=0;
```

```
        w1(b(i))=w;
```

```
        new_back_off_timer(b(i)) = randi(w1(b(i)),1,1);
```

```
        collision_time(b(i))= collision_time(b(i))+collision_detection_time(1,b(i));
```

Appendix-B

```
collision_detection_time(1,b(i))= new_back_off_timer(b(i));
collision_detection_time(2,b(i))= collision_detection_time(2,b(i))+1;
back_off_timer(b(i))=back_off_timer(b(i))+new_back_off_timer(b(i));
else
w1(b(i))=(2^m1(b(i)))*w1(b(i));
new_back_off_timer(b(i))=randi(w1(b(i)),1,1);
collision_time(b(i))=collision_time(b(i))+collision_detection_time(1,b(i));
collision_detection_time(1,b(i))=new_back_off_timer(b(i));
collision_detection_time(2,b(i))=collision_detection_time(2,b(i))+1;
back_off_timer(b(i))=back_off_timer(b(i))+new_back_off_timer(b(i));
end
end

else
w1(b(1))=w;
new_back_off_timer(b(1))=randi(w1(b(1)),1,1);
back_off_timer(b(i))=back_off_timer(b(i))+new_back_off_timer(b(i));
collision_detection_time(1,b(1))=new_back_off_timer(b(1));
transmission_detection(b(i))=transmission_detection(b(i))+1;
end
end

%.....
% backoff timer decrement
%.....

Function [ new_back_off_timer,delay_back_off,frezed_time ] =
back_off_timer_decrement( back_off_timer1,n,delay_back_off,frezed_time )
[back_off_timer11,transmitting_station]=sort(back_off_timer1);

for i=1:1:n
if ((back_off_timer1(i)==0)&&(i>1))
min_back_off_timer=back_off_timer11(i+1);
```

Appendix-B

```
channel_busy=1;
else
    min_back_off_timer=back_off_timer11(1);
    channel_busy=1;
end
end
delay_back_off=min_back_off_timer+delay_back_off;
if (channel_busy==1)
    for j=1:1:18
        for i=2:1:n
            % busy probability (frozen period ( $p_b$ )), where the frozen period=
            DIFS+SIFS+ACK=396  $\mu$ s
            freezed_time (transmitting_station(i))=freezed_time(transmitting_station(i))+396;
        end
    end
end
new_back_off_timer=back_off_timer1-min_back_off_timer;
end
```

Appendix-C

Appendix C: Codes for the Proposed Estimation Method of the MAC Layer Packet Delay Distribution for IEEE 802.11 DCF

C.1 Introduction

As mentioned in Chapter 5, the proposed model is based on the terminating renewal process theory. MATLAB was used for the purpose of simulation and Maple was used to undertake certain calculations of the equations. Appendix C presents the codes that were used to propose and implement the tasks in Chapter 5.

C.2 Maple Calculation

This section presents the Maple calculation to obtain the real root of the polynomial equation in terms of 20 and 30 nodes, as shown below in the red rectangular calculation. Then the obtained value of the real root was used to obtain the value of x .

Appendix-C

C.2.1 Maple Calculation over 20 nodes

$$0.3585t + 0.2453t^9 + 0.0189t^{10} + 0.3585t^{188} = 1$$

→ solve for t

```
[[t = 1.000261721], [t = 1.000025105+ 0.03224350599I], [t =
0.9991464781+ 0.06481489720I], [t = 0.9973145160
+ 0.09777942897I], [t = 0.9943159847+ 0.1310144815I], [t
= 0.9900608945+ 0.1643622630I], [t = 0.9845268135
+ 0.1976889069I], [t = 0.9777193476+ 0.2308884259I], [t
= 0.9696545166+ 0.2638743947I], [t = 0.9603521842
+ 0.2965723656I], [t = 0.9498340470+ 0.3289146552I], [t
= 0.9381235039+ 0.3608368354I], [t = 0.9252465296
+ 0.3922751854I], [t = 0.9112335038+ 0.4231646506I], [t
= 0.8961225090+ 0.4534372406I], [t = 0.8799651489
+ 0.4830215606I], [t = 0.8628362563+ 0.5118460344I], [t
= 0.8448470089+ 0.5398524135I], [t = 0.8261508512
+ 0.5670303758I], [t = 0.8069086891+ 0.5934702726I], [t
= 0.7871858206+ 0.6193711206I], [t = 0.7668693560
+ 0.6449218940I], [t = 0.7457489287+ 0.6701568482I], [t
= 0.7236691847+ 0.6949652366I], [t = 0.7005787674
+ 0.7191949435I], [t = 0.6764951991+ 0.7427159822I], [t
= 0.6514653596+ 0.7654315701I], [t = 0.6255448558
+ 0.7872703264I], [t = 0.5987903393+ 0.8081773004I], [t
= 0.5712575778+ 0.8281077795I], [t = 0.5430016710
+ 0.8470235856I], [t = 0.5140780144+ 0.8648910268I], [t
= 0.4845435724+ 0.8816799592I], [t = 0.4544583676
+ 0.8973637563I], [t = 0.4238871621+ 0.9119203246I], [t
= 0.3929011131+ 0.9253346548I], [t = 0.3615785538
+ 0.9376037262I], [t = 0.3300026137+ 0.9487443849I], [t
= 0.2982513226+ 0.9588025935I], [t = 0.2663761948
+ 0.9678561996I], [t = 0.2343755822+ 0.9759967155I], [t
= 0.2021882497+ 0.9832861265I], [t = 0.1697284760
+ 0.9897187354I], [t = 0.1369388680+ 0.9952260863I], [t
= 0.1038156750+ 0.9997161525I], [t = 0.07039913824
+ 1.003107782I], [t = 0.03675241229+ 1.005343345I], [t
= 0.002945988135+ 1.006386999I], [t = -0.03094989366
+ 1.006218838I], [t = -0.06486779363+ 1.004829742I], [t =
-0.09874331960+ 1.002217958I], [t = -0.1325145529
+ 0.9983871753I], [t = -0.1661213070+ 0.9933456534I], [t =
-0.1995044917+ 0.9871061228I], [t = -0.2326057449
+ 0.9796863132I], [t = -0.2653675468+ 0.9711100642I], [t =
-0.2977341969+ 0.9614089557I], [t = -0.3296542844
+ 0.9506241472I], [t = -0.3610854137+ 0.9388074380I], [t =
-0.3920013678+ 0.9260193722I], [t = -0.4223996125
+ 0.9123212988I], [t = -0.4523031637+ 0.8977602520I], [t =
-0.4817497534+ 0.8823525433I], [t = -0.5107694030
+ 0.8660785906I], [t = -0.5393640268+ 0.8488957534I], [t =
-0.5675024369+ 0.8307602540I], [t = -0.5951298084
+ 0.8116434284I], [t = -0.6221811360+ 0.7915366540I], [t =
-0.6485910357+ 0.7704486792I], [t = -0.6742985106
+ 0.7484007056I], [t = -0.6992483265+ 0.7254221400I], [t =
-0.7233907990+ 0.7015477648I], [t = -0.7466810942
+ 0.6768161428I], [t = -0.7690785672+ 0.6512688829I], [t =
-0.7905463637+ 0.6249504601I], [t = -0.8110513989
+ 0.5979083723I], [t = -0.8305648273+ 0.5701934593I], [t =
-0.8490631440+ 0.5418601584I], [t = -0.8665300610
+ 0.5129663111I], [t = -0.8829591394+ 0.4835718475I], [t =
-0.8983566101+ 0.4537353818I], [t = -0.9127427179
+ 0.4235079356I], [t = -0.9261487378+ 0.3929245236I], [t =
-0.9386073794+ 0.3619974426I], [t = -0.9501385733
+ 0.3307172205I], [t = -0.9607382394+ 0.2990637853I], [t =
-0.9703773735+ 0.2670224047I], [t = -0.9790110178
+ 0.2345951764I], [t = -0.9865901050+ 0.2018037189I], [t =
-0.9930700610+ 0.1686854706I], [t = -0.9984146546
+ 0.1352880887I], [t = -1.002596520+ 0.1016647620I], [t =
-1.005596193+ 0.06787119616I], [t = -1.007400829
+ 0.03396400368I], [t = -1.008003159], [t = -1.007400829
- 0.03396400368I], [t = -1.005596193- 0.06787119616I], [t =
-1.002596520- 0.1016647620I], [t = -0.9984146546
- 0.1352880887I], [t = -0.9930700610- 0.1686854706I]]
```

$$\ln(1.000261721) = x \cdot 50 \cdot 10^{-6}$$

→ solve for x

$$0.0002616867570 = \frac{1}{20000} x$$

[[x = 5.233735140]]

Appendix-C

C.2.2 Maple Calculation over 30 nodes

$$0.3617t + 0.2517t^9 + 0.0125t^{10} + 0.3617t^{188} = 1$$

→ solve for t

```
[x = 1.000172553], [x = 0.9999378037+ 0.03223391558I], [x =
- 0.9990633553+ 0.06479801950I], [x = 0.9972358281
+ 0.09775748043I], [x = 0.9942412835+ 0.1309886494I], [x =
- 0.9899898434+ 0.1643330830I], [x = 0.9844593230
+ 0.1976566890I], [x = 0.9776555055+ 0.2308534667I], [x =
- 0.9695945038+ 0.2638370641I], [x = 0.9602962101
+ 0.2965331448I], [x = 0.9497822957+ 0.3288741602I], [x =
- 0.9380760797+ 0.3607958385I], [x = 0.9252033842
+ 0.3922346400I], [x = 0.9111943252+ 0.4231257123I], [x =
- 0.8960865361+ 0.4534012618I], [x = 0.8799308704
+ 0.4829899868I], [x = 0.8628009802+ 0.5118200201I], [x =
- 0.8448065226+ 0.5398318047I], [x = 0.8261000952
+ 0.5670118334I], [x = 0.8068450016+ 0.5934459386I], [x =
- 0.7871134225+ 0.6193317305I], [x = 0.7667982961
+ 0.6448637564I], [x = 0.7456880192+ 0.6700837025I], [x =
- 0.7236221620+ 0.6948836243I], [x = 0.7005456531
+ 0.7191103964I], [x = 0.6764745158+ 0.7426322315I], [x =
- 0.6514553051+ 0.7653510121I], [x = 0.6255436867
+ 0.7871945640I], [x = 0.5987964192+ 0.8081074938I], [x =
- 0.5712693172+ 0.8280448353I], [x = 0.5430174370
+ 0.8469682400I], [x = 0.5140960346+ 0.8648438600I], [x =
- 0.4845618341+ 0.8816413472I], [x = 0.4544745192
+ 0.8973337498I], [x = 0.4238984366+ 0.9118984206I], [x =
- 0.3929043424+ 0.9253194112I], [x = 0.3615704371
+ 0.9375921918I], [x = 0.3299805402+ 0.9487314642I], [x =
- 0.2982150633+ 0.9587809019I], [x = 0.2663301068
+ 0.9678175541I], [x = 0.2343293260+ 0.9759359306I], [x =
- 0.2021535989+ 0.9832048545I], [x = 0.1697137477
+ 0.9896251467I], [x = 0.1369460554+ 0.9951303933I], [x =
- 0.1038418744+ 0.9996265075I], [x = 0.07043940244
+ 1.0030290321I], [x = 0.03680168319+ 1.0052776461I], [x =
- 0.002999854850+ 1.0063348041I], [x = -0.03089508586
+ 1.0061796261I], [x = -0.06481506394+ 1.0048024361I], [x =
- 0.09869520585+ 1.0022011161I], [x = -0.1324732301
+ 0.9983790435I], [x = -0.1660886493+ 0.9933441430I], [x =
- 0.1994820656+ 0.9871087334I], [x = -0.2325947154
+ 0.9796900279I], [x = -0.2653684605+ 0.9711112473I], [x =
- 0.2977465983+ 0.9614033213I], [x = -0.3296761380
+ 0.9506069428I], [x = -0.3611124205+ 0.9387740879I], [x =
- 0.3920265526+ 0.9259668363I], [x = -0.4224139525
+ 0.9122500406I], [x = -0.4522979526+ 0.8976757748I], [x =
- 0.4817200721+ 0.8822647647I], [x = -0.5107163264
+ 0.8659985586I], [x = -0.5392937498+ 0.8488318088I], [x =
- 0.5674233139+ 0.8307162123I], [x = -0.5950496524
+ 0.8116191159I], [x = -0.6221059278+ 0.7915294366I], [x =
- 0.6485247717+ 0.7704548198I], [x = -0.6742435454
+ 0.7484161893I], [x = -0.6992057874+ 0.7254430611I], [x =
- 0.7233609079+ 0.7015704593I], [x = -0.7466633662
+ 0.6768372034I], [x = -0.7690719004+ 0.6512851388I], [x =
- 0.7905490411+ 0.6249589691I], [x = -0.8110610224
+ 0.5979064624I], [x = -0.8305782029+ 0.5701788582I], [x =
- 0.8490761599+ 0.5418312630I], [x = -0.8665376458
+ 0.5129226536I], [x = -0.8829554724+ 0.4835147778I], [x =
- 0.8983358480+ 0.4536688412I], [x = -0.9127004570
+ 0.4234388923I], [x = -0.9260840051+ 0.3928623317I], [x =
- 0.9385241263+ 0.3619516130I], [x = -0.9500452618
+ 0.3306942890I], [x = -0.9606452393+ 0.2990651755I], [x =
- 0.9702937387+ 0.2670446445I], [x = -0.9789425278
+ 0.2346319012I], [x = -0.9865390572+ 0.2018478825I], [x =
- 0.9930360862+ 0.1687307682I], [x = -0.9983957200
+ 0.1353295183I], [x = -1.002589706+ 0.1016986598I], [x =
- 1.005598169+ 0.06789506285I], [x = -1.007408110
+ 0.03397630158I], [x = -1.008012211I], [x = -1.007408110
- 0.03397630158I], [x = -1.005598169- 0.06789506285I], [x =
- 1.002589706- 0.1016986598I], [x = -0.9983957200
- 0.1353295183I], [x = -0.9930360862- 0.1687307682I]]
```

$$\ln(1.000172553) = x \cdot 50 \cdot 10^{-6}$$

$$0.0001725381144 = \frac{1}{20000} x$$

→ solve for x

[x = 3.450762288]

Appendix-C

C.3 Mathematical Model

This section presents the terminating renewal process model codes, including the total time as a sequence of intervals of empty delay time (D_{Emp}), successful delay time (D_{Suc}), busy delay time (D_{Bus}), and collision delay time (D_{Col}). This leads to the calculation of the probabilities of the following states: idle state (P_{Emp}), one of neighbour's attempting to transmit packet (P_{Suc}), the sender station attempting to transmit packet (P_{Own}), a packet transmission simultaneous attempt (P_{Col}), and the channel busy by packet transmission or packet collision (P_{Bus}). Then, the process terminates can be estimated by:

$$P(M > t) \approx \frac{1 - F(\infty)}{X \cdot \mu} \cdot e^{-x \cdot t}$$

```
%.....  
% mathematical modelling  
%.....  
  
% clean up the workspace  
clc  
clear all  
close all  
%.....  
% System Parameters  
%.....  
SIFS=28*(10^-6);  
PS=50*(10^-6); %physical slot time  
CTS=350*(10^-6);  
Data=8200*(10^-6);
```

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```
DIFS=128*(10^-6);
RTS=350*(10^-6);
ACK=300*(10^-6);
n=10:20:30; % number of nodes

%.....
% time consumed for each scenario
%.....

Demp=PS; % 50 μs
Dsuc=RTS+SIFS+CTS+SIFS+Data+SIFS+ACK+DIFS;
Dbus=DIFS+SIFS+ACK;
Dcol=RTS+DIFS;

%.....
% Probabilities of the proposed model
%.....
% each node is equally likely to transmit
% uniform distribution



$$T_{tr}=1/n;$$


$$T_{nb}=1/n;$$



Pemp=(1-Ttr)*[(1-Tnb)^(n-1)];
Psuc=(n-1)*Tnb*(1-Ttr)*[(1-Tnb)^(n-2)];
Pown=Ttr*[(1-Tnb)^(n-1)];
Pcol=Ttr*(n-1)*Tnb*[(1-Tnb)^(n-2)];
Pbus=1-Pemp-Psuc-Pown-Pcol;
Finf=1-Pown;
```


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```
%.....  
% terminating renewal process  
%.....  
% solving equation (5.14)  
x=5.233735140; % at n=20  
x = 3.5; % at n=30  
 $\mu = [(D_{emp}) * (P_{emp} * \exp(x * (D_{emp}))) + [(D_{bus}) * (P_{bus} * \exp(x * (D_{bus}))) + [(D_{col}) * (P_{col} * \exp(x * (D_{col})) + [(D_{suc}) * (P_{suc} * \exp(x * (D_{suc})))];$  % solving equation (5.15)  
j=1;  
for t=10:10:201  
% by obtaining values of x and  $\mu$ , then the equation (5.12) can be solved:  

$$P(j) = [(1 - F_{inf}) * (\exp(-1 * x * (t * 10^{-3})))] / (x * \mu);$$
  
j=j+1;  
end  
t1=10:10:200; % service time  

$$\bar{t}(t1, P, 'r')$$
  
set(gca, 'XTick', 0:50:200)  
grid on;  
xlabel('Service Time');  
ylabel('Probability');
```

Appendix-C

C.4 Performance Evaluation

This section presents the proposed analytical model in comparison with the IEEE 802.11 DCF behaviour based on the work of Bianchi (2000).

```
%.....  
% Performance evaluation  
%.....  
  
% clean up the workspace  
clc  
clear all  
close all  
%.....  
% System Parameters  
%.....  
SIFS=28*(10^-6);  
PS=50*(10^-6);  
CTS=350*(10^-6);  
Data=8200*(10^-6);  
DIFS=128*(10^-6);  
RTS=350*(10^-6);  
ACK=300*(10^-6);  
n=10:20:30; % number of nodes  
%.....  
% time consumed for each scenario  
%.....  
Demp=PS; % 50 μs  
Dsuc=RTS+SIFS+CTS+SIFS+Data+SIFS+ACK+DIFS;  
Dbus=DIFS+SIFS+ACK;  
Dcol=RTS+DIFS;
```

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```

%.....
% Probabilities of the proposed model
%.....
% each node is equally likely to transmit
% uniform distribution

$$T_{tr}=1/n;$$


$$T_{nb}=1/n;$$


P_emp=(1-T_tr)*[(1-T_nb)^(n-1)];
P_suc=(n-1)*T_nb*(1-T_tr)*[(1-T_nb)^(n-2)];
P_own=T_tr*[(1-T_nb)^(n-1)];
P_col=T_tr*(n-1)*T_nb*[(1-T_nb)^(n-2)];
P_bus=1-P_emp-P_suc-P_own-P_col;
F_inf=1-P_own;

%.....
% terminating renewal process proposed model
%.....
% solving equation (5.14)
x=5.233735140; % at n=20
x = 3.5; % at n=30

$$\mu=[(D_{emp})*(P_{emp}*\exp(x*(D_{emp})))]+[(D_{bus})*(P_{bus}*\exp(x*(D_{bus})))]+[(D_{col})*(P_{col}*\exp(x*(D_{col})))]+[(D_{suc})*(P_{suc}*\exp(x*(D_{suc})))];$$
 % solving equation (5.15)
j=1;
for t=10:10:201
% by obtaining values of x and  $\mu$ , then the equation (5.12) can be solved:

$$P(2,j)=[(1-F_{inf})*(\exp(-1*x*(t*10^{-3})))]/(x*\mu);$$


j=j+1;
end
% t1=10:10:200;
% bar(t1,P)

```

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```
% hold on
%.....
% simulation parameters
%.....
for loop=1:1:2
W=256; % contention window size
% for comparing with the wireless network behaviour:

$$t_b = 2 / ((loop * W) + 1);$$

% same as mathematical model parameters for:
SIFS=28*(10^-6);
PS=50*(10^-6);
CTS=350*(10^-6);
Data=8200*(10^-6);
DIFS=128*(10^-6);
RTS=350*(10^-6);
ACK=300*(10^-6);
n=10:20:30; % nodes

%.....
% time consumed for each scenario
%.....
Demp=PS;
Dsuc=RTS+SIFS+CTS+SIFS+Data+SIFS+ACK+DIFS;
Dbus=DIFS+SIFS+ACK;
Dcol=RTS+DIFS;
```

Appendix-C

```
%.....  
% Probabilities  
%.....  
% uniform distribution considered to be same as  $\tau$  value in IEEE 802.11 DCF  


$T_{tr} = \tau;$   
 $T_{nb} = \tau;$

  
 $P_{tr} = 1 - ((1 - \tau)^n);$   
 $P_s = ((n * \tau * ((1 - \tau)^{(n-1)})) / p_{tr});$   
 $P_{emp} = 1 - P_{tr};$   
 $P_{suc} = p_{tr} * P_s;$   
 $P_{col} = p_{tr} * (1 - P_s);$   
 $F_{inf} = 1 - t_b;$   
  
%.....  
% terminating renewal process proposed model  
%.....  
 $x = 5.233735140;$  % at  $n=20$   
 $x = 3.5;$  % at  $n=30$   
 $\mu = [(Demp) * (Pemp * \exp(x * (Demp)))] + [(Dcol) * (Pcol * \exp(x * (Dcol)))] + [(Dsuc) * (Psuc * \exp(x * (Dsuc)))];$   
 $j = 1;$   
for  $t = 10:10:201$   
 $P1(loop, j) = [(1 - F_{inf}) * (\exp(-1 * x * (t * 10^{-3})))] / (x * \mu);$   
 $j = j + 1;$   
end  
end  
  
 $P(1, :) = \text{mean}(P1);$   
 $t1 = 10:10:200;$   
 $\text{bar}(t1, P', 'grouped')$ 
```

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```
hleg1 = legend('simulation','terminating process model','position',[10,20,500,500]);
clc
display('terminating process output at 200ms')

% display variable value to show agreement between mathematical model and
behaviour of IEEE 802.11 DCF
disp(P(2,20)) display('simulation output at 200ms')
disp(P(1,20))
set(gca,'XTick',0:50:200)
grid on;
xlabel('MAC Layer Service Time (ms)');
ylabel('Probability')
```

Appendix-D

Appendix D: Codes for the Proposed Backoff Algorithm of IEEE 802.11 DCF under Unsaturated Traffic Loads

D.1 Introduction

As mentioned in Chapter 6, a dynamic control backoff time algorithm (DCBTA) is proposed to enhance both the delay and throughput performances of IEEE 802.11 standard. In particular, the equilibrium point analysis (EPA) model is used to run and test the algorithm under non-saturated traffic load conditions. Appendix D presents the codes that were used to propose and implement the tasks in Chapter 6.

D.2 Performance Comparison of the Backoff Algorithms

D.2.1 Comparison of Throughput

This section presents the throughput performance program for the DCBTA algorithm compared with the BEB and ELBA algorithms under the EPA model. The system is simulated for 10 and 50 nodes and the results of throughput against different *CW* size.

Appendix-D

```
%.....  
% main program for the proposed algorithm under  $CW_{min}=8$  &  $m=6$   
%.....
```

```
clc  
clear all  
close all  
N=50; % number of nodes  
CWmin=8; % initial contention window  
traffic_load=1*10-3;  
CWmax=1024; % maximum contention window  
M=6; % maximum back off stage  
iterations_loop=1000; % iterations of loop
```

```
[throughput_DCBTA] = DCBTA (CWmax,traffic_load,CWmin,N,iterations_loop);  
[throughput_ELBA] = ELBA (CWmax,traffic_load,CWmin,N,iterations_loop);  
[throughput_EPA] = EPA_modified (traffic_load,CWmin,N,M,iterations_loop);
```

```
Plot (throughput_DCBTA (1,:), '-bo');  
hold on  
Plot (throughput_ELBA (1,:), '--rs');  
hold on  
Plot (throughput_EPA (1,:), 'g');  
grid on
```

```
legend ('CW=8 DCBTA-EPA', ' CW=8 ELBA-EPA', ' CW=8 BEB-EPA', 'Location',  
'southeast')
```

```
grid on;  
set(gca, 'XTickLabel', {'0%', '10%', '20%', '30%', '40%', '50%', '60%', '70%', '80%', '90%', '100  
%'})  
xlabel('Dynamic Traffic Load');  
ylabel('Throughput');
```


Appendix-D

```
%.....  
% Chanel sense  
%.....  
Function [min_back_off_timer,new_backoff_timer]=channel_sense(trans_stat1,N,CW,b  
ackoff_timer)  
for i=1:1:N  
    if ((trans_stat1(i)>0)&&(backoff_timer(i)<=0))  
        backoff_timer(i)=randi(CW(i),1);  
    end  
end  
  
backoff_timer1=sort(backoff_timer);  
ii=0;  
min_back_off_timer=0;  
for i=1:1:N  
    if ((backoff_timer1(i)<0)&&(i>1))  
        ii=i;  
    end  
end  
  
if (ii<N)  
    min_back_off_timer=backoff_timer1(ii+1);  
end  
new_backoff_timer=backoff_timer-min_back_off_timer;  
end  
  
%.....  
% idle state  
%.....  
Function [trans_stat, transmission_prob]=idle_state(N,a)transmission_prob=rand(1,N);  
th=(a/(2*10^-3)); % EPA model mechanism for transmission probability  
trans_stat=zeros(1,N);
```

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```
for i=1:1:N
    if (transmission_prob(i)<th)
        trans_stat(i)=1;
    end
end

%.....
% EPA analytical tools
%.....
%.BEB-EPA algorithm
Function [col]=EPA_modified(traffic_load,CWmin,N,M,iterations_loop)
m=zeros(1,N); % counter for back off stage
a=0; % traffic load
col=zeros(4,11);
R=zeros(1,N); % packet transmitting probability

for i=0:1:10
    traffic_load_percentage(i+1)=traffic_load*0.1*i;
end

for contention_window_loop=1:1:4

    for traffic_load_loop=2:1:11
        ccc=0;
        for ytt=1:1:iterations_loop
            a=traffic_load_percentage(traffic_load_loop); % dynamic traffic load
            backoff_timer=-1*ones(1,N);
            [trans_stat,prob_trans]=idle_state(N,a); % the first stage i,e I or idle state
            CW=CWmin*ones(1,N);
            collisions=0;
            for t=1:1:50
```

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```
[min_back_off_timer,new_backoff_timer]=channel_sense(trans_stat,N,CW,backoff_timer); % function for the channel sensing and generating the back off timer
% function to calculate number of collision based on double contention window
[backoff_timer,trans_stat,CW,m,collisions,R]=collosion_state_EPA(new_backoff_timer,N,CWmin,CW,a,trans_stat,m,M,collisions,prob_trans,R);
end
    ccc=ccc+collisions;
end
    collisions111 (contention_window_loop,traffic_load_loop)=ccc;
% to calculate the average of collisions
    Col (contention_window_loop,traffic_load_loop)=((ytt*t)-ccc)/(ytt*t) ;
end
    CWmin=CWmin*2; % BEB algorithm over EPA model
end
end

%.....
% collision state of EPA model
%.....
% main function
Function[new_backoff_timer,trans_stat,CW,m,collisions,R]=collosion_state_EPA(new_backoff_timer,N,CWmin,CW,a11,trans_stat,m,M,collisions,prob_trans,R)
[a,b]=sort(new_backoff_timer);
k=0;
k1=0;
j=0;
j1=0;
for i=1:1:N
    if (a(i)==0)
        k=k+1;
        j(k)=i;
    end
end
```

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```
if (a(i)<0)
    k1=k1+1;
    j1(k1)=i;
end
end
% ..... In EPA method, the packet transmission on basis of R .....
% ..... the value of R will be checked to decide whether there is collision or not
% ..... this is the main part of EPA model
if (k1==N)
    collisions=collisions+1;
    k1=0;
end

if (k>1&& k1<N)
    uy=1;
    for t1=(k1+1):1:j(k)
        R1(uy)=R(b(t1));
        uy=uy+1;
    end
end

    r1=sort(R1);
    if(r1(1)==r1(2))
        collisions=collisions+1;
    end
end

% rest is the same standard back off timer (BEB)
if (k>1&& k1<N)
    for t1=(k1+1):1:j(k)
        m(b(t1))=m(b(t1))+1;
        if (m(b(t1))==M)
            m(b(t1))=0;
        end
    end
end
```

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```
CW(b(t1))=CWmin;
else
    CW(b(t1))=(2*CW(b(t1))); % collision mechanism for BEB
    % packet sending with probability R per slot (EPA model mechanism)
    R(b(t1))=1/((2^1)*CWmin);
    end
    %      * .....
    transmission_prob=rand(1,1);
    th=(a11/(2*10^-3));
    if (transmission_prob<th)
        trans_stat(b((t1)))=1;
    end
    %      * .....
end

elseif (k==1)
    CW(b(j(1)))=CWmin;
    for lk=1:1:j
        % * .....
        transmission_prob=rand(1,1);
        th=(a11/(2*10^-3));
        if (transmission_prob<th)
            trans_stat(b((lk)))=1;
        end
        % * .....
    end
end
end
% this is also the part of EPA model as due to traffic load there will be some
% slots that do not have any transmitted packet.....
% therefore, it is counted as wasted time
```

Appendix-D

```
%.....  
%ELPA-EPA algorithm  
%.....  
% main function  
Function [col]=ELBA(CWmax,traffic_load,CWmin,N,iterations_loop)  
a=0;  
col=zeros(4,11);  
R=zeros(1,N);  
for i=0:1:10  
traffic_load_percentage(i+1)=traffic_load*0.1*i;  
end  
  
for contention_window_loop=1:1:4  
for traffic_load_loop=2:1:11  
ccc=0;  
for ytt=1:1:iterations_loop  
a=traffic_load_percentage(traffic_load_loop); % increment in traffic load  
backoff_timer=-1*ones(1,N);  
[trans_stat,prob_trans]=idle_state(N,a); % the first stage i,e I in EPA or idle state  
CW=CWmin*ones(1,N);  
collisions=0;  
for t=1:1:50  
[min_back_off_timer,new_backoff_timer]=channel_sense(trans_stat,N,CW,backoff_timer); % function for the channel sensing and generating the back off timer  
[backoff_timer,trans_stat,CW,collisions,R]=collosion_state_ELBA(new_backoff_timer,  
N,CWmin,CW,a,trans_stat,collisions,R,CWmax); % function to calculate the collision  
end  
ccc=ccc+collisions;  
end  
collisions111(contention_window_loop,traffic_load_loop)=ccc;  
col(contention_window_loop,traffic_load_loop)=((ytt*t)-ccc)/(ytt*t);  
end
```

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```
CWmin=CWmin*2;
end
end

%.....
% collision state of ELPA-EPA algorithm
%.....

Function[new_backoff_timer,trans_stat,CW,collisions,R]=collosion_state_ELBA(new_
backoff_timer,N,CWmin,CW,a11,trans_stat,collisions,R,CWmax)
[a,b]=sort(new_backoff_timer);
k=0;
k1=0;
j=0;
j1=0;
for i=1:1:N
    if (a(i)==0)
        k=k+1;
        j(k)=i;
    end
    if (a(i)<0)
        k1=k1+1;
        j1(k1)=i;
    end
end
if (k1==N)
    collisions=collisions+1;
    k1=0;
end
if (k>1&&k1<N)
    uy=1;
    for t1=(k1+1):1:j(k)
        R1(uy)=R(b(t1));
```

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```
    uy=uy+1;
end

r1=sort(R1);
if(r1(1)==r1(2))
    collisions=collisions+1;
end
end

%.....ELBA-EPA Algorithm...
%.....condition for collision.....
%..... increment in the contention window..
if (k>1&&k1<N)
    for t1=(k1+1):1:j(k)
        %.ELBA-EPA mechanism
        if (CW(b(t1))==CWmax)
            CW(b(t1))=CWmax;
        elseif (CW(b(t1))<512)
            CW(b(t1))=(2*CW(b(t1)));

        else
            CW(b(t1))=CW(b(t1))+CWmin;
        end

        R(b(t1))=1/((2^1)*CWmin);
        transmission_prob=rand(1,1);
        th=(a11/(2*10^-3));

        if (transmission_prob<th)
            trans_stat(b((t1)))=1;
        end
    end
end
```


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```
%.....condition for transmission.....
%..... decrement in the contention window....
elseif (k==1)
    if (CW(b(k))==CWmin)
        CW(b(k))=CWmin;
    elseif (CW(b(k))<=512)
        CW(b(k))=(CW(b(k))/2);

    else
        CW(b(k))=CW(b(k))-CWmin;
    end
end

for lk=1:1:j
    transmission_prob=rand(1,1);
    th=(a11/(2*10^-3));

    if (transmission_prob<th)
        trans_stat(b((lk)))=1;
    end
end
end

%.....
% DCBTA-EPA algorithm
%.....
Function [col]= DCBTA (CWmax,traffic_load,CWmin,N,iterations_loop)
a=0;
col=zeros(4,11);
R=zeros(1,N);
for i=0:1:10
    traffic_load_percentage(i+1)=traffic_load*0.1*i;
```

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```
end

for contention_window_loop=1:1:4
    for traffic_load_loop=2:1:11
        ccc=0;
        for ytt=1:1:iterations_loop
            a=traffic_load_percentage(traffic_load_loop); % increment in traffic load
            backoff_timer=-1*ones(1,N);
            [trans_stat,prob_trans]=idle_state(N,a); % the first stage i,e I or idle state
            CW=CWmin*ones(1,N);
            collisions=0;
            for t=1:1:50
                [min_back_off_timer,new_backoff_timer]=channel_sense(trans_stat,N,CW,backoff_timer); % function for the channel sensing and generating the back off timer

                [backoff_timer,trans_stat,CW,collisions,R]=collosion_state_DCBTA(new_backoff_timer,N,CWmin,CW,a,trans_stat,collisions,R,CWmax); % function to calculate the collision
            end

            ccc=ccc+collisions;
        end

        collisions111(contention_window_loop,traffic_load_loop)=ccc;
        col(contention_window_loop,traffic_load_loop)=((ytt*t)-ccc)/(ytt*t);
    end
    CWmin=CWmin*2;
end
end
```

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```
%.....  
% collision state of DCBTA-EPA algorithm  
%.....  
Function[new_backoff_timer,trans_stat,CW,collisions,R]=collosion_state_DCBTA  
(new_backoff_timer,N,CWmin,CW,a11,trans_stat,collisions,R,CWmax)  
[a,b]=sort (new_backoff_timer);  
k=0;  
k1=0;  
j=0;  
j1=0;  
for i=1:1:N  
    if (a(i)==0)  
        k=k+1;  
        j(k)=i;  
    end  
  
    if (a(i)<0)  
        k1=k1+1;  
        j1(k1)=i;  
    end  
end  
  
if (k1==N)  
    collisions=collisions+1;  
    k1=0;  
end  
if (k>1&& k1<N)  
    uy=1;  
    for t1=(k1+1):1:j(k)  
        R1(uy)=R(b(t1));  
        uy=uy+1;  
    end  
end
```

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```
r1=sort(R1);
if(r1(1)==r1(2))
    collisions=collisions+1;
end
end

%.....DCBTA-EPA Algorithm.....
%.....condition for collision.....
%..... increment in the contention window for heavy traffic load...
if (k>1&& k1<N)
    for t1=(k1+1):1:j(k)

        %DCBTA-EPA mechanism
        if (CW(b(t1))==CWmax)
            CW(b(t1))=CWmax;
        elseif (CW(b(t1))<512)
            CW(b(t1))=(2*CW(b(t1))); % Collision at low traffic load
        else
            CW(b(t1))=(2*CW(b(t1))+2); % Collision at high traffic load
        end
    end

R(b(t1))=1/((2^1)*CWmin);
    transmission_prob=rand(1,1);
    th=(a11/(2*10^-3));
    if (transmission_prob<th)
        trans_stat(b((t1)))=1;
    end
end

%.....condition for transmission.....
% decrement in the contention window for low traffic load and successful transmission
elseif (k==1)
    if (CW(b(k))==CWmin)
```

Appendix-D

```
CW(b(k))=CWmin;
```

```
elseif (CW(b(k))<=512)
    CW(b(k))=(CW(b(k))-1); % Successful transmission at low traffic load
else
    CW(b(k))=(CW(b(k))-2); % Successful transmission at high traffic load
end
end
end
```

```
for lk=1:1:j
    transmission_prob=rand(1,1);
    th=(a11/(2*10^-3));
    if (transmission_prob<th)
        trans_stat(b((lk)))=1;
    end
end
end
```

```
%.....
% main program for the proposed algorithm under different  $CW_{min} = 8, 16$  and  $32$ 
%.....
```

```
clc
clear all
close all
N=50; % number of nodes
CWmin=8; % initial contention window
traffic_load=1*10^-3;
CWmax=1024;
M=6; % maximum back off stage
```

Appendix-D

```
iterations_loop=1000;  
[throughput_DCBTA]=DCBTA (CWmax,traffic_load,CWmin,N,iterations_loop);  
[throughput_ELBA]=ELBA (CWmax,traffic_load,CWmin,N,iterations_loop);  
[throughput_EPA]=EPA_modified (traffic_load,CWmin,N,M,iterations_loop);
```

```
plot(throughput_DCBTA(1,:),'-rs'); % DCBTA algorithm at CWmin=8  
hold on  
plot(throughput_DCBTA (2,:),'-ks'); % DCBTA algorithm at CWmin=16  
hold on  
plot(throughput_DCBTA (3,:),'-bs'); % DCBTA algorithm at CWmin=32  
hold on
```

```
plot(throughput_ELBA(1,:),'-ro'); % ELPA algorithm at CWmin=8  
hold on  
plot(throughput_ELBA(2,:),'-ko'); % ELPA algorithm at CWmin=16  
hold on  
plot(throughput_ELBA(3,:),'-bo'); % ELPA algorithm at CWmin=32  
hold on
```

```
plot(throughput_EPA(1,:),'-r*'); % EPA algorithm at CWmin=8  
hold on  
plot(throughput_EPA(2,:),'-k*'); % EPA algorithm at CWmin=16  
hold on  
plot(throughput_EPA(3,:),'-b*'); % EPA algorithm at CWmin=32  
hold on
```

```
legend ('CWmin=8 DCBTA-EPA', 'CWmin=16 DCBTA-EPA','CWmin=32 DCBTA -  
EPA','CWmin=8 ELBA-EPA', 'CWmin=16 ELBA-EPA','CWmin=32 ELBA-  
EPA','CWmin=8 BEB-EPA', 'CWmin=16 BEB-EPA','CWmin=32 BEB-EPA',  
'Location', 'southeast')  
grid on;
```

Appendix-D

```
set(gca,'XTickLabel',{'0%','10%','20%','30%','40%','50%','60%','70%','80%','90%','100%'})
```

```
xlabel('Dynamic Traffic Load');
```

```
ylabel('Throughput');
```

```
% the rest of the program is similar the previous program but considering multi  
CWmin=8, 16, 32
```

D.2.2 Comparison of Delay

This section presents the delay calculation program of the IEEE 802.11 DCF, BEB algorithm under the EPA model, ELPA algorithm under the EPA model, and the DCBTA algorithm under the EPA model. The performance is measured under different numbers of nodes. In addition, the CW_{min} (16, 32 and 64) are taken into account. All of the assumptions related to this experiment are the same as in the previous section.

```
%.....  
% main program for calculating the average delay of the proposed algorithm  
%.....
```

```
clc
```

```
clear all
```

```
close all
```

```
N1=10; % number of users
```

```
CWmin=32; % initial contention window
```

```
CW_start=32; % also tested on 64 & 128
```

```
traffic_load=1*10-3;
```

```
CWmax=1024;
```

Appendix-D

```
M=6; % maximum back off stage
iterations_loop=1000;
RTS=350;
DIFS=128;
SIFS=28;
CTS=350;
DATA_TIME=8200;
ACK=300;
trans_time_packet= RTS + SIFS + CTS + SIFS + Data_TIME + SIFS + ACK + DIFS;
Delay_collision=(RTS+DIFS);
total_packets=(iterations_loop*2500); % .iterations loop

Delay_time_DCBTA =zeros(1,11);
Delay_time_ELBA=zeros(1,11);
Delay_time_EPA=zeros(1,11);
for n=1:1:10
    N=n*N1; % number of nodes=100

    [Collision_DCBTA,Delay_dcbta]=DCBTA(CWmax,traffic_load,CWmin,N,iterations_lo
op,CW_start);
    [Collision_ELBA,Delay_elba]=ELBA(CWmax,traffic_load,CWmin,N,iterations_loop,C
W_start);
    [Collision_EPA,Delay_epa]=EPA_modified(traffic_load,CWmin,N,M,iterations_loop,C
Wmax,CW_start);

    DCBTA_delay=sum(Delay_dcbta)/(total_packets-Collision_DCBTA);
    ELBA_delay=sum(Delay_elba)/(total_packets-Collision_ELBA);
    BEB_delay=sum(Delay_epa)/(total_packets-Collision_EPA);

    Delay_time_DCBTA(n+1)=DCBTA_delay+((Collision_DCBTA*Delay_collision)+(tra
ns_time_packet)/(total_packets-Collision_DCBTA));
```


Appendix-D

```
Delay_time_ELBA(n+1)=ELBA_delay+((Collision_ELBA*Delay_collision)+(trans_time_packet)/(total_packets-Collision_ELBA));
```

```
Delay_time_EPA(n+1)=BEB_delay+((Collision_EPA*Delay_collision)+(trans_time_packet)/(total_packets-Collision_EPA));
```

```
end
```

```
plot(Delay_time_DCBTA /1000,'bs-')
```

```
hold on
```

```
plot(Delay_time_ELBA/1000,'ro-')
```

```
hold on
```

```
plot(Delay_time_EPA/1000,'k--')
```

```
grid on
```

```
legend(' DCBTA ','ELBA','BEB','Location','NorthWest');
```

```
grid on
```

```
set(gca,'XTickLabel',{ '0','10','20','30','40','50','60','70','80','90','100'})
```

```
xlabel('Number of Nodes');
```

```
ylabel('Average Delay(mcsec)');
```

```
%.....
```

```
% Chanel sense
```

```
%.....
```

```
Function[min_back_off_timer,new_backoff_timer,delay_packet]=channel_sense(trans_stat1,N,CW,backoff_timer,delay_packet)
```

```
for i=1:1:N
```

```
    if ((trans_stat1(i)>0)&&(backoff_timer(i)<=0))
```

```
        backoff_timer(i)=randi(CW(i),1);
```

```
    end
```

```
end
```

```
[backoff_timer1,position_min]=sort(backoff_timer);
```

```
ii=0;
```

```
min_back_off_timer=0;
```

Appendix-D

```
for i=1:1:N
    if ((backoff_timer1(i)<0)&&(i>1))
        ii=i;
    end
end

if (ii<N)
    min_back_off_timer=backoff_timer1(ii+1);
    delay_packet(ii+1)=min_back_off_timer+delay_packet(ii+1);
end
new_backoff_timer=backoff_timer-min_back_off_timer;
end

%.....
% idle state
%.....

Function [trans_stat,transmission_prob]=idle_state(N,a)
transmission_prob=rand(1,N);
th=(a/(2*10^-3));
trans_stat=zeros(1,N);
for i=1:1:N
    if (transmission_prob(i)<th)
        trans_stat(i)=1;
    end
end

%.....
%EPA analytical tools
%.....
%.BEB-EPA algorithm

Function[col,delay_epa]=EPA_modified(traffic_load,CWmin,N,M,iterations_loop,
CWmax,CW_start)
```

Appendix-D

```
m= zeros (1,N); % counter for back off stage
a=0; % traffic load
col=0;
R= zeros (1,N); % packet transmitting probability
delay_epa=zeros(1,N);
for i=0:1:10
traffic_load_percentage(i+1)=trafic_load*0.1*i;
end

for contention_window_loop=1:1:1
    for traffic_load_loop=11:1:11
        ccc=0;
        for ytt=1:1:iterations_loop
            a=traffic_load_percentage(traffic_load_loop); % increment in traffic load
            backoff_timer=-1*ones(1,N);
            [trans_stat,prob_trans]=idle_state(N,a); % the first stage i,e I or idle state
            CW=CW_start*ones(1,N);
            delay_EPA_BEB=zeros(1,N);
            Collisions = 0;
            for t=1:1:2500
                [min_back_off_timer,new_backoff_timer,delay_EPA_BEB]=channel_sense(trans_stat,
                N,CW,backoff_timer,delay_EPA_BEB); % function for the channel sensing and
                generating the back off timer
                [backoff_timer,trans_stat,CW,m,collisions,R]=collosion_state_EPA(new_backoff_timer
                ,N,CWmin,CW,a,trans_stat,m,M,collisions,prob_trans,R); % function to calculate the
                collision
            end
            % to calculate the average of collisions time
            ccc=ccc+collisions;
            delay_epa(1,:)=delay_EPA_BEB(1,:)+delay_epa(1,:);
        end
    end
end
```

Appendix-D

```
collisions111(contention_window_loop,traffic_load_loop)=ccc;
col=((ytt*t)-ccc);
end
CWmin=CWmin*2;
end
end

%.....
% collision state of EPA model
%.....
% main function
Function[new_backoff_timer,trans_stat,CW,m,collisions,R]=collosion_state_EPA(new
_backoff_timer,N,CWmin,CW,a11,trans_stat,m,M,collisions,prob_trans,R)
[a,b]=sort(new_backoff_timer);
k=0;
k1=0;
j=0;
j1=0;
for i=1:1:N
    if (a(i)==0)
        k=k+1;
        j(k)=i;
    end

    if (a(i)<0)
        k1=k1+1;
        j1(k1)=i;
    end
end
end

% ..... In EPA method, the packet transmission on basis of R .....
% ..... the value of R will be checked to decide whether there is collision or not
```

Appendix-D

```
% ..... this is the main part of EPA model
if (k1==N)
%   collisions=collisions+1;
    k1=0;
end

if (k>1&&k1<N)
    uy=1;
    for t1=(k1+1):1:j(k)
        R1(uy)=R(b(t1));
        uy=uy+1;
    end
    r1=sort(R1);
    if(r1(1)==r1(2))
%       collisions=collisions+1;
    end
end

%   rest is the same standard back off algorithm (BEB)
if (k>1&&k1<N)
%   collisions=collisions+1;
    for t1=(k1+1):1:j(k)
        m(b(t1))=m(b(t1))+1;
        if (m(b(t1))==M)
            m(b(t1))=0;
            CW(b(t1))=CWmin;

        else
            CW(b(t1))=(2*CW(b(t1)));
            R(b(t1))=1/((2^m(b(t1)))*CWmin);
        end
    end
```

Appendix-D

```
%      *.....
transmission_prob=rand(1,1);
th=(a11/(2*10^-3));
if (transmission_prob<th)
    trans_stat(b((t1)))=1;
end
%      *.....
end
elseif (k==1)
    CW(b(j(1)))=CWmin;
    collisions=collisions+1;
    for lk=1:1:j
        % *.....
        transmission_prob=rand(1,1);
        th=(a11/(2*10^-3));
        if (transmission_prob<th)
            trans_stat(b((lk)))=1;
        end
        % *.....
    end
end

end
% this is also the part of EPA model as due to traffic load there will be some
% slots that do not have any transmitted packet.....
% therefore, it is counted as wasted time

%.....
%ELPA-EPA algorithm
%.....
% main function
Function[col,delay_elba]=ELBA(CWmax,traffic_load,CWmin,N,iterations_loop,CW_start)
```

Appendix-D

```
a=0;
col=0;
R=zeros(1,N);
for i=0:1:10
traffic_load_percentage(i+1)=traffic_load*0.1*i;
end
delay_elba=zeros (1,N);
for contention_window_loop=1:1:1
for traffic_load_loop=1:1:11
ccc=0;
for ytt=1:1:iterations_loop
a=traffic_load_percentage(traffic_load_loop); % increment in traffic load
backoff_timer=-1*ones (1,N);
[trans_stat,prob_trans]=idle_state(N,a); % the first stage i,e I or idle state
CW=CW_start*ones (1,N);
delay_ELBA=zeros (1,N);
Collisions = 0;
for t=1:1:2500
[min_back_off_timer,new_backoff_timer,delay_ELBA]=channel_sense(trans_stat,N,C
W,backoff_timer,delay_ELBA); % function for the channel sensing and generating the
back off timer
[backoff_timer,trans_stat,CW,collisions,R]=collosion_state_ELBA(new_backoff_timer,
N,CWmin,CW,a,trans_stat,collisions,R,CWmax); % function to calculate the collision
end

ccc=ccc+collisions;
delay_elba(1,:)=delay_ELBA(1,:)+delay_elba(1,:);
end

collisions111(contention_window_loop,traffic_load_loop)=ccc;
col=((ytt*t)-ccc);
end
```

Appendix-D

```
CWmin=CWmin*2;
end
end

%.....
% collision state of ELPA-EPA algorithm
%.....

Function[new_backoff_timer,trans_stat,CW,collisions,R]=collosion_state_ELBA(new_
backoff_timer,N,CWmin,CW,a11,trans_stat,collisions,R,CWmax)
[a,b]=sort(new_backoff_timer);
k=0;
k1=0;
j=0;
j1=0;
for i=1:1:N
    if (a(i)==0)
        k=k+1;
        j(k)=i;
    end

    if (a(i)<0)
        k1=k1+1;
        j1(k1)=i;
    end
end

if (k1==N)
% collisions=collisions+1;
    k1=0;
end

if (k>1&& k1<N)
```


Appendix-D

```
uy=1;
for t1=(k1+1):1:j(k)
    R1(uy)=R(b(t1));
    uy=uy+1;
end

r1=sort(R1);
if(r1(1)==r1(2))
%    collisions=collisions+1;
end
end

%.....ELBA Algorithm.....
%.....condition for collision.....
%..... increment in the contention window....
if (k>1&& k1<N)
    for t1=(k1+1):1:j(k)
        if (CW(b(t1))==CWmax)
            CW(b(t1))=CWmax;
        elseif (CW(b(t1))<512)
            CW(b(t1))=(2*CW(b(t1)));

        else
            CW(b(t1))=CW(b(t1))+CWmin;
        end

        R(b(t1))=1/((2^1)*CWmin);
        transmission_prob=rand(1,1);
        th=(a11/(2*10^-3));

        if (transmission_prob<th)
            trans_stat(b((t1)))=1;
        end
    end
end
```

Appendix-D

```
    end
end
%.....condition for transmission.....
%..... decrement in the contention window....
elseif (k==1)
collisions=collisions+1;
if (CW(b(k))==CWmin)
    CW(b(k))=CWmin;
elseif (CW(b(k))<=512)
    CW(b(k))=(CW(b(k))/2);

else
    CW(b(k))=CW(b(k))-CWmin;
end
end

for lk=1:1:j
    transmission_prob=rand(1,1);
    th=(a11/(2*10^-3));
    if (transmission_prob<th)
        trans_stat(b((lk)))=1;
    end
end

end

%.....
% DCBTA-EPA algorithm
%.....
Function[col,delay_DCBTA]=DCBTA(CWmax,traffic_load,CWmin,N,iterations_loop,
CW_start)
a=0;
```

Appendix-D

```
col=0;
R=zeros(1,N);
for i=0:1:10
traffic_load_percentage(i+1)=traffic_load*0.1*i;
end

delay_ DCBTA =zeros(1,N);
for contention_window_loop=1:1:1
    for traffic_load_loop=1:1:11
        ccc=0;
        for ytt=1:1:iterations_loop
            a=traffic_load_percentage(traffic_load_loop); % increment in traffic load
            backoff_timer=-1*ones(1,N);
            [trans_stat,prob_trans]=idle_state(N,a); % the first stage i,e I-state or idle state
            CW=CW_start*ones(1,N);
            delay_ DCBTA =zeros(1,N);
            collisions=0;
            for t=1:1:2500
                [min_back_off_timer,new_backoff_timer,delay_ DCBTA]=channel_sense(trans_stat,N,
                CW,backoff_timer,delay_ DCBTA); % function for the channel sensing and generating
                the back off timer

                [backoff_timer,trans_stat,CW,collisions,R]=collosion_state_DCBTA(new_backoff_tim
                er,N,CWmin,CW,a,trans_stat,collisions,R,CWmax);% function to calculate the collision
                end
                ccc=ccc+collisions;
                delay_ DCBTA (1,:)=delay_ DCBTA (1,:)+delay_ DCBTA (1,:);
            end
            collisions111 (contention_window_loop,traffic_load_loop)=ccc; % to calculate the
            average of collisions
            col=((ytt*t)-ccc);
        end
    end
end
```

Appendix-D

```
CWmin=CWmin*2;
end
end

%.....
% collision state of DCBTA-EPA algorithm
%.....

Function[new_backoff_timer,trans_stat,CW,collisions,R]=collosion_state_DCBTA
(new_backoff_timer,N,CWmin,CW,a11,trans_stat,collisions,R,CWmax)
[a,b]=sort(new_backoff_timer);
k=0;
k1=0;
j=0;
j1=0;
for i=1:1:N
    if (a(i)==0)
        k=k+1;
        j(k)=i;
    end

    if (a(i)<0)
        k1=k1+1;
        j1(k1)=i;
    end
end

if (k1==N)
% collisions=collisions+1;
k1=0;
end
if (k>1&&k1<N)
uy=1;
```

Appendix-D

```
for t1=(k1+1):1:j(k)
    R1(uy)=R(b(t1));
    uy=uy+1;
end
r1=sort(R1);
if(r1(1)==r1(2))
%    collisions=collisions+1;
end
end

%..... DCBTA-EPA Algorithm.....
%.....condition for collision.....
%..... increment in the contention window....
if (k>1&& k1<N)
    for t1=(k1+1):1:j(k)
        if (CW(b(t1))==CWmax)
            CW(b(t1))=CWmax;
        elseif (CW(b(t1))<512)
            CW(b(t1))=(2*CW(b(t1)));

        else
            CW(b(t1))=(2*CW(b(t1))+2);
        end

        R(b(t1))=1/((2^1)*CWmin);
        transmission_prob=rand(1,1);
        th=(a11/(2*10^-3)); %transmission probability based on EPA model
        if (transmission_prob<th)
            trans_stat(b((t1)))=1;
        end
    end
end
```

Appendix-D

```
%.....condition for transmission.....  
%..... decrement in the contention window....  
elseif (k==1)  
collisions=collisions+1;  
if (CW(b(k))==CWmin)  
    CW(b(k))=CWmin;  
elseif (CW(b(k))<=512)  
    CW(b(k))=(CW(b(k))-1);  
  
else  
    CW(b(k))=(CW(b(k))-2);  
end  
end  
  
for lk=1:1:j  
    transmission_prob=rand(1,1);  
    th=(a11/(2*10^-3));  
    if (transmission_prob<th)  
        trans_stat(b((lk)))=1;  
    end  
end  
end
```