Performance Modelling and QoS Support for Wireless Ad Hoc Networks

by

Khalid M. Jamil Khayyat

B.Eng. (Electrical and Computer), Umm Al-Qura University, Saudi Arabia, 1992
M.Sc. (Computer Engineering), Colorado State University, USA, 2002

A Dissertation Submitted in Partial Fullfillment of the
Requirements for the Degree of

Doctor of Philosophy

in the Department of Electrical and Computer Engineering

Performance Modelling and QoS Support for Wireless Ad Hoc Networks

by

Khalid M. Jamil Khayyat

B.Eng. (Electrical and Computer), Umm Al-Qura University, Saudi Arabia, 1992
M.Sc. (Computer Engineering), Colorado State University, USA, 2002

Supervisory Committee

Dr. Fayez Gebali, Supervisor
(Department of Electrical and Computer Engineering)

Dr. Panajotis Agathoklis, Department Member
(Department of Electrical and Computer Engineering)

Dr. Hong-Chuan Yang, Department Member
(Department of Electrical and Computer Engineering)

Dr. Kui Wu, Outside Member
(Department of Computer Science)

Supervisory Committee

Dr. Fayez Gebali, Supervisor
(Department of Electrical and Computer Engineering)

Dr. Panajotis Agathoklis, Department Member
(Department of Electrical and Computer Engineering)

Dr. Hong-Chuan Yang, Department Member
(Department of Electrical and Computer Engineering)

Dr. Kui Wu, Outside Member
(Department of Computer Science)

Abstract

We present a Markov chain analysis for studying the performance of wireless ad hoc networks. The models presented in this dissertation support an arbitrary backoff strategy. We found that the most important parameter affecting the performance of binary exponential backoff is the initial backoff window size. Our experimental results show that the probability of collision can be reduced when the initial backoff window size equals the number of terminals. Thus, the throughput of the system increases and, at the same time, the delay to transmit the frame is reduced.

In our second contribution, we present a new analytical model of a Medium Access Control (MAC) layer for wireless ad hoc networks that takes into account frame retry limits for a four-way handshaking mechanism. This model offers flexibility to address some design issues such as the effects of traffic parameters as well as possible improvements for wireless ad hoc networks. It effectively captures important network performance characteristics such as throughput, channel utilization, delay, and average energy. Under this analytical framework, we evaluate the effect of the Request-to-Send (RTS) state on unsuccessful transmission probability and its effect on performance particularly when the hidden terminal problem is dominant, the traffic is heavy, or the data frame length is very large. By using our proposed model, we show that the probability of collision can be reduced when using a Request-to-Send/Clear-to-Send (RTS/CTS) mechanism. Thus, the throughput increases and, at the same time, the delay and the average energy to transmit the frame decrease.

In our third contribution, we present a new analytical model of a MAC layer for wireless ad hoc networks that takes into account channel bit errors and frame retry limits for a two-way handshaking mechanism. This model offers flexibility to address design issues such as the effects of traffic parameters and possible improvements for wireless ad hoc networks. We illustrate that an important parameter affecting the performance of binary exponential backoff is the initial backoff window size. We show that for a low bit error rate (BER) the throughput increases and, at the same time, the delay and the average energy to transmit the frame decrease. Results show also that the negative acknowledgment-based (NAK-based) model proves more useful for a high BER.

In our fourth contribution, we present a new analytical model of a MAC layer for wireless ad hoc networks that takes into account Quality of Service (QoS) of the MAC layer for a two-way handshaking mechanism. The model includes a high priority traffic class (class 1) and a low priority traffic class (class 2). Extension of the model to more QoS levels is easily accomplished. We illustrate an important parameter affecting the performance of an Arbitration InterFrame Space (AIFS) and small backoff window size limits. They cause the frame to start contending the channel earlier and to complete the backoff sooner. As a result, the probability of sending the frame increases. Under this analytical framework, we evaluate the effect of QoS on successful transmission probability and its effect on performance, particularly when high priority traffic is dominant.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACK	Acknowledgment
AIFS	Arbitration Inter-Frame Space period
AWGN	Additive white Gaussian noise
ARQ	Automatic Repeat reQuest
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
CW	Contention Window size
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
DCF	Distributed Coordination Function
DIFS	DCF Inter-Frame Space period
DSSS	Direct Sequence Spread Spectrum
EDCA	Enhanced Distributed Channel Access
EDCF	Enhanced Distributed Coordination Function
FEC	Forward Error Correction
IHCCA	HCF-Controlled Channel Access
IHCF	Hybrid Coordination Function
IFS	Inter-Frame Space period
LOS	Line of Sight
MAC	Medium Access Control
MPDU	MAC Protocol Data Unit
NAK	Negative Acknowledgement
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing

PCF	Point Coordination Function
PDF	Probability Density Function
PHY	PHYsical layer
PIFS	PCF Inter Frame Space period
QoS	Quality of Service
RTS	Request to Send
SA	Scheduled Access
SIFS	Short Inter Frame Space period
SNR	Signal to Noise Ratio
TC	Traffic Class
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMM	Wi-Fi MultiMedia

List of Symbols

a	Arrival probability
a_1	Arrival probability for high-priority class
a_2	Arrival probability for low-priority class
α	Probability that a terminal reserves a particular time slot
α_1	Probability that a terminal reserves a particular time slot for class 1
α_2	Probability that a terminal reserves a particular time slot for class 2
b	Maximum number of bits can be corrected
E_a	Average energy required to successfully transmit a frame
E_a^R	Average energy required to successfully transmit a frame including RTS and data frames
E_0	Average energy required to transmit the data frame
E_1	Average energy required to transmit the RTS frame
E_{a_1}	Average energy for high-priority class
E_{a_2}	Average energy for low-priority class
e_b	Bit Error Rate (BER)
e_f	Probability that a transmitted frame is in error
f	Channel free probability
γ	Scaling factor
L_F	Length of the MAC frame in bits
m	Number of backoff stages
N	Number of terminals
N_1	Number of terminals in high-priority class
N_2	Number of terminals in low-priority class
n	Time steps for frame transmission
n_1	Time steps for AIFS_1 for high-priority class

n_2	Time steps for $AIFS_2$ for low-priority class
n_3	Time steps for frame transmission in QoS classes
N_a	Average input traffic to the system
n_a	Average number of frame retransmissions
n_{a_1}	Average number of frame retransmissions for high-priority class
n_{a_2}	Average number of frame retransmissions for low-priority class
p	Frame collision probability
p_a	Average frame acceptance probability
p_{a_1}	Average frame acceptance probability for high-priority class
p_{a_2}	Average frame acceptance probability for low-priority class
t	Time step
T_c	Average time that the channel has a collision
T_s	Average time that the channel is sensed
Th	Throughput
Th_1	Throughput for high-priority class
Th_2	Throughput for low-priority class
$threshold$	Specified error tolerance
u	Probability that a terminal starts to send at a given time step
u_1	Probability that a terminal in class 1 starts to send at a given time step
u_2	Probability that a terminal in class 2 starts to send at a given time step
v	Probability that a terminal is not sending
v_1	Probability that a terminal in class 1 is not sending
v_2	Probability that a terminal in class 2 is not sending
w	Backoff window size
w_1	Backoff window size for high-priority class
w_2	Backoff window size for low-priority class

Acknowledgments

In the name of Allah, the most Gracious, the most Merciful. All praise be to Allah the Almighty who has given me knowledge, patience, and perseverance to complete my Ph.D. dissertation.

My sincere thanks to my parents who stood all the way behind me with their support, encouragement, and prayers until this work was done. I would also like to express my special thanks to my wife for her advice and support.

My deepest thanks to my supervisor Dr. Fayez Gebali for his invaluable scholarly advice, inspiration, help, and guidance that helped me through my Ph.D. dissertation work. I will always be indebted to him for all he has done for me, and it is a pleasure to acknowledge his guidance and support. Thank you very much for being such a fantastic supervisor.

I would like to acknowledge the advice and support from my supervisory committee members: Dr. Panajotis Agathoklis, Dr. Hong-Chuan Yang, and Dr. Kui Wu , as well as the external examiner: for making my dissertation complete and resourceful.

I would like to thank my employer, Umm Al-Qura University, College of Computer and Information System, Ministry of Higher Education of Saudi Arabia, and Saudi Arabian Cultural Bureau for the study leave and financial support.

I feel a special gratitude to Ahmed Morgan and Muhammad Marsono and for their guidance, support, and beneficial discussions. They have provided me with so much help and valuable advices.

There is no research work in isolation. I would like to give special thanks to Haytham Azmi, Ahmed Awad, and Newaz Rafiq for their invaluable support and enlightening discussions.

I would like to mention grateful thanks for my other colleagues: Omar Hamdy, Mohammed Yasein, Mohamed Fayed, Bassam Sayed, Mohamed El-Gamal, and Yousry Abdel-Hamid and many others for their generous friendship.

Khalid M. Jamil Khayyat, Victoria, BC, Canada

Dedication

To my parents who instill the importance of education above other things in this world.

To my wife for being my lover and my best friend.

And to my daughters and my son.

Chapter 1

Introduction

An ad hoc network connection method is most often associated with wireless terminals. The connection is established for the duration of one session and does not require a base terminal. Instead, terminals discover others within range to form a network. Especially for upcoming Wireless Local Area Network (WLAN) hotspots, the ad hoc mode is an interesting option to decrease installation costs. The demand for wireless network systems of increasing complexity and ubiquity has led to the need for a better understanding of dynamic connectivity, unpredictable latency, and limited resources in wireless network systems. The IEEE 802.11 WLAN MAC/PHY specifications [1–4] are those of the recommended international standards for WLANs that support ad hoc wireless networks.

A Medium Access Control (MAC) layer arbitrates access to the physical medium in a network. In arbitrating resources among multiple terminals, it is vital not to degrade the overall performance of the system while serving the disparate requirements of individual terminals. To this end, various performance models for predicting network behaviour, including queuing models and Markov chain models have appeared in the literature [5–10].

Generally, prediction of network behaviour is fundamental to gaining insight and to understanding the interaction of system variables. We can achieve insight and understanding by developing a performance model for the network of interest and identifying the parameters of the model that affect performance. With such a performance model and its corresponding metrics, we may establish a strategy or justify a policy or a heuristic that achieve some requirements of system performance, which, in turn, we may apply to the real network.

The focus of the analytical evaluation of a wireless network is on the physical layer, the MAC layer, and the network layer. If the analysis of ad hoc networks is considered, the physical layer discussions share ground with research on other kinds of wireless networks, for example, cellular networks. The MAC and network layers are more specific to ad hoc networks and they are the distinguishing features of ad hoc networks. Performance of the network layer depends on the performance of the MAC layer. Therefore, the MAC layer analytical model can be considered a key to analytical evaluation of ad hoc networks.

The research presented in this dissertation centres on modelling the performance of a WLAN consisting of wireless terminals associated with an ad hoc network sharing a single channel. The sharing of a common channel introduces contention. Within a network, individual terminals contend among one another for bandwidth. In a wireless network, the scarce bandwidth available, the imperfect channel, and the demand for Quality of Service (QoS) from various applications accentuate the problem. For any given network, designers seek to provide reliable services and efficient resource utilization through the proper management and control of resource contention.

1.1 Wireless MAC Protocol

The IEEE 802.11 medium access protocol used in ad hoc networks uses a Distributed Coordination Function (DCF) based on the Carrier Sense Multiple Access with a

Collision Avoidance (CSMA/CA) mechanism. A distributed coordination function is the basis for ad hoc wireless networking.

In the IEEE 802.11 specification [1], there are two access protocols, namely, basic CSMA/CA and CSMA/CA with Request to Send/Clear to Send (RTS/CTS). With the basic CSMA/CA protocol (as shown in Figure 1.1), a terminal, before initiating a transmission, senses the medium to determine if any other terminal is transmitting. The terminal proceeds with its transmission if the medium is sensed idle for an interval that exceeds the Distributed Inter-Frame Space (DIFS). If the medium is sensed busy, the terminal will defer its transmission until the end of the current transmission. Prior to retransmission, the terminal will initiate a backoff interval, a random interval selected from $[0, w_0)$, where w_0 is the contention window to initiate the backoff timer. The backoff timer is decremented only when the medium is idle, and it is frozen when the medium becomes busy. After a busy period, the backoff timer resumes only after the medium is idle longer than the DIFS. A terminal initiates a transmission when the backoff timer reaches zero. If the frame is successfully received at the destination, the receiver will send an acknowledgment (ACK) back to the sender after a Short Inter Frame Space (SIFS).

The carrier sense mechanism combines the Network Allocation Vector (NAV) state and the user transmitter status with physical carrier sense to determine the busy/idle state of the medium. A network allocation vector predicts the future traffic on the medium based on the information provided by the output of a frame decoder. The NAV is used by those terminals to predict the duration of the busy channel without physically sensing the channel. The frame decoder checks if the frame is destined to the current user, and also decodes the duration information from it. The duration information is used to update the NAV value. The value of NAV indicates an idle/busy state of the medium.

In CSMA/CA with RTS/CTS (shown in Figure 1.2), whenever a terminal wishes

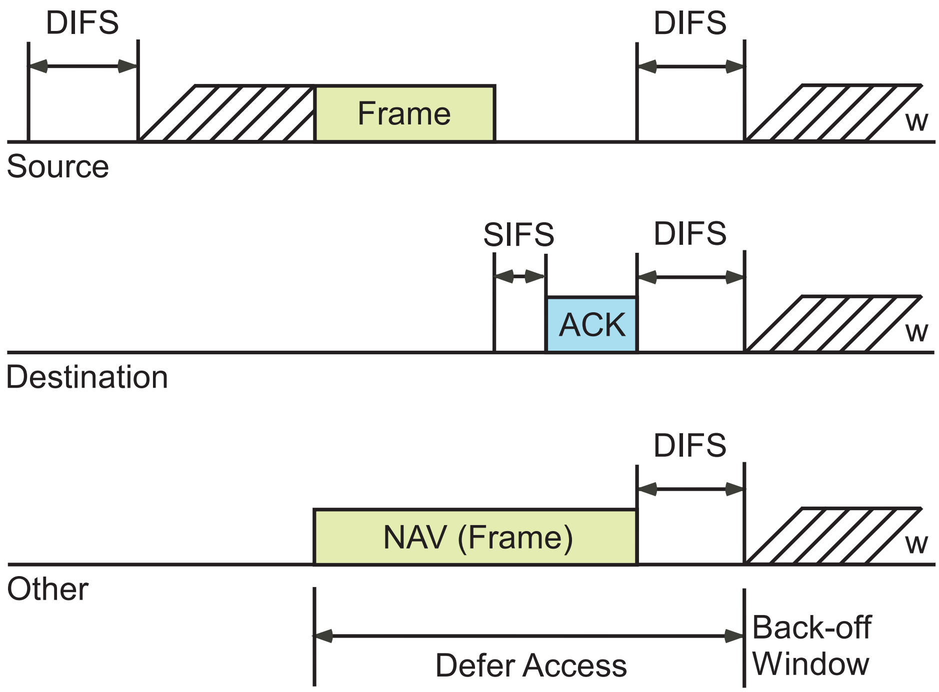


Figure 1.1: Basic CSMA/CA protocol [1]

to send a data frame, it will broadcast a short RTS containing the length of the data frame that will follow. Upon receiving the RTS, the destination responds by broadcasting a CTS frame that also contains the length of the upcoming data frame. Any terminal hearing either of these two control frames must be silent long enough to allow transmission of the data frame to be transmitted. After this exchange, the transmitter will begin the frame transmission. This signalling frame exchange reduces the hidden terminal problem [11–14], which occurs when pairs of mobile terminals are unable to hear each other.

The hidden terminal problem is not completely solved since the RTS and CTS messages are sent with CSMA. Thus, they may still suffer from the hidden terminal problem. But a collision occurs only for a short time duration, as shown in Figure 1.3. Once a collision may occur only on the RTS frame, and is identified by the lack of

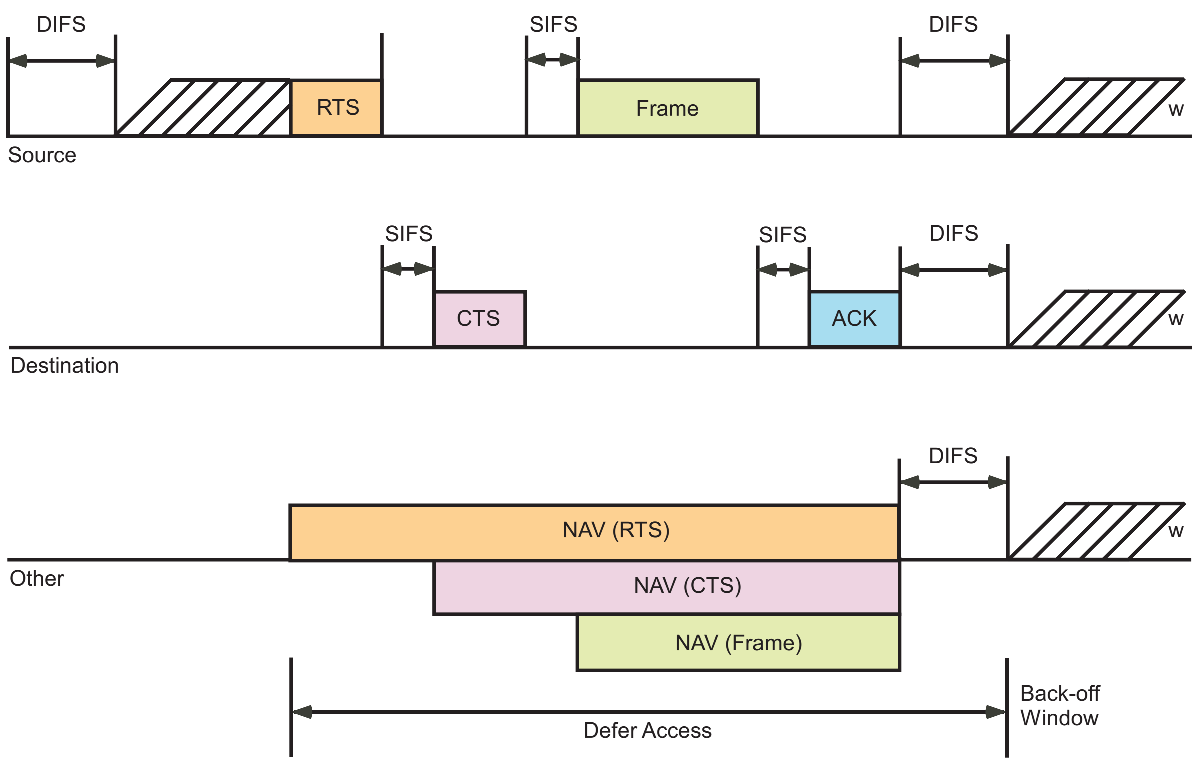


Figure 1.2: CSMA/CA with RTS/CTS protocol [2]

CTS reply, the RTS/CTS mechanism permits to increase the system performance by decreasing the period of a collision as soon as long frames are transmitted.

1.2 Exponential Backoff Algorithm

Backoff is a well known method to resolve contention between different terminals attempting to access the medium. The method requires each terminal to choose a random number between 0 and a given number, wait for this number of slots before accessing the medium, and always check whether the channel is sensed idle or busy. The slot time is defined in such a way that a terminal will always be capable of determining if other terminals have accessed the medium at the beginning of the

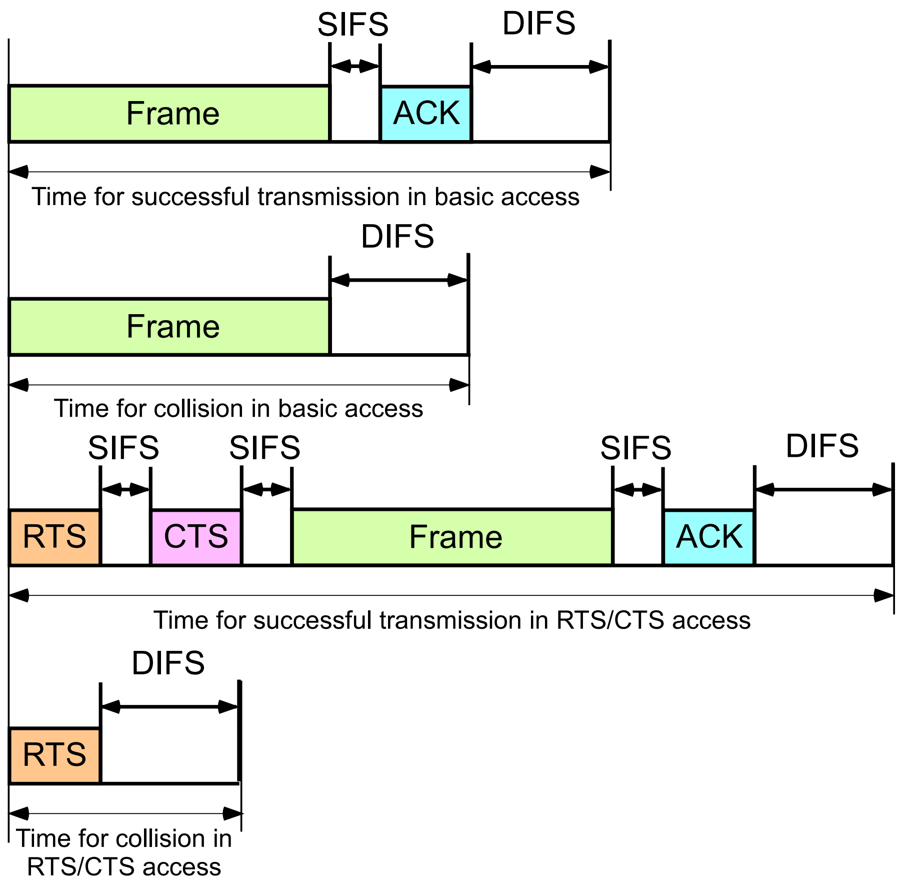


Figure 1.3: Comparison of duration time of collision with basic access and RTS/CTS access [2]

previous slot. This reduces the collision probability by half [2]. In case a terminal is incapable of sensing whether another terminal has started to transmit at the beginning of the previous slot, the vulnerable time is twice the frame transmission time, whereas in case the time slot is defined as described above, the vulnerable time is the frame transmission time.

The standard DCF cannot efficiently utilize the limited wireless channel bandwidth when many terminals in the WLAN are accessing the same channel. The major reason is that the initial Contention Window size (CW) is kept fixed regardless of the traffic activity, whereas ideally it should be large when the number of active terminals is large, and vice versa. In addition, hidden terminal problems may significantly reduce the performance. The RTS/CTS mechanism reduces collision probability in the hidden terminal case, because the hidden user will hear CTS and reserves the medium as busy until end-of-transmission. As well, since RTS and CTS are short frames, the RTS/CTS mechanism reduces overhead of collisions in the case when data frames are significantly bigger than the RST and CTS frames. On the other hand, the RTS/CTS scheme has advantages in large network scenarios, even with fairly limited frame sizes.

1.3 Negative Acknowledgement Signalling

In an event where an ACK frame is missed, this would conclude in a failed DATA frame transmission, when this occurs the sender can only assume that the cause of the frame loss was a collision or link errors. Consequently, there is no way for the sender to tell precisely what caused the frame loss; however, a Negative Acknowledgement (NAK) control frame would indicate that the previous DATA frame was not received. The basis or foundation behind this is to show that the MAC DATA frame can be divided into two useful portions, the header and the payload. The header would contain the frame destination address, type, and source. The MAC header and the form of the DATA frame would be ruined if multiple terminals were to transmit at the same time. If there is frame corruption or loss because of link errors, then there is still a chance for the receiver to get the MAC header, because it is shorter in length, although the body will be corrupted. After the header, the receiver can then gather the source address and then send it back as a NAK frame to indicate frame loss because of link errors. In this circumstance, the NAK is applied the same way as an ACK frame, and the only variance is in the frame type field value; this can be repaired by a single bit. Because the NAK frame inhabits the time kept for the ACK frame, its application does not essentially decrease the overall network throughput.

1.4 Quality of Service in MAC Protocol

Quality of Service is usually defined as a set of service requirements that needs to be met by the network while transporting a frame from a source to its destination.

The most recently published IEEE 802.11-2007 or 802.11e [4] provided an Enhanced Distributed Channel Access (EDCA) which is a QoS extension to legacy 802.11 DCF. Using EDCA, high priority traffic has a higher chance of being sent than lower priority traffic. This is accomplished by using a shorter contention window (w) and a shorter Arbitration Inter-Frame Space (AIFS) for higher priority frames. Thus, a terminal with higher priority traffic will wait less time before it sends its frame, on average, than a terminal with low priority traffic. Each data frame is assigned a Traffic Class (TC) in the MAC header, based on its priority as determined in the higher layers. During the contention process, an Enhanced Distributed Coordination Function (EDCF) uses AIFS[TC], initial contention window size w_0[TC] and maximum contention window size w_{max}[TC] instead of DIFS, w_0 and w_{max} of the DCF, respectively, for a frame belonging to a particular TC. More recent works [15–22] also seek to improve performance through variations of algorithms by tuning different EDCA parameters.

The IEEE 802.11-2007 [4] standard specifies the Hybrid Coordination Function (HCF) with two MAC protocols: the contention-based EDCA and the contention-free HCF-Controlled Channel Access (HCCA). EDCA is a distributed scheme so it can be used in both infrastructure and ad hoc networks. However, it cannot provide any QoS guarantees; only service differentiation. On the other hand, HCCA can provide QoS guarantees through resource reservation, but it is a centralized and more complex scheme useful in infrastructure networks only. Since the standardization of HCF, we have seen Wi-Fi MultiMedia (WMM), which is a subset of EDCA, replacing the DCF as the dominant medium access scheme for IEEE 802.11-based wireless networks. At the same time, WMM-Scheduled Access (WMM-SA), a subset of HCCA, has been ignored by the Wi-Fi (IEEE 802.11). Thus, we believe that any realistic QoS proposal for IEEE 802.11 networks should be distributed and compatible with EDCA. However, since EDCA can provide service differentiation only, the motivation of our work is to find a distributed QoS solution that offers contention-based medium access.

1.5 Motivation

With the increasing economic importance and deregulation of last-mile communication networks, cost efficient network deployment has become more important. In WLANs, cost presents itself as opposing requirements of maximizing performance and fulfilling QoS. In line with this, systematic means are needed for comparing different deployment alternatives, access policies, pricing strategies, and so forth. Designers address performance evaluation of WLANs from field studies, simulation, measurement, and model-based perspectives. In this dissertation, we utilize a model-based approach of performance evaluation. A model allows a rapid performance estimate without intrusive measurements on actual networks or lengthy simulations.

However, modelling efforts have become complicated in view of recent changes in the area of data communications. New services such as Youtube, Skype, and Torrents generate complex usage patterns. The increasing size, increasing demands, and integration of various access networks have pushed guarantees onto best effort networks. With such changes to the network at large, we have seen considerable discussion of the efficient utilization of WLANs serving these emerging services.

Given the promising applications of WLAN, it is imperative to study the factors contributing to efficiency. Furthermore, to understand better the effect on throughput of various features known to influence performance, such as backoff, user access probability, and timing interval, we can incorporate these features into performance models. While research on QoS in 802.11 WLAN remains active, an understanding of how QoS parameters affect network performance is needed. Very few performance models for WLAN reported in the literature consider the effect of QoS provisioning mechanisms of the MAC layer on overall utilization. Given the recent incorporation of the IEEE 802.11e recommendations into the main standard document, our efforts are complementary to understand the nature of QoS provisioning.

With these considerations in mind, the focus of this dissertation is on accurate characterization of network performance in 802.11e WLANs. We seek to maintain efficient resource performance in the presence of channel noise while supporting disparate QoS over common wireless ad hoc networks.

1.6 Objectives

We have five objectives for this work.

1. We develop a realistic model of the MAC layer of the wireless ad hoc networks using a discrete-time Markov chain for a two-way handshaking mechanism. Our model gives some form of flexibility to the study of the behaviour of the WLAN operations.

2. We investigate the effect of the initial backoff window parameter on the throughput to determine the optimum initial window size for an exponential backoff strategy under different WLAN loads (number of users and access probability). In this work, we model the wireless ad hoc networks using a

discrete-time Markov chain. Based on the proposed model in objective 1, we study the effect of initial backoff window size on the wireless ad hoc network performance.

3. We develop a realistic model of a four-way handshaking mechanism of the wireless ad hoc networks using a discrete-time Markov chain. Our model provides sufficient flexibility to study the behaviour of the four-way handshaking mechanism.

4. We propose a cross-layer model of the MAC layer for wireless ad hoc networks that takes into account channel bit errors and frame retry limits for a two-way handshaking mechanism.

5. We evaluate the effects of QoS on the performance of wireless ad hoc networks. Quality of Service offers priority, available to improve wireless ad hoc network performance. By utilizing a two-way handshaking mechanism in objective 1, we evaluate the effects of QoS on the performance of wireless ad hoc networks.

1.7 Dissertation Organization

We begin in Chapter 2 with a literature review whose purpose is the analysis of the prominent technology in WLANs, namely the IEEE 802.11 (IEEE-Std- 802.11-2007, 2007) standard. We briefly review the fundamental operation of WLANs and discuss performance models for 802.11 access mechanisms. We give particular attention to the characterization of protocol performance in terms of throughput, capacity, and utilization. Most of the models presented in the literature rely on tools from both queuing theory and stochastic processes.

In Chapter 3, we propose a model for a wireless ad hoc network using a two-way handshaking mechanism. This model uses Markov chain analysis for studying the performance of the IEEE 802.11 DCF. The model supports an arbitrary backoff strategy. We find that the most important parameter affecting the performance of binary exponential backoff is the initial backoff window size. Our experimental results show that the probability of collision diminishes when the initial backoff window size equals the number of network terminals. Thus, while the throughput of the system increases, the delay to transmit decreases.

Chapter 4 proposes a model for a wireless ad hoc network using a four-way handshaking mechanism. This model offers flexibility in addressing such design issues as the effects of traffic parameters and possible improvements for wireless ad hoc networks. It effectively captures the important network performance characteristics such as throughput, channel utilization, delay, and average energy used to transmit the frames. Under this analytical framework, we evaluate the effect of the RTS state on unsuccessful transmission probability and its effect on performance, in particular when the hidden terminal problem is dominant, the traffic is heavy, or the data frame length is very large. By using our proposed model, we show that the probability of collision can be reduced when using a RTS/CTS mechanism. Thus, the throughput increases and, at the same time, the delay and the average energy to transmit the frame decrease.

Chapter 5 proposes a cross-layer model of wireless ad hoc networks in the presence of channel noise. We present a new analytical model of the MAC layer for wireless ad hoc networks that takes into account channel bit errors and frame retry limits for a two-way handshaking mechanism. This model offers flexibility in addressing design issues such as the effects of traffic parameters as well as possible improvements for wireless ad hoc networks. We show that an important parameter affecting the performance of binary exponential backoff is the initial backoff window size. As expected, we find that for a low bit error rate (BER) the throughput increases and, at the same time, the delay and the average energy to transmit the frame decrease.

Results show also that a NAK-based model proves more useful for a high BER.

In Chapter 6, we propose a model for the operation of EDCA in an 802.11e. Once again, we analyze and model the WLAN. The chapter begins with a recollection of earlier studies conducted on modelling the predecessor of EDCA. While modelling the 802.11 MAC backoff is a well-treated issue in the literature, an in-depth investigation of the interactions of the various MAC parameters on channel utilization is absent. We propose a Markov model for network performance and its corresponding solution to address the issue and we derive a set of performance metrics from the solution of the Markov model for further analysis.

In Chapter 7, we state our contributions and suggest directions for future research.

Chapter 2

Literature Review

This chapter presents a review of the literature related to the work presented in this dissertation. We aim mainly at providing a state-of-the-art survey for different topics related to our research. Therefore, this chapter summarizes the work done by different modelling of wireless ad hoc networks research groups not only before our work but in parallel to it as well.

This chapter is organized as follows. We first review several analytical and numerical models that have been employed to evaluate the performance of the basic model, a two-way handshaking mechanism. Then, we present several schemes proposed to evaluate the backoff window algorithm of the IEEE 802.11 MAC protocol. In addition, we review previous work on a four-way handshaking mechanism. Furthermore, we review work on NAK signalling and BER. Finally, we review some recent work that considers the QoS on wireless networks. Representative papers from each category are discussed in detail to explain their methodology and to highlight their drawbacks.

2.1 Analytical and Numerical Models Using a Two-Way Handshaking Mechanism

Several analytical and numerical models have been proposed to evaluate the performance of the IEEE 802.11 MAC protocol [23–25]. Earlier analysis of the DCF were given in [26, 27]. One of the most well known models was developed by Bianchi [9, 28, 29]. Bianchi [9] proposed a technique to evaluate the saturation throughput of fully-connected networks based on modelling the binary exponential backoff algorithm used in the IEEE 802.11 DCF MAC. Using discrete-time Markov chain analysis, Bianchi modelled the backoff time counter. His model is based on the assumption that each frame collides with a constant and independent probability (p) at each transmission attempt, regardless of the number of retransmissions already undertaken. He used Markov chain analysis to acquire the steady state probability (τ) that a node transmits a frame at any time as a function of the conditional collision probability (p) and some parameters of the IEEE 802.11 DCF back-off algorithm. References [30–32] followed Bianchi's approach based on the same model and assumptions.

Ziouva et al. [33] improved Bianchi's model by taking into consideration busy periods detected by the carrier sense mechanism in the IEEE 802.11. Ziouva's model assumed that after every successful transmission, a station could transmit if the medium is idle without entering the reservation stage. However, the model also assumed an infinite number of retransmissions. Moreover, the model proposed by Ziouva targeted general CSMA/CA protocols. Hence, their model does not accurately reflect the IEEE 802.11 DCF operation. Xiao et al. [34] improved Bianchi's and Ziouva's models and computed the probability and time of frame-dropping. Xiao's model assumed that the collision probability equals the channel busy probability and assumed every station always has a frame available for transmission, which implies that a station never enters the idle state. Ergen et al. [35], followed Ziouva's approach with respect to the effect of the carrier sensing mechanism, but focused on the IEEE 802.11 itself. In their model, however, they made the very simplifying assumption that the conditional collision probability is equal to the probability of detecting the channel busy. Ziouva's model made this same simplifying assumption, particularly when the number of nodes in the network is large. Foh and Tantra [36] improved Ziouva's model by evaluating the channel access probabilities and the terminal collision probabilities conditioned upon the channel status.

Bianchi and Tinnirello [37] presented an approach that relies on elementary conditional probability arguments rather than bidimensional Markov chains to evaluate the performance of the 802.11 DCF. Tinnirello et al. [38] present improved backoff counter decrement rules without freezing a backoff state. Therefore, the slot immediately following a successful transmission can be accessed only by the terminal that has successfully transmitted in the previous channel access. However, this approach is limited to undersaturated conditions.

However, the performance analyses in the works presented in [9,33–36,38,39] are limited to undersaturated conditions, i.e. the interface queue between the network layer and the MAC layer has at least one frame always ready for transmission. Their models include only backoff strategies without considering the transmission states. They assume a fixed number of active stations, known in advance. These models do not address DCF performance across the whole traffic load spectrum. A model that works not only in saturated traffic is needed to improve DCF performance in all traffic conditions.

2.1.1 Back-off Window Algorithm

Several analytical and numerical models have been proposed to evaluate the backoff window algorithm of the IEEE 802.11 MAC protocol. For instance, Cali et al. [8, 40] proposed an approach to acquire the optimum performance. They estimated the system states using a fixed window size (w) regardless of the number of active users waiting for retransmission and load configuration.

Ni et al. [41] presented a Slow Decrease (SD) scheme to ease the level of contention for channel access. The SD scheme depends on the fact that collisions indicate congestion prevalent in the network and, once present, congestion is unlikely to drop sharply.

Banchs et al. [42] extended 802.11 DCF protocols to provide throughput guarantees by adapting the contention window according to the service class. Xiao [43] proposed a backoff-based priority scheme using an analytical model of the 802.11e EDCF. Tinnirello et al. [44] investigated the performance effects of differentiating initial window size and a window increasing factor respectively, and then proposed a joint differentiation scheme involving initial window size. Celik et al. [45] proposed a model that takes into account the Multipacket Reception (MPR) capability at the physical layer and an alternative backoff mechanism to improve the throughput. Su and Qiu [32] proposed a model that takes into account the number of retransmissions to adjust the initial window size, w_0, and the maximum window size, w_{max}.

The works presented in [8, 32, 39] do not discuss the relation between the initial contention window and the number of the stations, and its effect on the throughput. However, most of these works provide solutions with the assumption of ideal channel conditions or homogeneous link qualities among the participating hosts, which is impractical in realistic wireless environments.

2.2 Request to Send/Clear to Send Mechanism

Design and analysis of a four-way handshaking mechanism have been the focus of many studies. Karn [46] first proposed a three-way handshaking mechanism as the Multiple Access with Collision Avoidance (MACA) protocol. Bharghavan et al. [47] extended the MACA protocol by adding an ACK frame from the destination to reduce the delay caused by erroneous cycles at the transport layer.

The analytical model of Bianchi [9] used the average time that the channel is sensed, T_s, and the average time that the channel has a collision, T_c, as absolute values to evaluate the throughput. However, this model does not represent the actual performance accurately. A better approach is to consider the RTS state, which leads to more realistic results.

The performance analyses works presented in [9, 33–35, 39] are limited to saturated conditions. Their models target backoff strategies without consideration of transmission states or RTS state.

Xu et al. [48, 49] proposed a simple scheme to reduce an interference range between terminals. Zhai et al. [50] and Ho, et al. [51] used physical layer information to explore the effectiveness of using RTS/CTS for wireless networks. The works presented in [52–54] add RTS/CTS duration in obtaining the performance estimate of the RTS/CTS mechanism. In the work presented in this dissertation, we add the state of RTS in the transmitting states. Our model provides more realistic results when we put the RTS state in the model.

One common approach to reduce collisions between different types of frames is to exploit the advantage of using different channels for the control frames, RTS and CTS frames, and the DATA frames [55–57]. However, in this dissertation, we propose a realistic model for a four-way handshaking mechanism using Markov chain analysis for a single channel. We subsequently analyze the effect of various network parameters on its performance and show how to use this model to design optimal four-way handshaking wireless networks.

2.3 Negative Acknowledgement Signalling and Bit Error Rate

The models evaluated by Gebali [23, 24], Bianchi [9], Ziouva et al. [33], Ergen et al. [35], and Khayyat et al. [58, 59] use the idealistic assumption that the frame is retransmited only if a collision happens (ideal channel environment). Chatzimisios et al. [60, 61] considered a non-ideal channel environment, but the channel in their models is stationary. Lee et al. [62] considered a non-ideal channel environment with time-varying channels. Therefore, the BER could be changed according to the channel state. Samhat et al. [63] provide a detailed discussion of how to calculate the BER depending on the signal to noise ratio (SNR) for different modulation schemes. However, the performance analyses by Chatzimisios et al. [60,61], by Lee et al. [62], and by Samhat et al. [63] are limited to retransmission of a frame only if a collision or error occurs after doubling the backoff window size. Chang et al. [64] assumed that the unsuccessful transmission probability, which results from collisions or corrupted random bits, is constant. However, independent probability for each frame being transmitted in a randomly chosen time slot is used. Thus, each time a station transmits a packet, the unsuccessful transmission probability is constant at steady state in a generic slot. However, this assumption is not valid for a large number of terminals.

2.4 Quality of Service in Medium Access Control Protocol

Several analytical models evaluate the performance of IEEE 802.11e MAC. Xiao [65] proposed an analytical model for a simple priority scheme by differentiating the initial window size, the window-increasing factor, and the maximum backoff stage. Xiao [66] showed that the throughput of the high class traffic in EDCA is higher than that of the low class traffic. Xiao proposed an analytical model to derive the performance of saturation throughput and saturation delay in EDCA. In the work of Kong [67], the saturation model proposed by Bianchi [9] is extended to the IEEE 802.11e. Kong et al. proposed an analytical model for EDCA with some features of the EDCA: the virtual collision, different AIFS, and w.

Some related works presented in [20–22, 68–71] analyzed several performance metrics of the normalized throughput, delay, and collision probability for IEEE 802.11e under different impact factors: numbers of terminals, minimum contention window, and AIFS periods. Some studies presented in [15, 17, 72–75] analyzed the performance of delay and capacity for wireless LAN.

In IEEE 802.11, EDCA does not partition the collision domains among different classes of traffic while sending frames successfully, it significantly increases collisions. Thus, in this dissertation, we propose a model based on the discrete-time Markov chain model to guarantee a higher class of traffic having higher access probability and to suppress collisions from the same class traffic and different classes of traffic.

Chapter 3

Analytical Modelling for Wireless ad hoc Networks Using a Two-Way Handshaking Mechanism

In this chapter, we present a Markov chain analysis for studying the performance of the IEEE 802.11 DCF. The model allows us to optimize the backoff strategy to improve the system throughput. We find that the most important parameter affecting the performance of binary exponential backoff is the initial backoff window size. Our results show that the probability of frame collision can be reduced when the initial backoff window size equals the number of terminals. Thus, the throughput of the system increases and, at the same time, the delay to transmit the frame decreases.

We recommend several improvements in the analytical modelling of a two-way handshaking mechanism. More precisely, the proposed model removes the saturated traffic assumption, freezes the backoff counter when the channel is busy, considers finite retransmission attempts, and supports any arbitrary backoff strategy. The relationship between the optimum performance, delay, the initial backoff window size, and the number of backoff stages is investigated.

We improved the work done in [9, 33–35, 39]. In our study, the performance analyses are no longer limited to saturated conditions. The model is for backoff strategies with consideration of transmission states using a two-way handshaking mechanism (basic model). We also discuss the relation between the initial contention window and the number of stations, and its effect on the throughput.

In discussing these matters, we first present the proposed analytical model of a two-way handshaking mechanism. This includes the assumptions, transition probabilities for the model, estimating the free channel and collision probabilities, and the performance metrics for the model. We follow with experimental results of the proposed model to evaluate the optimized initial backoff window size.

3.1 Proposed Backoff Model

Figure 3.1 shows the basic transmission for a two-way handshaking mechanism between two terminals, a source and a destination, and the NAV setting of their neighbours. A data frame [MAC protocol data unit (MPDU)] sent from the source is acknowledged by the destination through an acknowledgement (ACK) frame. The data transfer continues only on the successful receipt of the ACK frame. In presenting an analytical model of two-way handshaking mechanism, we outline the assumptions, the transition probabilities, and the free channel and collision probabilities for the model. Then we obtain the performance metrics for the model.

3.1.1 Model Assumptions

A DCF terminal can be in one of several states: an idle state, I; a backoff state, B; and a transmitting state, T. Most previous models assumed a saturated traffic condition; and, hence, did not consider the idle state. The work presented in this dissertation

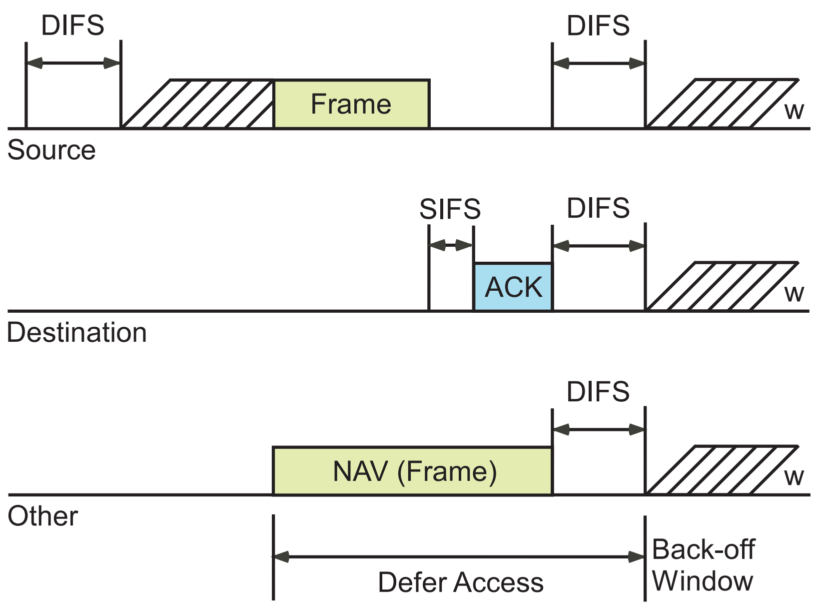


Figure 3.1: Two-way handshaking mechanism

---

fills these open gaps in wireless networks research that consider the transmitting state and could be met for both saturated and unsaturated conditions.

The current state of a terminal depends only on its immediate past history. Hence, we can model the terminal state using Markov chain analysis [24].

In the DCF mode, sending terminals compete with each other to access the medium. Before sending a frame, the terminal senses the presence of the carrier on the channel. If the channel is idle for at least the DIFS period, the terminal is allowed to send. The duration of contention slot is equal to the DIFS, which is the time needed at any terminal to detect the transmission of a frame from any other terminal. It is the sum of propagation delay, the time needed to switch from the receiving to the transmitting state, and the time to signal to the MAC layer the state of the channel (also known as busy detect time) [1].

A collision takes place when two or more terminals try to send frames at the same time. In the case of a busy channel, the terminal waits a random backoff period before attempting to retransmit.

For this study, we make the following assumptions:

1. All network terminals, N, are in radio contact with each other. This means that the effects of hidden terminal problems are not considered.

2. The time step, t, equals the DIFS period. This implies that all actions that results after the SIFS delay are modelled as transitions out of the last transmit state.

3. An idle terminal issues a request to transmit a frame during a time step with probability a.

4. All MAC frames have fixed length and require n time steps for transmission.

5. The backoff counter freezes when the channel is sensed busy and decrements by one for each time step when the channel is sensed free.

6. An error control protocol is used so that the channel appears noise free, as far as the MAC protocol is concerned.

3.1.2 State Transition Diagram

Figure 3.2 shows a Markov transition diagram for the transmission states of a tagged terminal. In the figure, p denotes the probability of frame collision and f is the probability that the channel is free. At backoff stage i, the probability of choosing random backoff value is given by

$$\alpha_i = 1/w_i \tag{3.1}$$

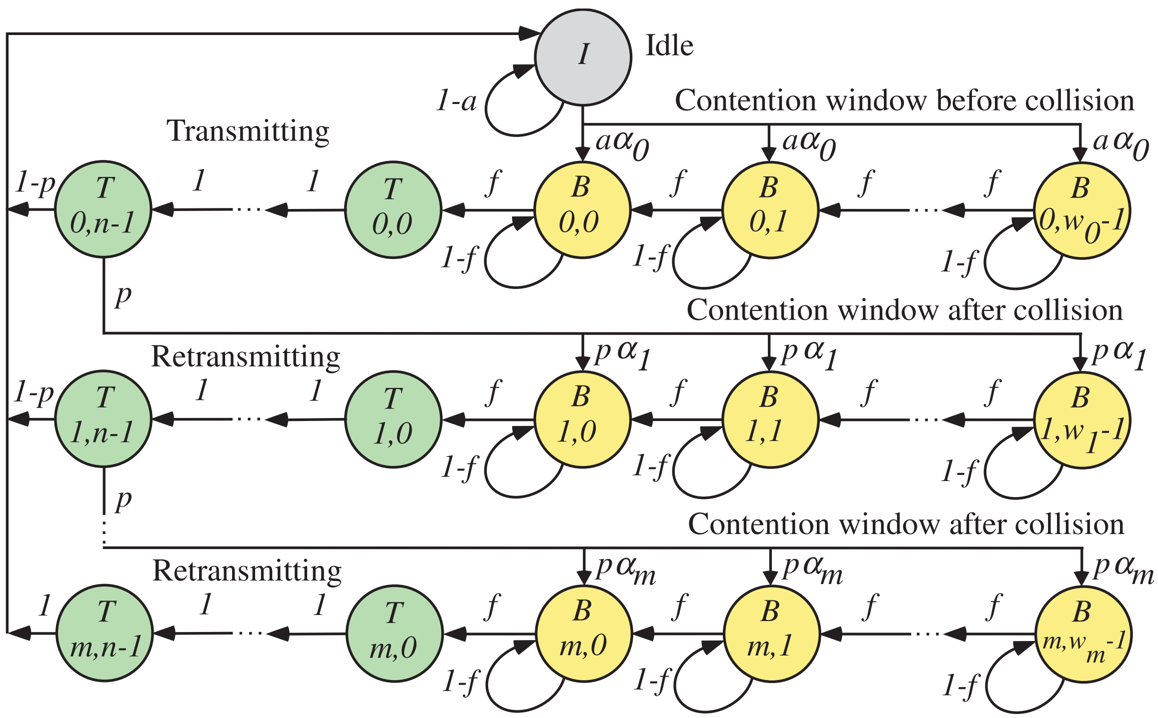


Figure 3.2: State transition diagram for Markov chain model of a two-way handshaking mechanism terminal in transmission

where w_i is the size of the backoff window.

The random backoff procedure is started when a frame is to be sent. At the first transmission attempt, w_0 is set equal to w_{min}, which is called the minimum contention window. After each collision, w is doubled up to a maximum value, $w_{\max} = 2^m\ w_0$, where m defines the maximum number of collisions that a terminal may reach during the exponential backoff procedure.

Although this backoff strategy is employed in this dissertation, our model is flexible enough to support different arbitrary backoff mechanisms. Accordingly, our model supports different values of base factors, number of retransmissions, m, and initial window size, w_0. The backoff states can be organized into the sets, $\mathcal{B}_i$ $(0 \leq i \leq m)$,

$$\mathcal{B}_i = \left\{ \begin{array}{cccc} B_{i,0} & B_{i,1} & \cdots & B_{i,w_i-1} \end{array} \right\} \tag{3.2}$$

For simplicity, we used the same symbol to denote the state name as well as state value. In that case $B_{i,0}$ denotes the left most backoff state at stage i as shown in Figure 3.2. It also represents the probability that the terminal is in that state. Similarly, the transmission states can be organized into the sets $\mathcal{T}_i$ $(0 \leq i \leq m)$

$$\mathcal{T}_i = \left\{ \begin{array}{cccc} T_{i,0} & T_{i,1} & \cdots & T_{i,n-1} \end{array} \right\} \tag{3.3}$$

At steady state, we can apply flow balance to the first set of backoff states, $\mathcal{B}_0$, in Figure 3.2, so that

$$B_{0,j} = \frac{(w_0 - j)a}{w_0\ f} \times I, \quad \text{where} \quad 0 \leq j < w_0 \tag{3.4}$$

The probability that a terminal starts to send at stage 0 is given by

$$T_{0,0} = B_{0,0} \times f = a \times I \tag{3.5}$$

From the state transition diagram in Figure 3.2, we can easily prove that all the probabilities of transmission states in the set $\mathcal{T}_0$ are equal:

$$T_{0,0} = T_{0,1} = \cdots = T_{0,n-1} \tag{3.6}$$

Using the preceding argument, we can find expressions for the states in the sets $\mathcal{B}_i$ and $\mathcal{T}_i$ as

$$B_{i,j} = \frac{(w_i - j)a}{w_i\ f} \times I\ p^i \tag{3.7}$$

$$T_{i,j} = a\ I\ p^i \tag{3.8}$$

where $\quad 0 \leq i \leq m \quad$ and $\quad 0 \leq j < w_i$.

The sum of all components of the state vector must be unity

$$I + \sum_{i=0}^{m} \sum_{j=0}^{n-1} T_{i,j} + \sum_{i=0}^{m} \sum_{j=0}^{w_i-1} B_{i,j} = 1 \tag{3.9}$$

From (3.7) and (3.8), we can get an expression for state I as

$$I = \frac{1}{1 + n \times a \sum_{i=0}^{m} p^i + (a/f) \sum_{i=0}^{m} \sum_{j=0}^{w_i-1} (w_i - j) p^i / w_i} \tag{3.10}$$

3.1.3 Estimating the Probabilities f and p

State I depends on the probabilities f and p. These two probabilities depend in turn on the states of the terminal. This is a highly nonlinear system and we have to use iterative techniques [76] to estimate the terminal states (I, T, and B). The associated probabilities f and p for a given traffic level are defined below.

The probability, u, that a terminal starts to send at a given time step is given by

$$u = \sum_{i=0}^{m} f \times B_{i,0} = \sum_{i=0}^{m} T_{i,0} \tag{3.11}$$

The probability, v, that a terminal is not sending is given by

$$v = I + \sum_{i=0}^{m} \sum_{j=1}^{w_i-1} B_{i,j} + (1 - f) \sum_{i=0}^{m} B_{i,0} \tag{3.12}$$

The probability, f, that the channel is free is when all terminals are not sending is

$$f = v^{N-1} \tag{3.13}$$

The collision probability, p, is the probability that two or more terminals start to send simultaneously, and is

$$p = \sum_{k=2}^{N} \binom{N}{k} u^k v^{N-k} \tag{3.14}$$

Algorithm 1 is used to estimate the probabilities f and p. The algorithm is iterative [76] where in each iteration the values of f and p involved in the computation of error are determine using equations (3.13) and (3.14). The values f and p are updated using $f = f + \gamma \times error_f$ and $p = p + \gamma \times error_p$. The iteration is terminated when the absolute error become less than a specified error tolerance. Figure 3.3 shows that the collision and channel free probabilities converge.

3.1.4 Performance Metrics

The throughput, Th, is defined as the average number of successfully transmitted frames per time step. Th is given by

$$Th = (1-p)N \sum_{i=0}^{m} \sum_{j=0}^{n-1} T_{i,j} \tag{3.15}$$

Substituting (3.8) into (3.15) yields the throughput expression:

$$Th = N \times n \times a \times I(1 - p^{m+1}) \tag{3.16}$$

The terminal access probability, p_a, essentially gives the ratio of frames transmitted through the system relative to the total number of frames arriving in one time step [24]. Terminal access probability is given by:

$$p_a = \frac{Th}{N_a} \quad \text{where} \quad N_a = N \times a \tag{3.17}$$

Algorithm 1 Iterative Absolute Error Minimization

```
Initial value of f, p, error, γ, and threshold
where γ is a scaling factor and threshold is a specified error tolerance.
while error > threshold do
    Compute f_c using equation (3.13)
    Compute p_c using equation (3.14)
    error_f = f_c − f
    error_p = p_c − p
    f = f + γ × error_f
    p = p + γ × error_p
    Ensure 0 ≤ f, p ≤ 1
    Calculate update states
    error = |error_f| + |error_p|
end while
Return f, p
```

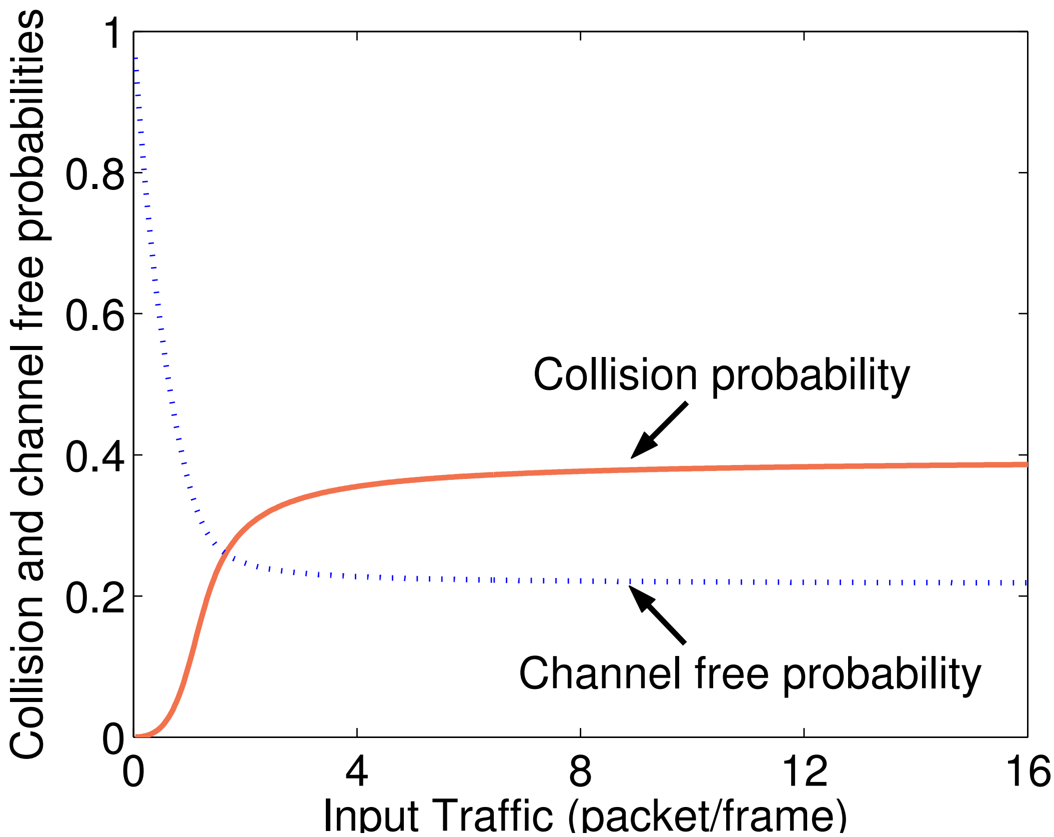


Figure 3.3: Collision, p, and channel free, f probabilities when $N = 16$

The delay occurs due to frame retransmission due to channel errors or frame collisions. The average number of frame retransmissions, n_a, is calculated in [24]. As m goes to infinity, n_a simplifies to

$$n_a = \frac{1 - p_a}{p_a}, \quad m \to \infty \tag{3.18}$$

The average energy, E_a, required to successfully transmit a frame is an important performance measure, especially for mobile wireless systems. The average energy is estimated by counting the number of retransmissions until the frame is correctly received. Then E_a is calculated as m goes to infinity. E_a simplifies to

$$E_a = \sum_{i=0}^{m}(i+1)(1-p_a)^i p_a E_0 \tag{3.19}$$

$$E_a = \frac{E_0}{p_a}, \qquad m \to \infty \tag{3.20}$$

where E_0 is the energy required to transmit the data frame. We can normalize E_a in equation (3.20) as

$$\overline{E_a} = \frac{E_a}{E_0} = \frac{1}{p_a} \tag{3.21}$$

and we can express it in dB as

$$\overline{E_a}(dB) = -10 \log p_a \tag{3.22}$$

3.2 Optimizing Backoff Window Size

In this section, we obtain important performance parameters of the protocol and show their dependence on the initial backoff window, w_0. To investigate the effect of the backoff window on throughput, we varied w_0 and N. Table 3.1 shows the parameters values that we used for our analytical model of a two-way handshaking mechanism. Previous work assumed an infinite number of retransmission. However, the work presented in this dissertation aims at analyzing the effect of finite retransmission attempts on the overall system performance. Using finite retransmission is useful in enhancing the channel utilization and reducing the delay and channel contention time. Therefore, different values of m have been experimented. For retransmission attempts greater than 3, we found that the effect on performance is minimal. As a result, $m = 3$ is used throughout this dissertation. Moreover, our model allows the backoff counter to be decremented only if the channel is free. Otherwise, the counter is frozen. This backoff freezing procedure directly affects the probabilities f and p.

Parameter	**Value**
w_0	4, 8, 16, 32, 64, 128
n	4
N	8,16
m	3

Table 3.1: Parameter values for the analytical model of a two-way handshaking mechanism

Figure 3.4 shows the dependence of the throughput on the value of the backoff window, w_0. Figure 3.4(a) shows the throughput versus input traffic for the case when $m = 3$, $n = 4$, $N = 8$, and the backoff window was varied as $w_0 = 2$, 4, 8, 16, 32, 64, and 128. We see that when $w_0 \approx N$, the throughput shows its maximum value over most of the input traffic range. Moreover, for $w_0 < N$, the throughput reaches its peak at a very low input traffic. However, as the input traffic increases, the throughput decays. This is because of the high collision probability corresponding to this low window size. On the other hand, for $w_0 > N$, the throughput has no peak similar to that of $w_0 < N$. However, the maximum value is still less than the peak throughput of $w_0 = N$. The large window size reduces the channel utilization as the sender might wait while the channel is already free.

Figure 3.4(b) shows the throughput versus input traffic for the case when $m = 3$, $n = 4$, $N = 16$, and the backoff window was varied as $w_0 = 2$, 4, 8, 16, 32, 64, and 128. Similar to $N = 8$, we see that when $w_0 \approx N$ the throughput shows its maximum value over most of the input traffic range. We conclude that the throughput exhibits its best behaviour when $w_0 = N$.

Moreover, for $w_0 < N$, the throughput reaches its peak at a very low input traffic. However, as the input traffic increases, the throughput decays. This is because of the high collision probability corresponding to this low window size. On the other hand, for $w_0 > N$, the throughput has no peak similar to that of $w_0 < N$. However, the maximum value is still less than the peak throughput of $w_0 = N$. The large window size reduces the channel utilization as the sender might wait while the channel is already free.

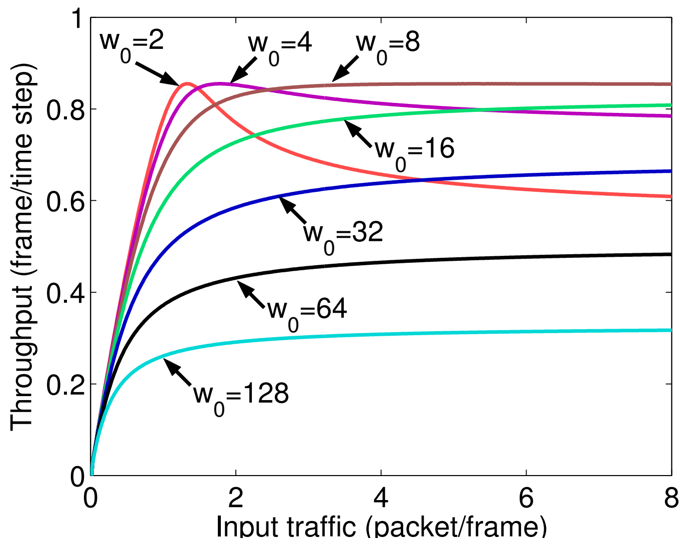
Figure 3.5 shows the effects of initial backoff window size on terminal access probability. In Figure 3.5(a), the number of terminals is 8, while in Figure 3.5(b) the number of terminals is 16. We observe from these two figures that the terminal access probability is maximum when $w_0 = N$.

Figure 3.6 shows the effects of initial backoff window size on the average frame delay. In Figure 3.6(a), the number of terminals is 8, while in Figure 3.6(b) the number of terminals is 16. We observe from these two figures that the average frame delay reaches the least value when $w_0 = N$.

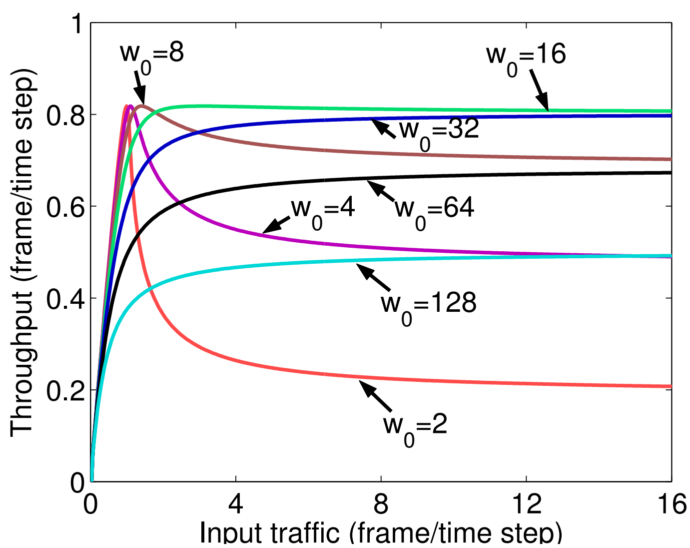
Figure 3.7 shows the effects of initial backoff window size on the average energy that spent to retransmit the frame. We observe from this figure that the average energy reaches the least value when $w_0 = N$.

3.3 Chapter Summary

We proposed a realistic model for a two-way handshaking mechanism using a Markov chain model. This model can be used to analyze the performance of DCF due to changes of backoff strategies, finite retransmission attempts, and the freezing of the backoff counter. Using the developed model, we analyzed the effects of the initial backoff window size on the performance of DCF and found that an initial backoff window size equal to the number of terminals gives best performance in terms of throughput, terminal access probability, and delay.

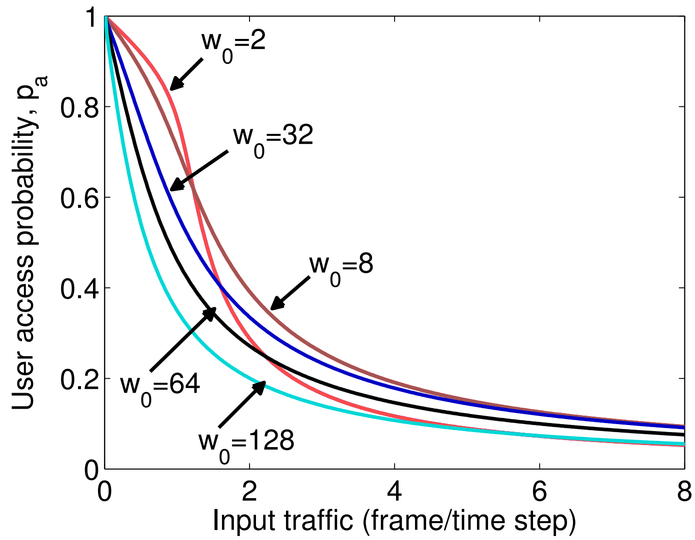


(a)

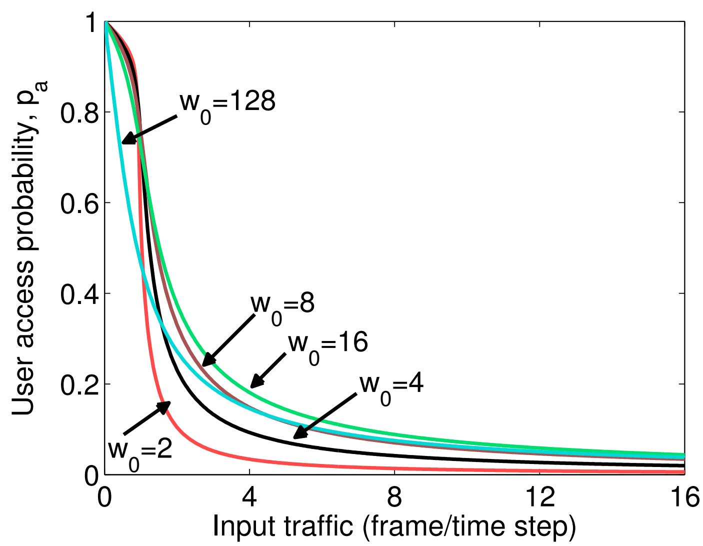


(b)

Figure 3.4: Throughput versus input traffic for different values of the initial backoff window size w_0 (a) Case when $N = 8$ (b) Case when $N = 16$

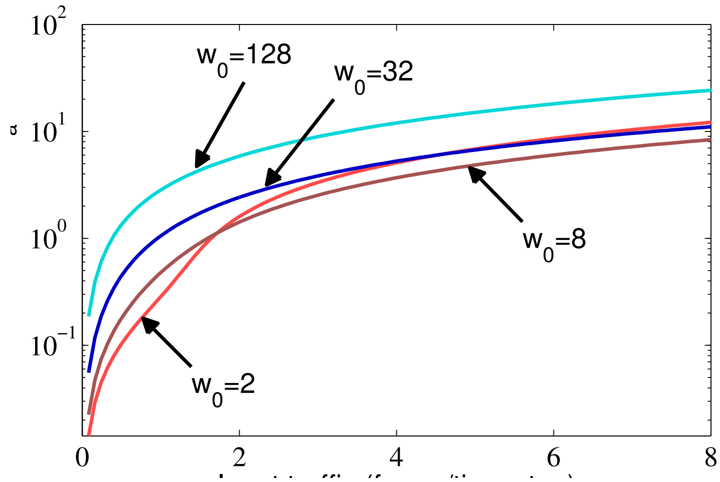


(a)

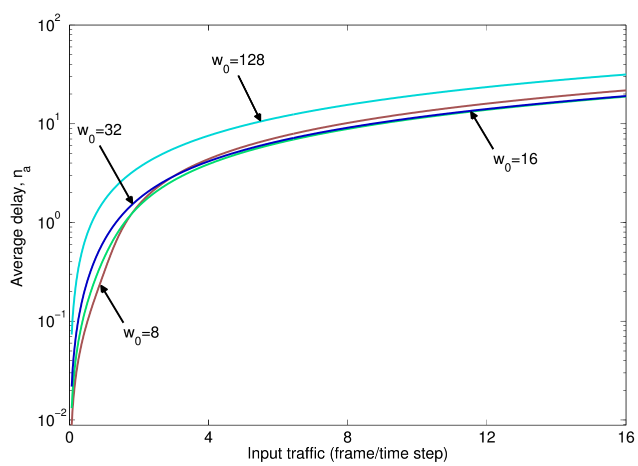


(b)

Figure 3.5: Terminal access probability for two-way handshaking mechanism versus input traffic for different values of the initial backoff window size w_0 (a) Case when $N = 8$ (b) Case when $N = 16$



(a)



(b)

Figure 3.6: Average delay for two-way handshaking mechanism versus input traffic for different values of the initial backoff window size w_0 (a) Case when $N = 8$ (b) Case when $N = 16$

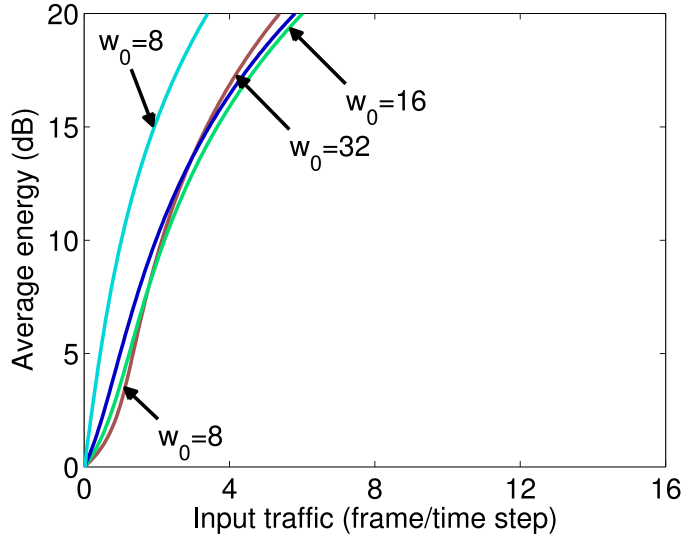


Figure 3.7: Average energy for two-way handshaking mechanism versus input traffic for different values of the initial backoff window size, w_0, when $N = 16$

With realistic protocol modelling, any improvement of protocol parameters can be modelled and analyzed. This work is extended in the next chapter to include a RTS/CTS mechanism that improves performance of wireless ad hoc networks.

Chapter 4

Wireless ad hoc Networks Using a Four-Way Handshaking Mechanism

A four-way handshaking mechanism is beneficial during the transmission of large frames to guarantee reliable data transmission [77–79] and to combat the hidden terminal problem, where a hidden terminal is a terminal that is out of range of other terminals or of a collection of terminals [80, 81].

We present a new analytical model of a MAC layer for wireless ad hoc networks that takes into account frame retry limits for a four-way handshaking mechanism. The terms frame retry limit and number of retransmissions are used interchangeably in this dissertation. Our contributions are:

(a) Proposing a model that considers all levels of traffic and finite retransmission attempts, including an arbitrary backoff strategy;

(b) Comparing our model to a two-way handshaking mechanism, which shows that the four-way handshaking mechanism is better in terms of throughput, average number of retransmissions, and energy.

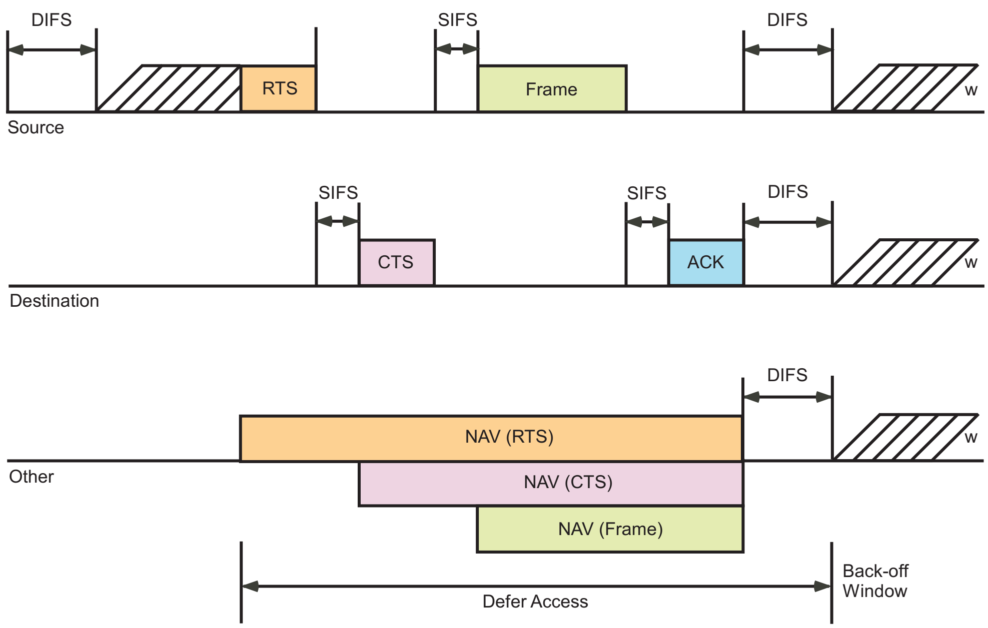


Figure 4.1: Four-way handshaking mechanism

We present the proposed analytical model of ad hoc networks using four-way handshaking. This includes the assumptions, transition probabilities for the model, estimating the free channel and collision probabilities, and the performance metrics for the model. We follow with an analysis of the proposed model.

4.1 Modelling Wireless ad hoc Networks using Four-Way Handshaking

The four-way handshaking technique involves sending of additional RTS/CTS control frames before the actual data transfer, as shown in Figure 4.1. This exchange of RTS and CTS frames is beneficial both during the transmission of large frames and in combatting the hidden terminal problem. Figure 4.2 shows how the four-way

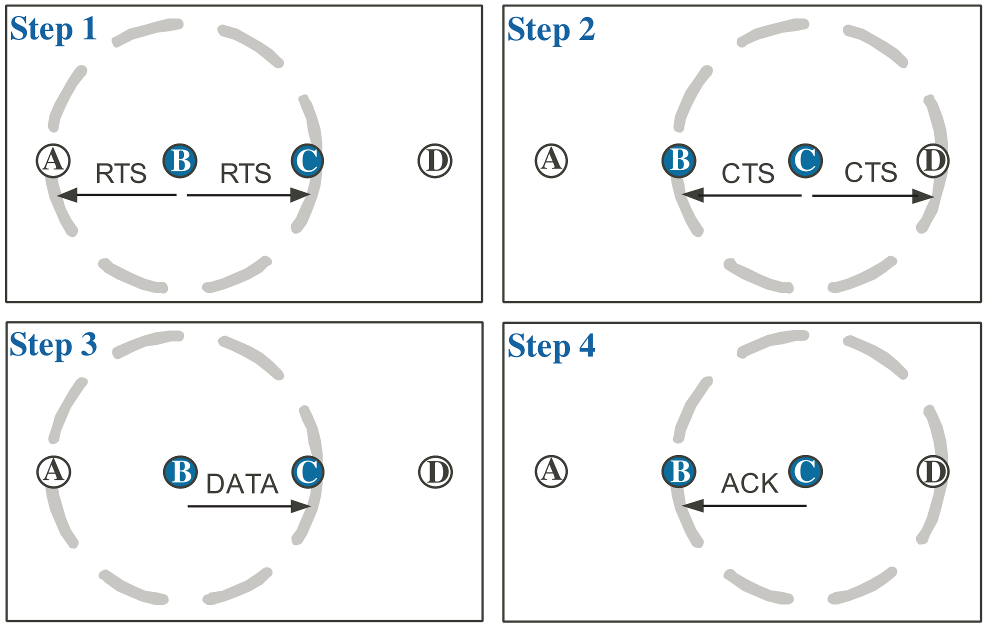


Figure 4.2: Effectiveness of RTS/CTS handshake with transmission ranges

---

handshaking minimizes the collisions among hidden terminals.

The analytical model of Bianchi [9] used the average time that the channel is successful in transmission, T_s, and the average time that the channel has a collision, T_c, as absolute values to evaluate the throughput. However, this model did not represent the actual performance accurately because it did not consider the RTS state. In our model, we consider the RTS state, which leads to more realistic results.

4.1.1 Model Assumptions

A terminal in transmission can be in one of several states: an idle state, a backoff state, a RTS/CTS state, and a transmitting state. The current state of a terminal depends only on its immediate past history. Hence, we can model the terminal state using Markov chain analysis [24].

A collision occurs when two or more terminals try to send RTS frames at the same time or when any terminal tries to send a RTS frame and a terminal in receiver range is either active or starts to send its own RTS frame. In the case of a busy channel, the terminal waits for a random backoff period before attempting to retransmit. For this study, we make the following assumptions:

1. N is the number of terminals in the contact range of a terminal in two-hop scenarios.

2. The time step, t, equals the DIFS.

3. All MAC frames have fixed length and require n time steps for transmission.

4. The backoff counter freezes when the channel is sensed busy and decrements by one for each time step when the channel is sensed free.

5. An error control protocol is used so that the channel appears noise free, as far as the MAC protocol is concerned.

6. The probability that a terminal reserves a particular time slot in stage i is $\alpha_i = 1/w_i$, where w_i is the size of the backoff window in the i-th backoff stage.

4.1.2 State Transition Diagram

A terminal in transmission can be in one of several states: an idle state, a backoff state, a RTS state, and a transmitting state. The RTS state is labeled R in Figure 4.3. Figure 4.3 shows a Markov transition diagram for the transmission states of a tagged terminal. In the figure, p denotes the probability of frame collision and f is the probability that the channel is free. At backoff stage i, the probability of choosing random backoff value is given by

$$\alpha_i = 1/w_i \tag{4.1}$$

where w_i is the size of the backoff window.

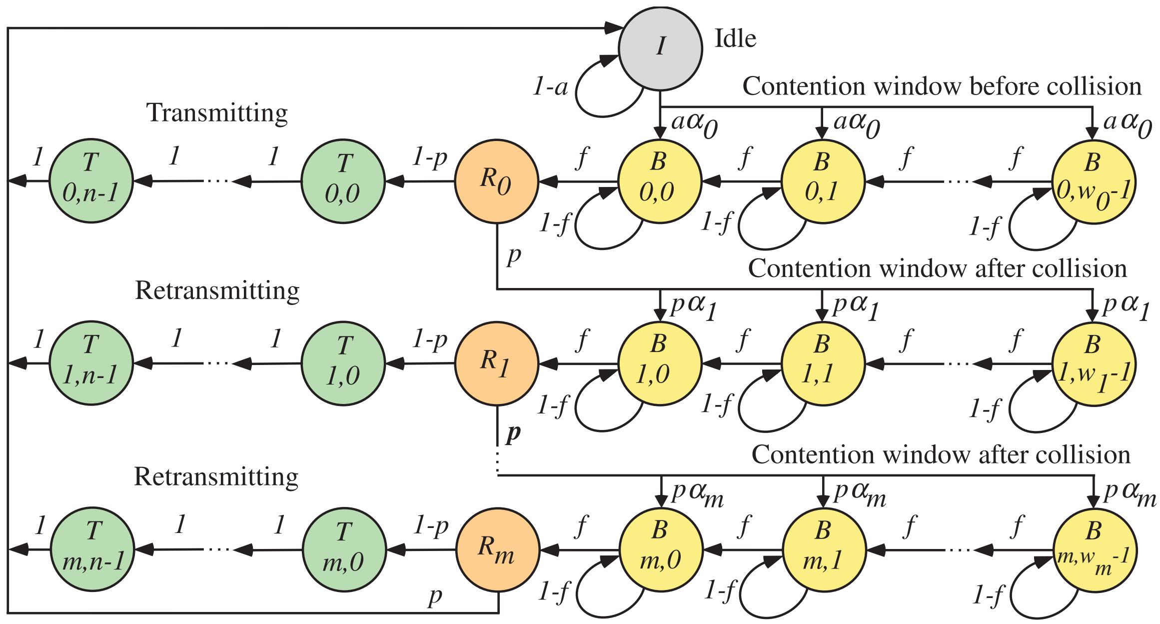


Figure 4.3: State transition diagram for Markov chain model of ad hoc networks with RTS/CTS

By using the model shown in Figure 4.3, we can evaluate the performance of wireless ad hoc networks using RTS/CTS mode. From Figure 4.3, the state R_0 has two transition possibilities. The first is successfully to transmit the RTS frame with probability $(1-p)$. The second possibility is that the RTS frame suffers a collision with probability p. After m failed attempts, the sender gives up and returns to the idle state. At steady state, we can apply flow balance [25] to the first set of backoff states, $\mathcal{B}_0$, in Figure 4.3, so that

$$B_{0,j} = \frac{(w_0 - j)\ a\ I}{w_0\ f}, \quad \text{where} \quad 0 \le j < w_0 \tag{4.2}$$

and where f is the probability that the channel is free. The probability that a terminal starts to send RTS at stage 0 is given by

$$R_0 = B_{0,0} \times f = a\ I \tag{4.3}$$

The probability that a terminal starts to send a data frame at stage 0 is given by

$$T_{0,0} = R_0\ (1-p) = a\ I\ (1-p) \tag{4.4}$$

From the state transition diagram in Figure 4.3, we can easily prove that all transmission states in the set $\mathcal{T}_0$ are equal, so that

$$T_{0,0} = T_{0,1} = \cdots = T_{0,n-1} \tag{4.5}$$

Using the preceding argument, we can find expressions for the states in the sets $\mathcal{B}_i$ and $\mathcal{T}_i$ as

$$B_{i,j} = \frac{(w_i - j)\ a\ I\ p^i}{w_i\ f} \tag{4.6}$$

$$T_{i,j} = a\ I\ p^i\ (1-p) \tag{4.7}$$

where $0 \le i \le m$ and $0 \le j < w_i$. Also, we can find expressions for the RTS states as

$$R_i = a\ I\ p^i \tag{4.8}$$

Since the sum of all components of the state vector must be unity,

$$I + \sum_{i=0}^{m} R_i + \sum_{i=0}^{m}\sum_{j=0}^{n-1} T_{i,j} + \sum_{i=0}^{m}\sum_{j=0}^{w_i-1} B_{i,j} = 1 \tag{4.9}$$

From (4.6), (4.7), (4.8), and (4.9) we can get an expression for state I as

$$I = \frac{1}{1+[n(1-p)+1]a\sum_{i=0}^{m} p^i + (a/f)\sum_{i=0}^{m}\sum_{j=0}^{w_i-1} X_i} \tag{4.10}$$

where $X_i = (w_i - j)\ p^i\ /\ w_i$.

4.1.3 Estimating the Probabilities f and p

State I depends on the probabilities f and p. These two probabilities depend in turn on the states of the terminal. This is a highly nonlinear system and we have to use iterative techniques to estimate the terminal states (I, B, R, and T). The associated probabilities, f and p, for a given traffic level are defined below. The probability, u_R, that a terminal starts to send RTS at a given time step is given by

$$u_R = \sum_{i=0}^{m} f \times B_{i,0} = \sum_{i=0}^{m} T_{i,0} \tag{4.11}$$

The probability, v, that a terminal is not sending is given by

$$v = I + \sum_{i=0}^{m} \sum_{j=1}^{w_i-1} B_{i,j} + (1-f) \sum_{i=0}^{m} B_{i,0} \tag{4.12}$$

The probability, f, that the channel is free is when all terminals are not sending is

$$f = v^{N-1} \tag{4.13}$$

The collision probability, p, is the probability that two or more terminals start to send RTS simultaneously, and is

$$p = \sum_{k=2}^{N} \binom{N}{k} u_R^k v^{N-k} \tag{4.14}$$

We used Algorithm 1 and equations (4.13) and (4.14) to estimate the probabilities f and p.

4.1.4 Performance Metrics

The throughput, Th, is defined as the average number of successfully transmitted frames per contention slot. Th is given by

$$Th = N \sum_{i=0}^{m} \sum_{j=0}^{n-1} T_{i,j} \tag{4.15}$$

The terminal access probability, p_a, essentially gives the ratio of frames transmitted through the system relative to the total number of arriving frames in one time step [24]:

$$p_a \quad = \quad \frac{Th}{N_a}, \qquad \text{where} \qquad N_a = N \times a \tag{4.16}$$

The delay occurs due to RTS frame retransmission. The average number of RTS frame retransmissions, n_a, before a terminal gets access to the medium for finite retransmission attempts is calculated as

$$n_a = \sum_{i=0}^{m} i(1 - p_a)^i \; p_a \tag{4.17}$$

By using the summation of arithmetic-geometric series, we find

$$n_a = \frac{(1-p_a)\left[1-(m+1)(1-p_a)^m+m(1-p_a)^{m+1}\right]}{p_a}, \tag{4.18}$$

and, as m goes to infinity, n_a simplifies to

$$n_a = \frac{1 - p_a}{p_a} \tag{4.19}$$

The average energy, E_a, required to successfully transmit a frame is an important performance measure, especially for mobile wireless systems. The average energy is estimated by counting the number of retransmissions until the frame is correctly received. At very low traffic value, a four-way handshaking mechanism requires extra energy in the beginning of the traffic. The average energy, E_a^R, required to transmit a frame including RTS and data frames is given by,

$$E_a^R = \quad \textstyle\sum_{i=0}^{m} \left[(i+1)E_1 + E_0\right](1 - p_a)^i p_a \tag{4.20}$$

where E_1 is the average energy required to transmit RTS frames. We can rewrite equation (4.20) as

$$E_a^R =$$

$$\frac{E_1}{p_a}\left[p_a - p_a(1-p_a)^{m+1}\right] +$$
$$\frac{E_1(1-p_a)}{p_a}\left[1-(m+1)(1-p_a)^m + m(1-p_a)^{m+1}\right] +$$
$$E_0\left[1-(1-p_a)^{m+1}\right] \tag{4.21}$$

As m goes to infinity, equation (4.21) reduces to

$$E_a^R = \frac{E_1}{p_a} + E_0 \tag{4.22}$$

We can normalize E_a^R in equation (4.22) as

$$\overline{E_a^R} = \frac{E_a^R}{E_0} = \frac{E_1}{E_0 p_a} + 1 \tag{4.23}$$

and we can express it in dB as

$$\overline{E_a^R}(dB) = 10\log\left[\frac{E_1}{E_0 p_a} + 1\right] \tag{4.24}$$

4.2 Results Analysis

Here, we report important performance parameters of the protocol and show the effect of a RTS/CTS frame on network performance. Figure 4.4 shows the dependence of throughput versus input traffic for a two-way handshaking mechanism and a four-way handshaking mechanism. The throughput shows its maximum value over all of the input traffic range when using a four-way handshaking mechanism. Moreover, for a two-way handshaking mechanism, the throughput reaches its peak at very low input traffic. However, the maximum value is still less than the peak throughput of a four-way handshaking mechanism. According to the discussion in Section 1.1 and Figure **??**, this could be caused by the large data frame length, which reduces the channel utilization as the sender might send while the channel is already busy.

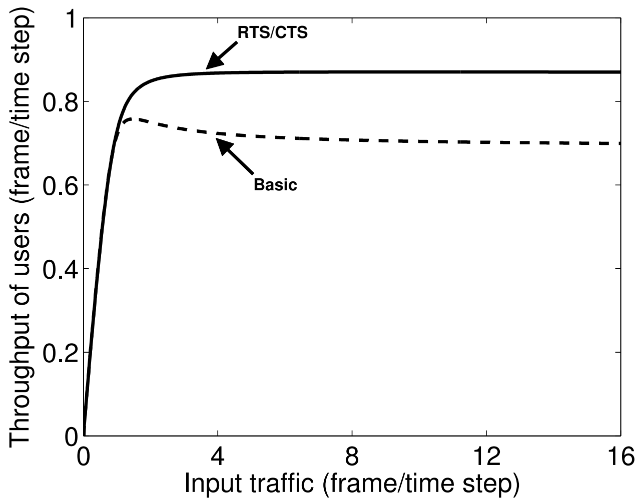


Figure 4.4: Throughput versus input traffic for two-way and four-way handshaking mechanisms when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, and $L_F = 512$ Bytes

Figure 4.5 shows the effects of RTS/CTS on terminal access probability. A four-way handshaking mechanism results in slightly higher terminal access probability than the two-way handshaking mechanism.

Figure 4.6 shows that the effects of RTS/CTS on the average frame delay occurs due to frame retransmission, in turn due to frame collisions. It is clear that using a four-way handshaking mechanism results in less delay than does a two-way handshaking mechanism.

Figure 4.7 shows that the effects of a four-way handshaking mechanism on the average energy occur due to frame retransmission, in turn due to frame collisions. We observe from this figure that a four-way handshaking mechanism requires extra energy at very low traffic value, according to equation (4.24). Figure 4.7 shows also that the average energy has a lower value over most of the input traffic range when using a four-way handshaking mechanism.

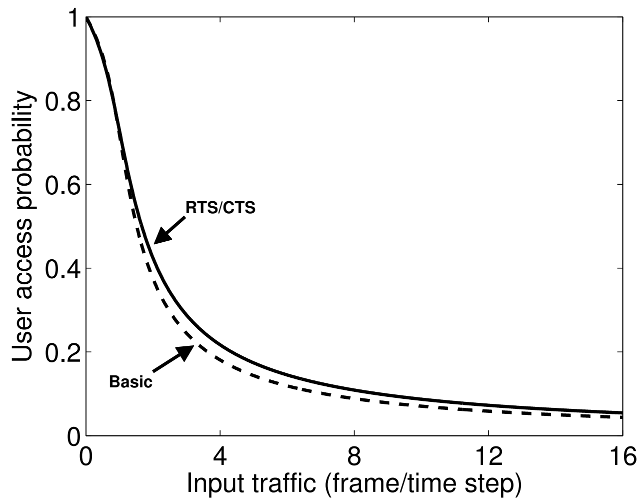


Figure 4.5: Terminal access probability versus input traffic for Basic and RTS/CTS mechanisms when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, and $L_F = 512$ Bytes

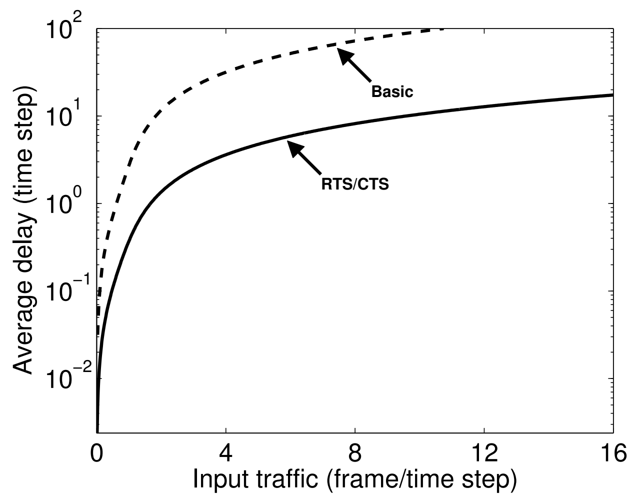


Figure 4.6: Average number of frame retransmissions for ad hoc networks versus input traffic for two-way and four-way handshaking mechanisms when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, and $L_F = 512$ Bytes

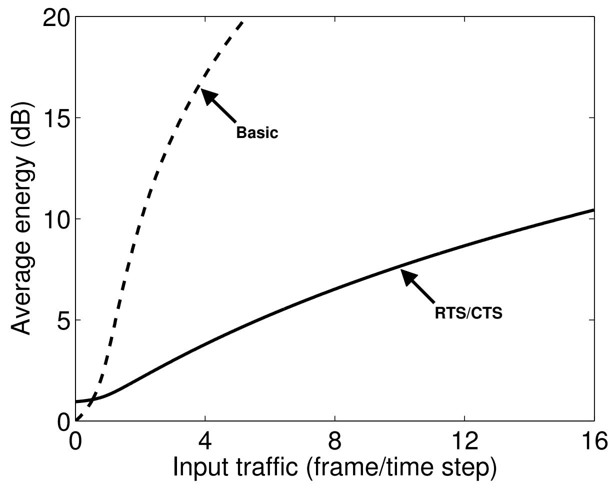


Figure 4.7: Average energy of terminal versus input traffic for two-way and four-way handshaking mechanisms when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, and $L_F = 512$ Bytes

4.3 Chapter Summary

We propose a realistic model for wireless ad hoc networks using a Markov chain model. With this model, we can analyze the performance of wireless ad hoc networks due to changes of backoff strategies, finite retransmission attempts, and the freezing of the backoff counter. Our work predicts ad hoc protocol performance very accurately considering the RTS frame. Using the developed model, results illustrate that the protocol performance is strongly enhanced by using the four-way handshaking mechanism.

Chapter 5

Modelling of Wireless ad hoc Networks in the Presence of Channel Noise

In this chapter, we present a cross-layer model of a MAC layer for wireless ad hoc networks that takes into account channel bit errors and frame retry limits for a two-way handshaking mechanism. Our contributions are:

(a) Proposing a model that considers all levels of terminal traffic and finite retransmission attempts, and which also supports an arbitrary backoff strategy and takes channel errors into account;

(b) Verifying that using a NAK message in wireless ad hoc networks could achieve better system performance since, due to channel errors, if the receiver sends a ACK/NAK, the sender could retransmit using the same backoff window size;

(c) Evaluating the effect of frame error probability on the throughput, access probability, and average number of retransmissions.

ty on the throughput, access probability, and average number of retransmissions. We first outline the model of channel BER. Then, we present the proposed analytical model of wireless ad hoc networks with a non-ideal channel condition. This includes the assumptions, transition probabilities for the model, estimating the free channel and collision probabilities, and the performance metrics for the model. We follow with experimental results of the proposed model. We also compare our results with the model in Chapter 3.

5.1 Channel Bit Error Rate Model

The derivation of the BER for a given signal modulation scheme and channel fading model is provided by Proakis [82] and Goldsmith [83,84]. As with most fading channel BER estimations, these authors based their analysis on the evaluation of the bit error rate,

$$e_b = \int_0^\infty \rho(\gamma) g(\gamma) d\gamma \tag{5.1}$$

where $\rho(\gamma)$ is the probability density function (PDF) of the received SNR, γ, and $g(\gamma)$ is a function that depends on the type of modulation used for transmission. Thus, we can summarize the BER for a slow fading Rayleigh channel as

$$e_b^{Rayleigh} = \frac{1}{2}\left(1 - \sqrt{\frac{\frac{E_b}{N_0}}{1 + \frac{E_b}{N_0}}}\right) \tag{5.2}$$

The Nagakami fading channel encompasses the case of a Rayleigh environment with non line of sight and the case of a Rician-environment with Line of Sight (LOS) fading channels [82,85]. The error probability distribution for linear BPSK signalling in the Nagakami fading channel is derived from the Nagakami probability distribution (given by Proakis [82]) by evaluating the integral in equation (5.1):

$$e_b^{Nagakami} = \frac{m^m}{2\Gamma(m)\gamma} \int_0^\infty \frac{\alpha^{m-1}}{e^{\frac{m\alpha}{\gamma}}} \sqrt{\alpha} d\alpha \tag{5.3}$$

where α is the amplitude of the transmitted signal and m is the ratio of moments [82]. The Gamma function, $\Gamma(m)$, is given by

$$\Gamma(m) = \int_0^{\infty} t^{m-1} e^{-t} \, dt \tag{5.4}$$

Assuming hard decoding and forward error correction (FEC), the probability that the payload of a transmitted frame is in error, e_f, is given by:

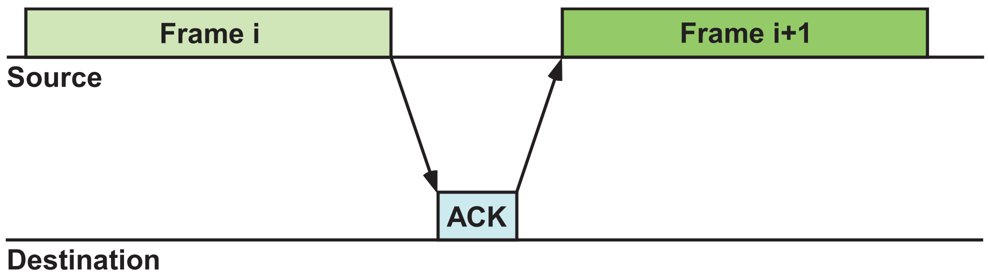
$$e_f \;=\; 1 - (1 - e_b)^{L_P - b} \tag{5.5}$$

where e_b is the BER, L_P is the length of the payload of the MAC frame in bits, and b is the maximum number of bits that can be corrected. According to the modulation scheme, substituting the BER from (5.2) or (5.3) into (5.30) yields the probability that a transmitted frame is in error.

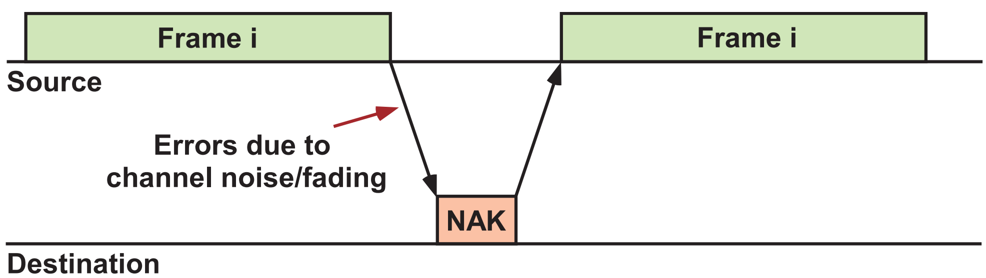
5.2 A MAC Protocol with Error Control

A terminal in transmission can be in one of several states: an idle state, a backoff state, or a transmitting state. The current state of a terminal depends only on its immediate past history. Hence, we can model the terminal state using Markov chain analysis [24]. The sending terminals compete with each other to access the medium.

A collision takes place when two or more terminals try to send frames at the same time. In the case of a busy channel, the terminal waits for a random backoff period before attempting to retransmit. Figure 5.1 shows identification of frame errors in a two-way handshaking mechanism using ACK/NAK. Figure 5.1(a) shows the case when the receiver received the frame without any error or collision, while Figure 5.1(b) shows the case when the receiver received the frame in error. Table 5.1 compares the frame transmitting events for a cross-layer model with error control and a standard MAC model without error control. In the standard MAC model, the sender knows



(a)



(b)

Figure 5.1: Identification of frame errors in two-way handshaking mechanism (a) Case when receiver receives frame without any error (b) Case when receiver receives frame in error

a collision happens when the sender does not receive feedback information from the receiver for a duration of the timeout period. The sender knows an error happens when the sender receives a NAK from the receiver.

We see that in the standard model, frame errors are equivalent to frame collisions as far as the sender is concerned. For this study, we make the following assumptions:

1. All network terminals, N, are in radio contact with each other. This means that the effects of hidden terminal problems and captures are not considered in the given analysis.

Event	**Cross-Layer Model Mac + Error Control**	**Standard MAC Model No Error Control**
No Collision - No Error	ACK	ACK
No Collision - Error	NAK	Timeout
Collision - No Error	Timeout	Timeout
Collision - Error	Timeout	Timeout

Table 5.1: Frame transmitting events

2. A two-way handshaking mechanism using ACK/NAK.
3. The time step, t, equals the DIFS period.
4. An idle terminal issues a request to transmit a frame during a time step with probability a.
5. All MAC frames have fixed length and require n time steps for transmission.
6. The backoff counter freezes when the channel is sensed busy and decrements by 1 when the channel is sensed free.
7. The probability that a terminal reserves a particular time slot in the i-th stage is $\alpha_i = 1/w_i$, where w_i is the size of the backoff window in the i-th backoff stage.

Figure 5.2 shows a Markov transition diagram for the transmission states of a tagged terminal. In the figure, e_f is the probability that a transmitted frame is in error or received ACK is in error and p is the collision probability, the probability that two or more terminals start to send simultaneously. At backoff stage i, the probability of choosing random backoff value is given by

$$\alpha_i = 1/w_i \tag{5.6}$$

where w_i is the size of the backoff window.

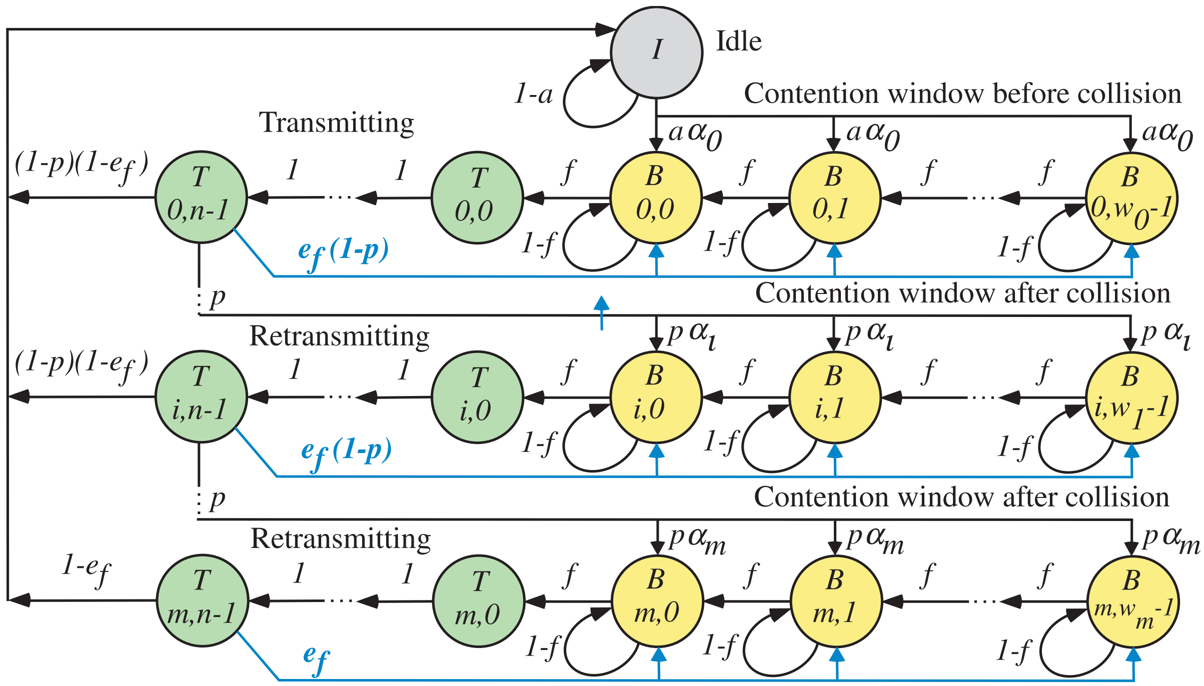


Figure 5.2: State transition diagram for MAC model with differentiation between error and collisions

We characterize two causes for frame loss: frame error and collision. By using the model shown in Figure 5.2, we can evaluate the performance of wireless ad hoc networks under different values of e_b. From Figure 5.2, the state $T_{i,n-1}$ has three transition possibilities. First, it may successfully transmit the frame with no collision and no error. It will return back to state I. In the second possibility, the frame is in error with no collision. It will return back to same the backoff stage. In the third possibility, the frame collides with or without errors. The frame will retransmit after doubling the backoff window size in the next stage. After m collision attempts, the sender gives up and returns to the idle state. Therefore, in the last stage, it does not matter whether collision occurs or not. At steady state, we can apply flow balance to the first set of backoff states, $\mathcal{B}_0$, in Figure 5.2, so that

$$B_{0,j} = \frac{(w_0 - j)}{w_0\ f} \times [a\ I + e_f(1-p)\ T_{0,n-1}] \tag{5.7}$$

where $0 \leq j < w_0$. The probability that a terminal starts to send at stage 0 is given by

$$T_{0,0} = B_{0,0} \times f = a\ I + e_f(1-p)\ T_{0,n-1} \tag{5.8}$$

From the state transition diagram in Figure 5.2, as the transition probabilities for transmission states are equal to 1, we can prove that all transmission states in the set $\mathcal{T}_0$ are equal, namely,

$$T_{0,0} = T_{0,1} = \cdots = T_{0,n-1} \tag{5.9}$$

From (5.7) and (5.8), we obtain an expression for state $T_{0,0}$ as

$$T_{0,0} = a\ I + e_f(1-p)\ T_{0,0} \tag{5.10}$$

$$T_{0,0} = \frac{a\ I}{1 - e_f(1-p)} \tag{5.11}$$

Using the preceding argument, we can find expressions for the states in the sets $\mathcal{B}_i$ and $\mathcal{T}_i$ as

$$T_{i,j} = \frac{a\ I\ p^i}{[1 - e_f(1-p)]^{(i+1)}} \tag{5.12}$$

$$B_{i,j} = \frac{w_i - j}{w_i\ f}\,[p\ T_{i-1,n-1} + e_f(1-p)\ T_{i,n-1}] \tag{5.13}$$

where $0 \leq i \leq m$ and $0 \leq j < w_i$. From (5.12) and (5.13), we can get an expression for state $B_{i,j}$ as

$$B_{i,j} = \frac{(w_i - j)\ a\ I\ p^i}{w_i\ f} \times \left[\frac{1}{[1-E]^i} + \frac{E}{[1-E]^{i+1}}\right] \tag{5.14}$$

where $E = e_f(1-p)$. The sum of all components of the state vector must be unity:

$$I + \sum_{i=0}^{m}\sum_{j=0}^{n-1} T_{i,j} + \sum_{i=0}^{m}\sum_{j=0}^{w_i-1} B_{i,j} = 1 \tag{5.15}$$

Finally, from (5.14) and (5.12), we can get an expression for state I,

$$I = \frac{1}{1 + n\ a\sum_{i=0}^{m} X_i + \frac{a}{f}\sum_{i=0}^{m}\sum_{j=0}^{w_i-1}\frac{(w_i-j)\ p^i}{w_i}\left[Y_i + Z_i\right]} \tag{5.16}$$

where $X_i = \frac{p^i}{\left[1-e_f(1-p)\right]^{(i+1)}}$, $Y_i = \frac{1}{[1-e_f(1-p)]^i}$, and $Z_i = \frac{e_f(1-p)}{[1-e_f(1-p)]^{i+1}}$

5.3 Estimating the Free Channel (f), and Collision Probabilities (p)

State I depends on the probability e_f as well as on the probabilities f and p. Once again, this is a highly nonlinear system and we have to use iterative techniques to estimate the terminal states (I, T, and B) [58]. The associated probabilities, f and p, for a given traffic level are defined below. The probability, u, that a terminal starts to send at a given time step is given by

$$u = \sum_{i=0}^{m} f \times B_{i,0} = \sum_{i=0}^{m} T_{i,0} \tag{5.17}$$

The probability, v, that a terminal is not sending is given by

$$v = I + \sum_{i=0}^{m}\sum_{j=1}^{w_i-1} B_{i,j} + (1-f)\sum_{i=0}^{m} B_{i,0} \tag{5.18}$$

The probability, f, that the channel is free when all terminals are not sending is

$$f = v^{N-1} \tag{5.19}$$

The collision probability, p, the probability that two or more terminals start to send simultaneously, is

$$p = \sum_{k=2}^{N}\binom{N}{k} u^k v^{N-k} \tag{5.20}$$

We used Algorithm 1 and equations (5.19) and (5.20) to estimate the probabilities f and p.

5.4 Performance Metrics

The throughput, Th, is defined as the average number of successfully transmitted frames per contention slot. Th is given by

$$Th = (1-p)(1-e_f)N \sum_{i=0}^{m}\sum_{j=0}^{n-1} T_{i,j} \tag{5.21}$$

The average input traffic to the system N_a is given by

$$N_a = N \times a \tag{5.22}$$

The average frame acceptance probability, p_a, for a given terminal is defined as the probability that a terminal is able to access the channel when it is ready to send. The probability p_a can be written as the ratio of frames transmitted through the system relative to the total number arriving of frames in one time step [24], so that

$$p_a = \frac{Th}{N_a} \tag{5.23}$$

The delay occurs due to frame retransmission, in tern due to channel errors or frame collisions. The average number of frame retransmissions, n_a, is calculated as

$$n_a = \sum_{i=0}^{\infty} i(1-p_a)^i \tag{5.24}$$

$$n_a = \frac{1-p_a}{p_a} \tag{5.25}$$

The average energy, E_a, required to successfully transmit a frame is an important performance measure, especially for mobile wireless systems. The average energy is estimated by counting the number of retransmissions until the frame is correctly received and is calculated as

$$E_a = E_0 \quad p_a \sum_{i=0}^{\infty}(1+i)(1-p_a)^i \tag{5.26}$$

$$E_a = \frac{E_0}{p_a} \tag{5.27}$$

We can normalize E_a in equation (5.27) as

$$\overline{E_a} = \frac{E_a}{E_0} = \frac{1}{p_a} \tag{5.28}$$

and we can express it in dB as

$$\overline{E_a}(dB) = -10 \log p_a \tag{5.29}$$

5.5 Numerical Results

We investigated the effect of transmission errors by plotting throughput versus input traffic. The other parameters were $N = 16$, $m = 3$, $n = 7$, $L_F = 512$ Bytes, and e_b was varied as $e_b = 10^{-6}$, 10^{-5}, 10^{-4}, and 10^{-3}. The initial window size, w_0, was selected to be equal to the number of terminals, N. The probability that a transmitted frame is in error, e_f, is given by:

$$e_f = 1 - (1 - e_b)^{L_F - b} \tag{5.30}$$

where e_b is the BER, L_F is the length of the MAC frame in bits, and b is the maximum number of bits that can be corrected.

Table 5.2 shows the relationship between e_f and e_b when $L_F = 512$ Bytes and $b = 0$ based on equation (5.30). In Chapter 3, we showed that this selection of the initial window size achieves the best performance in terms of throughput, terminal access probability, delay, and average energy. Figure 5.3 shows the throughput versus input traffic in presence of channel noise. For small values of e_b, the throughput approaches

e_b	e_f
10^{-6}	5.12×10^{-4}
10^{-4}	49.92×10^{-3}
10^{-3}	4.01×10^{-1}
10^{-2}	9.94×10^{-1}

Table 5.2: Probability of frame error versus BER

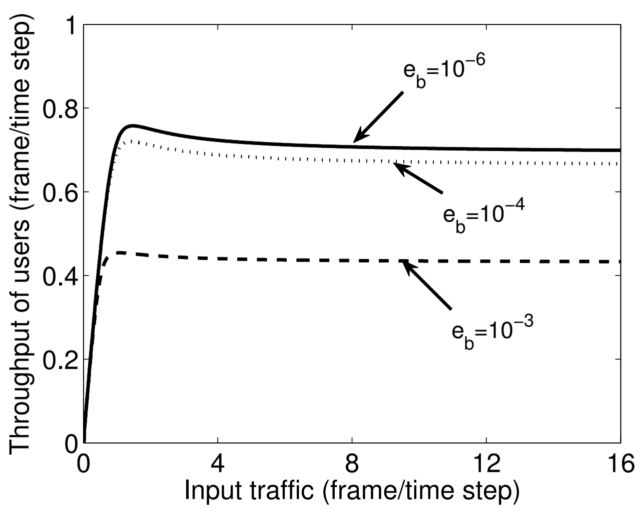


Figure 5.3: Throughput versus input traffic for different values of e_b when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, $L_F = 512$ Bytes, and $e_b = 10^{-6}$, 10^{-4}, and 10^{-3}

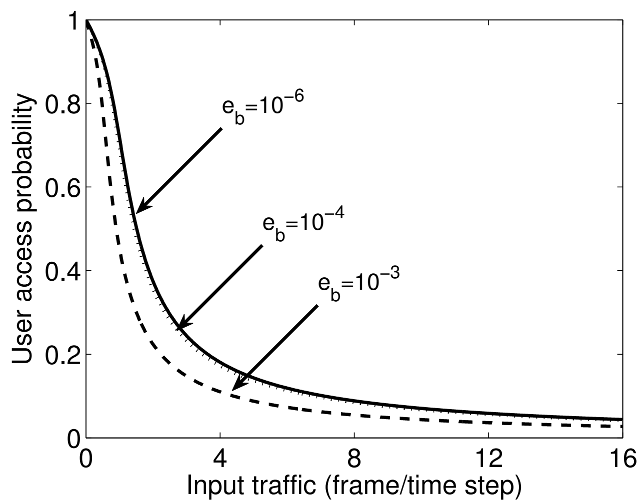


Figure 5.4: Terminal access probability versus input traffic when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, $L_F = 512$ Bytes, and $e_b = 10^{-6}$, 10^{-4}, and 10^{-3}

its maximum value over all of the input traffic range. We conclude that the throughput exhibits its best behaviour when e_b has minimum value. Moreover, the figure shows that the useable range of errors in wireless ad hoc networks is between 10^{-6} – 10^{-3}, where 10^{-3} is the maximum tolerable error. This agrees with previous work [84, 86]. On the one hand, if the error becomes more than 10^{-3}, the throughput decreases dramatically. On the other hand, any error less than 10^{-4} results in approximately the same throughput.

Figure 5.4 shows the effects of e_b on terminal access probability. The figure indicates that as the value of e_b decreases, the terminal access probability increases for the same input traffic.

Figure 5.5 shows that the effects of e_b on the average frame delay occur due to frame retransmission caused by channel errors, or frame collisions. The figure indicates that as the value of e_b decreases, the average number of frame

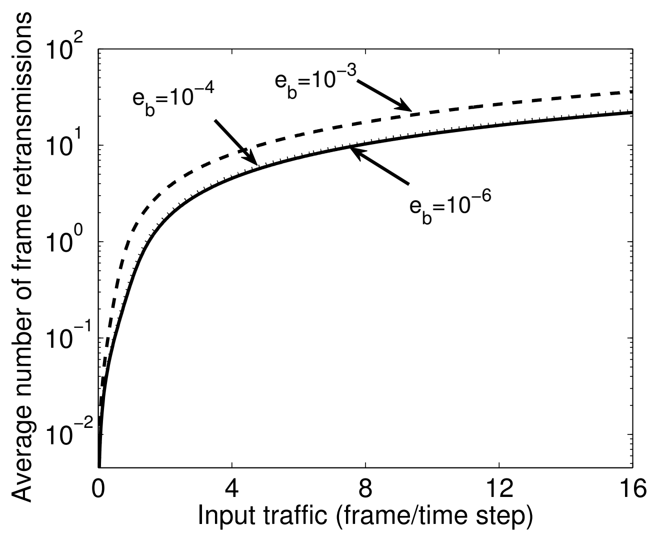


Figure 5.5: Average number of frame retransmissions versus input traffic when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, $L_F = 512$ Bytes, and $e_b = 10^{-6}$, 10^{-4}, and 10^{-3}

retransmissions decreases for the same input traffic.

Figure 5.6 shows that the effects of e_b on the average energy occurs due to frame retransmission, perhaps due to channel errors or frame collisions. The figure indicates that as the value of e_b decreases, the average energy decreases for the same input traffic.

5.5.1 Basic Model in Presence of Channel Errors

By comparing a cross-layer model with error control with the standard MAC model, we can verify the effect of channel errors. A cross-layer model assumes that, due to channel errors, the receiver sends an ACK/NAK and, hence, the sender could retransmit using the same backoff window size. Figure 5.7 shows a Markov transition diagram for the transmission states of a tagged terminal for the Standard IEEE 802.11 in the presence of channel errors. By using the model shown in Figure 5.7,

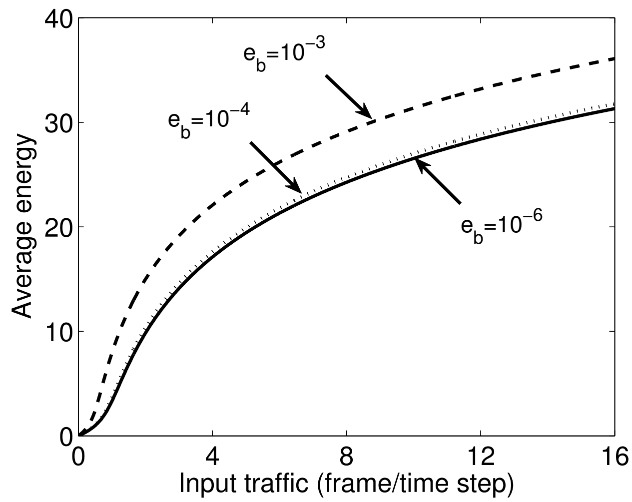


Figure 5.6: Average energy versus input traffic for different values of e_b when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, $L_F = 512$ Bytes, and $e_b = 10^{-6}$, 10^{-4}, and 10^{-3}

we can evaluate the performance of wireless ad hoc networks under different values of e_b. From Figure 5.7, the state $T_{i,n-1}$ has two transition possibilities. In the first, successfully transmitting the frame without collisions and no errors, with probability $1 - p - e_f$, it will return to state I. In the second, the frame collides or the frame is in error, with probability $p + e_f$, the frame will retransmit after doubling the backoff window size in the next stage. In both cases, a terminal detects collision or frame errors due to lack of ACK signal for the timeout period. After m failed attempts, the sender gives up and returns to the idle state. Therefore, in the last stage, it does not matter whether collision or error occurred. Accordingly, the probability of collision, p, and the probability that the frame is in error, e_f, are not included in the output of the last state. At steady state, we can apply flow balance to the first set of backoff states, $\mathcal{B}_0$, in Figure 5.7, so that

$$B_{0,j} = \frac{(w_0 - j)a}{w_0\ f} \times I \quad \text{, where} \quad 0 \leq j < w_0 \tag{5.31}$$

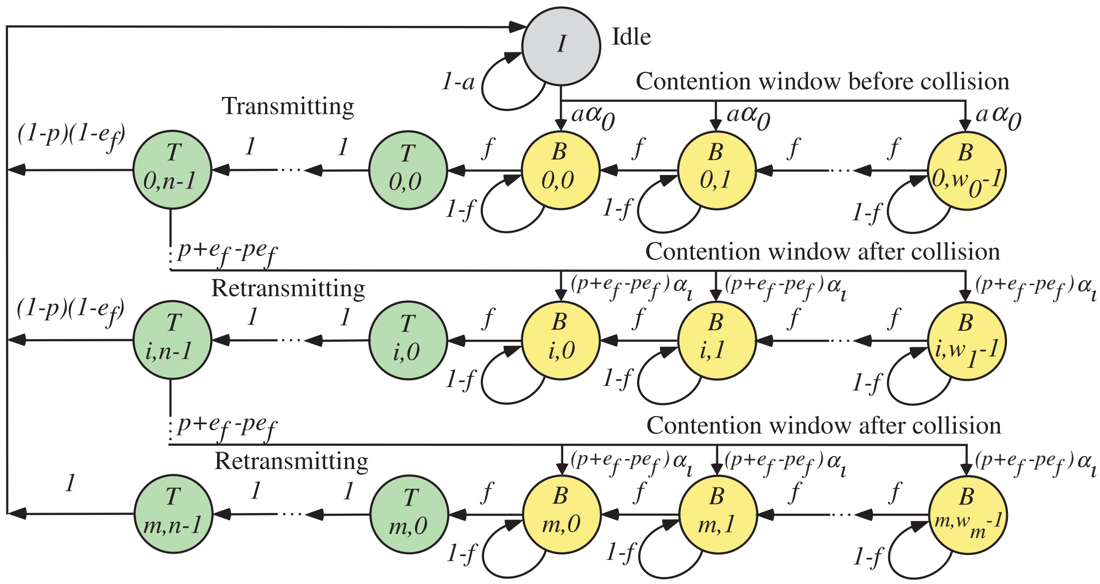


Figure 5.7: State transition diagram for MAC model without differentiation between error and collisions

The probability that a terminal starts to send at stage 0 is given by

$$T_{0,0} = B_{0,0} \times f = a \times I \tag{5.32}$$

From the state transition diagram in Figure 5.7, as the transition probabilities for transmission states are equal to 1, we can prove that all transmission states in the set $\mathcal{T}_0$ are equal:

$$T_{0,0} \;=\; T_{0,1} = \cdots = T_{0,n-1} \tag{5.33}$$

Using the preceding argument, we can find expressions for the states in the sets $\mathcal{B}_i$ and $\mathcal{T}_i$ as

$$B_{i,j} = \frac{(w_i - j)a}{w_i\ f} \times I\ (p + e_f)^i \tag{5.34}$$

$$T_{i,j} \;=\; a\ I\ (p + e_f)^i \tag{5.35}$$

where $0 \leq i \leq m$ and $0 \leq j < w_i$. The sum of all components of the state vector must be unity:

$$I + \sum_{i=0}^{m} \sum_{j=0}^{n-1} T_{i,j} + \sum_{i=0}^{m} \sum_{j=0}^{w_i-1} B_{i,j} = 1 \tag{5.36}$$

From (5.34) and (5.35), we can obtain an expression for state I as

$$I = \frac{1}{1 + n \times a \sum_{i=0}^{m} (p + e_f)^i + (a/f) \sum_{i=0}^{m} \sum_{j=0}^{w_i-1} (w_i - j)(p + e_f)^i / w_i} \tag{5.37}$$

The throughput, Th, is given by

$$Th = (1 - p - e_f) N \sum_{i=0}^{m} \sum_{j=0}^{n-1} T_{i,j} \tag{5.38}$$

5.5.2 Comparing the Two Models

To investigate the effect of error control on throughput, we compared a cross-layer model with error control to the standard MAC model. Figure 5.8 compares the throughput that resulted from the two models in Figure 5.2 and Figure 5.7. The figure shows that the cross-layer model proves more useful for a high BER. We see that when $e_b < 10^{-4}$ the throughput shows its maximum value over most of the input traffic range for both models. For the same given bit error rate and channel conditions, the standard MAC model reduces system performance. We also observed that the throughput exhibits its best behaviour when $e_b < 10^{-4}$. On the other hand, for $e_b > 10^{-4}$, the throughput has no peak similar to that of $e_b < 10^{-4}$. However, the maximum value is still less than the peak throughput of $e_b = 10^{-6}$. We conclude that using a cross-layer model is highly recommended to enhance the throughput when $e_b > 10^{-4}$.

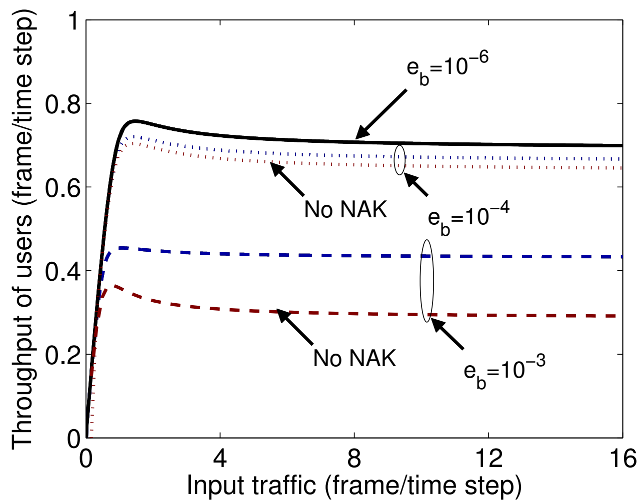


Figure 5.8: Comparison of throughput between NAK-based model and standard IEEE 802.11 model when $N = 16$, $w_0 = 16$, $m = 3$, $n = 7$, $L_F = 512$ Bytes, and $e_b = 10^{-6}$, 10^{-4}, and 10^{-3}

5.6 Chapter Summary

We proposed a realistic model for wireless ad hoc networks that considers transmission errors. This model can be used to analyze the performance of ad hoc networks due to changes of backoff strategies, finite retransmission attempts, and the freezing of the backoff counter. Our work becomes important and meaningful as it predicts ad hoc protocol performance very accurately when considering transmission errors. Using the developed model, results illustrate that the protocol performance strongly depends on the BER. When the BER increases, throughput degrades and frame delay, as well as average energy, increases. For a high BER, a cross-layer model results in better performance than does the standard MAC model.

With realistic protocol modelling, any improvement to protocol parameters can be modelled and analyzed. This work can be extended to include RTS/CTS mechanisms, adaptive backoff based on the traffic load, and dynamic backoff window size adjustment.

Chapter 6

Modelling Quality of Service of Wireless ad hoc Networks using Enhanced Distributed Channel Access

With the growing popularity and acceptance of IEEE 802.11 WLANs, it is essential to focus on QoS enhancement at the MAC layer of wireless ad hoc networks. The EDCF proposed by the IEEE 802.11e [3, 4] is a contention-based MAC protocol supporting service differentiation through different inter-frame spaces, contention window limits, and persistence factors for different traffic priority classes. A short AIFS and small backoff window size limits allow the high-priority frames to start contending for the channel earlier and to complete their backoff sooner. As a result, the probability of sending the frame increases.

Here, we present a new analytical model of a MAC layer for wireless ad hoc networks that takes into account QoS of the MAC layer for a two-way handshaking mechanism. The model assumes two service classes: high-priority traffic class (class 1) and low-priority traffic class (class 2). An extension of the model to more QoS levels is easily accomplished.

This model offers flexibility in addressing important design issues, such as the effect of traffic parameters and possible improvements of wireless ad hoc networks. The model identifies the parameters that affect network performance characteristics, including throughput, channel utilization, delay, and average energy. Under this analytical framework, we evaluate the effect of QoS on successful transmission probability and its effect on the performance, particulary when high-priority traffic is dominant.

Our contributions are:

(a) Proposing models that support an arbitrary backoff strategy and take the QoS into account for two service classes that consider all levels of terminal traffic and finite retransmission attempts;

(b) Verifying that using an AIFS duration and minimum backoff window size in wireless ad hoc networks achieve better system performance;

(c) Evaluating the effect of QoS on the throughput, access probability, average number of retransmissions, and average energy.

Initially, we present a proposed analytical model of wireless ad hoc networks with a high-priority traffic class and a low-priority traffic class. This includes the assumptions, transition probabilities for the model, estimating the free channel and collision probabilities, and the performance metrics for the model. We follow with experimental results of the proposed models to evaluate the AIFS and backoff window size.

6.1 Deriving the Models for Two Service Classes

Figure 6.1 shows the basic transmission for an EDCA mechanism between traffic of two different classes. The fixed periods A_1 and A_2 represent $AIFS_1$ and $AIFS_2$ for

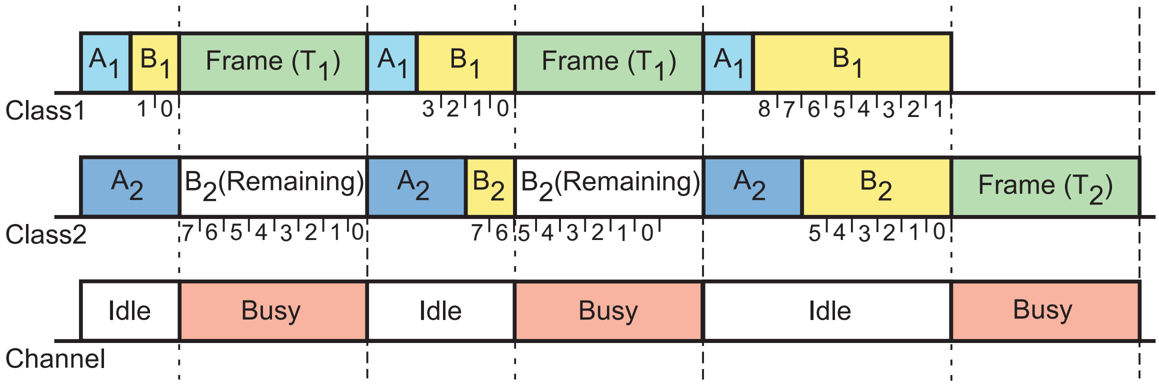


Figure 6.1: EDCA mechanism

class1 and class2 respectively. The random backoff periods B_1 and B_2 represent the backoff window sizes for calss1 and class2 respectively. A data frame is sent from any class when the backoff counter value is zero.

6.1.1 Model Assumptions

In presenting an analytical model of EDCA mechanism, we outline the assumptions, the transition probabilities, and the free channel and collision probabilities for the model. Then we obtain the performance metrics for the model.

For this study, we make the following assumptions:

1. There are two classes of terminals. N_1 is the number of terminals in the high-priority class. N_2 is the number of terminals in the low-priority class.

2. All network terminals are in radio contact with each other. This means that the effects of hidden terminal problems are not considered in the analysis.

3. An idle terminal issues a request to transmit a frame during a time step with probability a_1 and a_2 for high-priority traffic and low-priority traffic, respectively.

4. The total time steps for $AIFS_1$, high-priority class, is n_1.

5. The total time steps for $AIFS_2$, low-priority class, is n_2.

6. All MAC frames have fixed length and require n_3 time steps for transmission.

7. The probability that a terminal reserves a particular time slot for class 1 is $\alpha_1 = 1/w_1$, and for class 2 is $\alpha_2 = 1/w_2$, where w_1 is the size of the backoff window for class 1 and w_2 is the size of the backoff window for class 2.

8. We use a constant backoff window size for simplicity.

6.1.2 State Transition Diagram

A terminal can be in one of several states: an idle state, an AIFS state, a backoff state, or a transmitting state. The current state of a terminal depends only on its immediate past history. Hence, we can model the terminal state using Markov chain analysis [24]. The sending terminals compete with each other to access the medium.

Figure 6.2 shows a Markov transition diagram for the transmission states of a tagged terminal for high-priority traffic class. In the figure, p denotes the probability of frame collision and f is the probability that the channel is free. The probability of choosing random backoff value is given by

$$\alpha_1 = 1/w_1 \tag{6.1}$$

where w_1 is the backoff window size for class 1.

From Figure 6.2, the state $T_1(n_3 - 1)$ at the bottom left has two transition possibilities. First, it may successfully transmit the frame with no collision, with probability $1 - p$. It will return back to state I_1. In the second possibility, the frame collides, with probability p. It will return back to state $AIFS_1$. The $AIFS_1$ counter

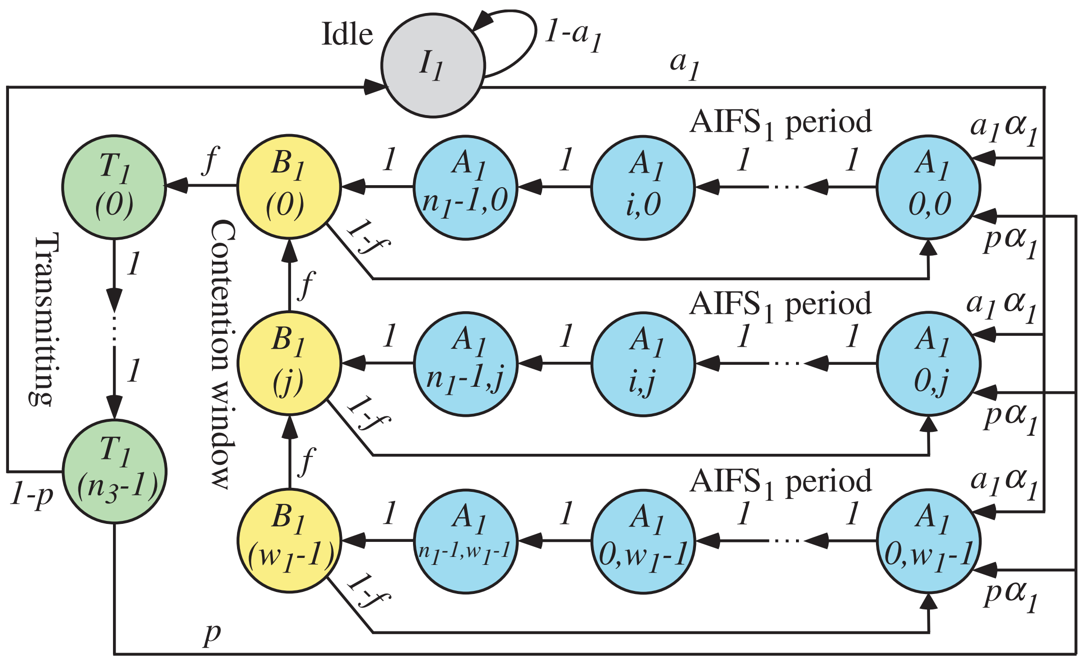


Figure 6.2: State transition diagram for Markov chain model of wireless ad hoc networks, QoS model with high-priority class (class 1)

decrements by 1 and the backoff counter returns to AIFS_1 when the channel is sensed busy, with probability $1 - f$ and decrements when the channel is sensed free.

At steady state, we can apply flow balance [25] to the high-priority class. The AIFS_1 state for class 1 is given by

$$A_1(0,j) = A_1(1,j) = \cdots = A_1(i,j) = \cdots = A_1(n_1 - 1, j) \tag{6.2}$$

$$A_1(0,j) = a_1\alpha_1 I_1 + p\alpha_1 T_1(0) + (1-f)B_1(j) \tag{6.3}$$

The backoff state for class 1 is given by

$$B_1(w_1 - 1) = A_1(w_1 - 1) \tag{6.4}$$

$$B_1(j) = fB_1(j+1) + A_1(0,j), \quad \text{where} \quad 0 \le j < w_1 \tag{6.5}$$

The probability that a terminal starts to send is given by

$$T_1(0) \;=\; f \times B_1(0) \tag{6.6}$$

From the state transition diagram in Figure 6.2, we can easily prove that all transmission states for the high-priority class in the set $\mathcal{T}_1$ are equal, so that

$$T_1(0) \;=\; T_1(1) = \cdots = T_1(n_3 - 1) \tag{6.7}$$

The sum of all components of the state vector must be unity

$$I_1 + n_3 T_1(0) + n_1 \sum_{j=0}^{w_1-1} A_1(0,j) + \sum_{j=0}^{w_1-1} B_1(j) = \;1 \tag{6.8}$$

From (6.3), (6.5), (6.6) and (6.7), we can get an expression for state I_1.

Figure 6.3 shows a Markov transition diagram for the transmission states of a tagged terminal for the low-priority traffic class. In the figure, the AIFS_2 counter decrements by 1 when the channel is sensed free and returns to the initial state when the channel is sensed busy.

From Figure 6.3, the state $T_2(n_3 - 1)$ has two transition possibilities. First, it may successfully transmit the frame with no collision, with probability $1 - p$. It will return to state I_2. In the second possibility, the frame collides, with probability p. It will return to state AIFS_2. The AIFS_2 counter decrements by 1 for the first n_1 states of AIFS_2. For the later states, AIFS_2 counter and the backoff state decrement by probability f when the channel is sensed free. The AIFS_2 counter and the backoff state return to the initial AIFS_2 state when the channel is sensed busy, with probability $1 - f$. The probability of choosing random backoff value is given by

$$\alpha_2 \;=\; 1/w_2 \tag{6.9}$$

where w_2 is the backoff window size for class 2.

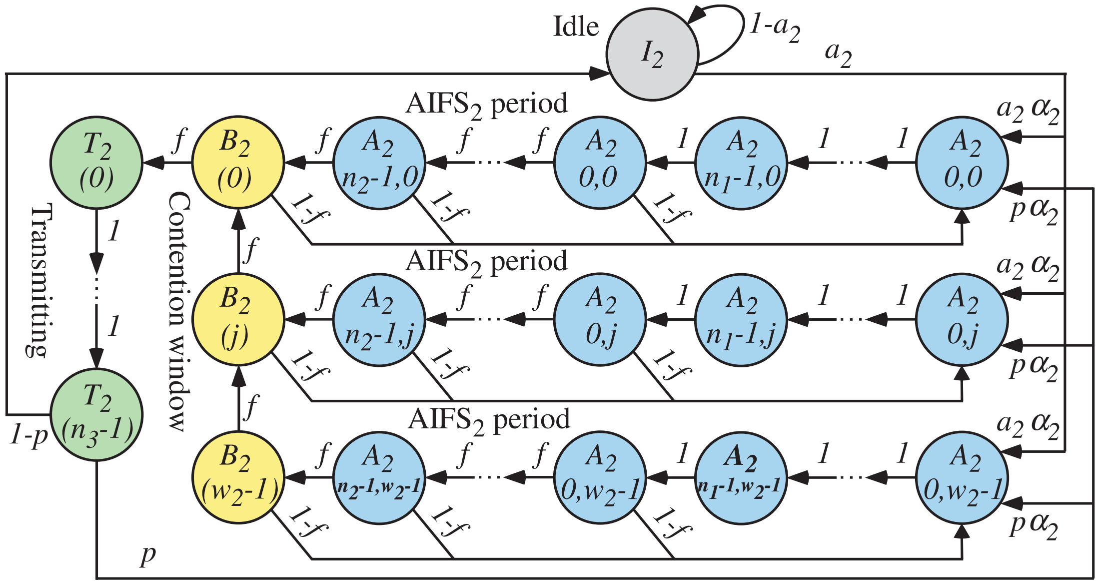


Figure 6.3: State transition diagram for Markov chain model of wireless ad hoc networks, QoS model with low-priority class (class 2)

At steady state, we can apply flow balance [25] to the low-priority class. The AIFS states for class 2 are given by

$$A_2(0,j) = A_2(1,j) = \cdots = A_2(n_1-1,i) \tag{6.10}$$

$$A_2(n_2-n_1,j) = fA_2(0,j) \tag{6.11}$$

$$A_2(n_2-n_1+1,j) = f^2A_2(0,j) \tag{6.12}$$

$$A_2(n_2-1,j) = f^{(n_2-n_1)}A_2(0,j) \tag{6.13}$$

$$A_2(0,j) = a_2\alpha_2 I_2 + p\alpha_2 T_2(0) + (1-f)B_2(j) + (1-f)A_2(0,j)\sum_{i=n_1}^{n_2-1} f^{(i+1-n_1)} \tag{6.14}$$

where $0 \leq j < w_2$. The backoff state for class 2 is given by

$$B_2(w_2-1) = f^{(n_2-n_1+1)}A_2(n_2-1,w_2-1) \tag{6.15}$$

$$B_2(j) = fB_2(j+1) + f^{(n_2-n_1+1)}A_2(0,j) \tag{6.16}$$

where $0 \leq j < w_2$. The probability that a terminal starts to send is given by

$$T_2(0) = f \times B_2(0) \tag{6.17}$$

From the state transition diagram in Figure 6.3, we can easily prove that all transmission states for high-priority class in the set $\mathcal{T}_1(0)$ are equal, so that

$$T_2(0) = T_2(1) = \cdots = T_2(n_3 - 1) \tag{6.18}$$

The sum of all components of the state vector must be unity:

$$I_2 + n_3 T_2(0) + n_1 \sum_{j=0}^{w_2-1} A_2(0,j) + \sum_{i=n_1}^{n_2-1} \sum_{j=0}^{w_2-1} f^{i+1-n_1} A_2(0,j) + \sum_{j=0}^{w_2-1} B_2(j) = 1 \tag{6.19}$$

From (6.14), (6.16), (6.17) and (6.18), we can get an expression for state I_2.

6.1.3 Estimating the Probabilities f and p

States I_1 and I_2 depend on the probabilities f and p. These two probabilities depend in turn on the phase of the states of the terminal. This is a highly nonlinear system and we have to use iterative techniques to estimate the terminal states (I_1, I_2, A_1, A_2, B_1, B_2, T_1, and T_2). In order to estimate f and p, we need to estimate the probability of a terminal starting to send and the probability of a terminal not sending.

The probability, u_1, that a terminal in class 1 starts to send at a given time step is given by

$$u_1 = f \times B_1(0) \tag{6.20}$$

The probability, u_2, that a terminal in class 2 starts to send at a given time step is given by

$$u_2 = f \times B_2(0) \tag{6.21}$$

The probability, v_1, that a terminal in class 1 is not sending is given by

$$v_1 = I_1 + \sum_{i=0}^{n_1-1} A_1(i) + \sum_{i=1}^{w_1-1} B_1(i) + (1-f)B_1(0) \tag{6.22}$$

The probability, v_2, that a terminal in class 2 is not sending is given by

$$v_2 = I_2 + \sum_{i=0}^{n_2-1} A_2(i) + \sum_{i=1}^{w_2-1} B_2(i) + (1-f)B_2(0) \tag{6.23}$$

The probability, f, that the channel is free is when all terminals in class 1 and class 2 are not sending is

$$f = v_1^{N_1} v_2^{N_2} \tag{6.24}$$

The collision probability, p, is given by

$$p = \sum_{i=0}^{2} \sum_{j=2-i}^{2} \gamma_{i,j} \tag{6.25}$$

where $i = 0$ implies no terminal from class 1 starts sending, $i = 1$ implies one terminal from class 1 start sending, and $i = 2$ implies two or more terminals from class 1 starts sending. A similar definition applies to index j of class 2 terminals. Therefore, we have

$$\gamma_{0,2} = v_1^{N_1}[1 - v_2^{N_2} - N_2 u_2 v_2^{N_2-1}] \tag{6.26}$$

$$\gamma_{1,2} = N_1 u_1 v_1^{N_1-1}[1 - v_2^{N_2} - N_2 u_2 v_2^{N_2-1}] \tag{6.27}$$

$$\gamma_{2,2} = [1 - v_1^{N_1} - N_1 u_1 v_1^{N_1-1}][1 - v_2^{N_2} - N_2 u_2 v_2^{N_2-1}] \tag{6.28}$$

$$\gamma_{1,1} = [N_1 u_1 v_1^{N_1-1}][N_2 u_2 v_2^{N_2-1}] \tag{6.29}$$

$$\gamma_{2,1} = N_2 u_2 v_2^{N_2-1}[1 - v_1^{N_1} - N_1 u_1 v_1^{N_1-1}] \tag{6.30}$$

$$\gamma_{2,0} = v_2^{N_2}[1 - v_1^{N_1} - N_1 u_1 v_1^{N_1-1}] \tag{6.31}$$

We used Algorithm 1 and equations (6.24) and (6.25) to estimate the probabilities f and p.

6.1.4 Performance Metrics

The throughput, Th_1, is defined as the average number of successfully transmitted frames for high-priority class per contention slot. Th_1 is given by

$$Th_1 = (1-p)N_1 \sum_{i=0}^{n_3-1} T_1(i) \tag{6.32}$$

The average input traffic to the system $N_{1_{a_1}}$ is given by

$$N_{1_{a_1}} = N_1 \times a_1 \tag{6.33}$$

The average high-priority frame acceptance probability, p_{a_1}, for a given terminal is defined as the probability that a terminal is able to access the channel when it is ready to send. The probability, p_{a_1}, can be written as the ratio of frames transmitted through the system relative to the total number arriving of frames in one time step [24], so that

$$p_{a_1} = \frac{Th_1}{N_{1_{a_1}}} \tag{6.34}$$

The delay occurs due to frame collisions. The average number of high-priority frame retransmissions, n_{a_1}, is calculated as

$$n_{a_1} = \sum_{i=0}^{\infty} i(1-p_{a_1})^i \tag{6.35}$$

$$n_{a_1} = \frac{1-p_{a_1}}{p_{a_1}} \tag{6.36}$$

The average energy for high-priority class, E_{a_1}, required to transmit successfully a high frame is an important performance measure, especially for mobile wireless systems. The average energy is estimated by counting the number of retransmissions until the frame is correctly received. E_a is calculated as

$$E_{a_1} = E_0 \quad p_{a_1} \sum_{i=0}^{\infty}(1+i)(1-p_{a_1})^i \tag{6.37}$$

$$E_{a_1} = \frac{E_0}{p_{a_1}} \tag{6.38}$$

We can normalize E_{a_1} in equation (6.38) as

$$\overline{E_{a_1}} = \frac{E_{a_1}}{E_0} = \frac{1}{p_{a_1}} \tag{6.39}$$

and we can express it in dB as

$$\overline{E_{a_1}}(dB) = -10 \log p_{a_1} \tag{6.40}$$

The performance metrics for the low-priority traffic class are similar to those of the high-priority traffic class.

6.2 Numerical Results

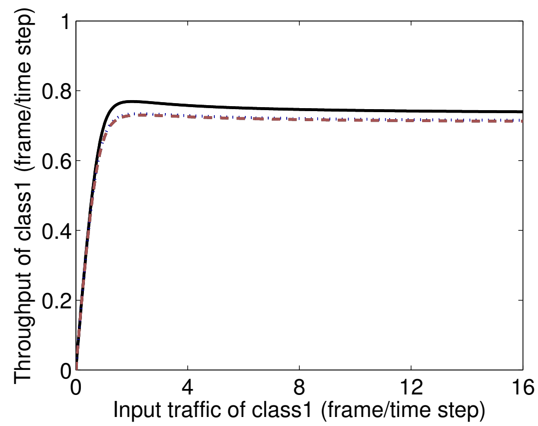
To investigate the effect of QoS on performance metrics, we compared the performance of the class1 model with that of the class2 model.

Figure 6.4 (a) shows the throughput versus the input traffic of class1 when $N_1 = 16$, $w_1 = 16$, $n_1 = 4$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes. Figure 6.4(b) is an expanded view of Figure 6.4 (a). The effect of class 2 traffic is illustrated.

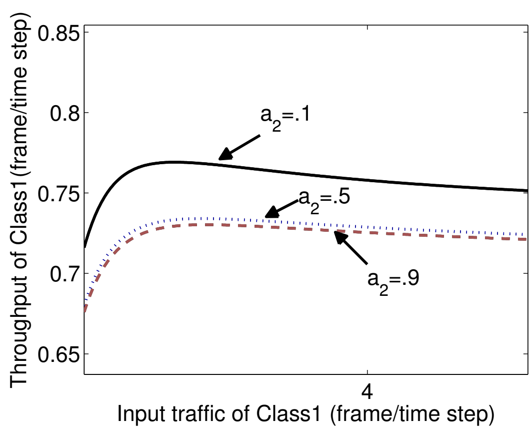
Figure 6.5 (a) shows the throughput versus the input traffic of class1 when $N_2 = 16$, $w_2 = 32$, $n_2 = 4$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes. Figure 6.5(b) is an expanded view of Figure 6.5 (a). The effect of class 1 traffic is illustrated.

Comparing Figures 6.4 and 6.5 we note that the throughput of class1 is higher than the throughput of class2. Moreover, from one hand, the effect of class2 traffic on throughput for class1 is small compared with the effect of class 1 traffic on the throughput for class 2. One the other hand, the effect of class1 traffic on throughput for class2 is significantly affect the throughput of class2 against the traffic variation of class1. For example, by increasing the traffic of class1 from 0.1 to 0.9, the throughput of class2 decreases by about 22.7%. Figure 6.5(b) explain this in more details.

Figure 6.6 (a) shows the terminal access probability versus the input traffic of class1 when $N_1 = 16$, $w_1 = 16$, $n_1 = 4$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.

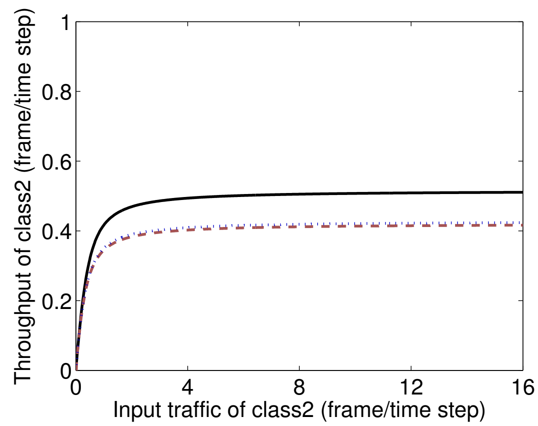


(a)

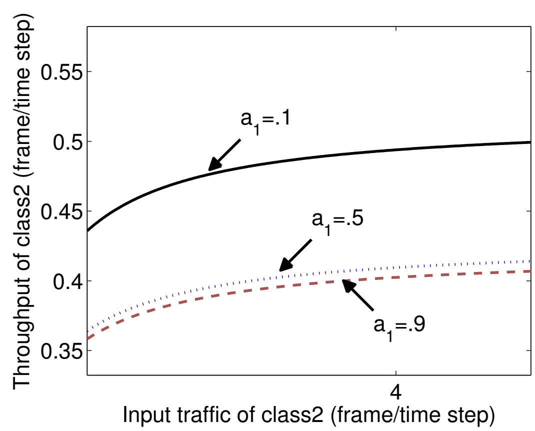


(b)

Figure 6.4: Throughput for class1 versus input traffic of class1. (a) Full range. (b) Limited range. The solid line is the throughput when the $a_2 = 0.1$, the dotted line is the throughput when the $a_2 = 0.5$, and the dashed line is the throughput when the $a_2 = 0.9$. In case when $N_1 = 16$, $N_2 = 16$, $w_1 = 16$, $w_2 = 32$, $n_1 = 4$, $n_2 = 8$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.



(a)



(b)

Figure 6.5: Throughput for class2 versus input traffic of class2. (a) Full range. (b) Limited range. The solid line is the throughput when the $a_1 = 0.1$, the dotted line is the throughput when the $a_1 = 0.5$, and the dashed line is the throughput when the $a_1 = 0.9$. In case when $N_1 = 16$, $N_2 = 16$, $w_1 = 16$, $w_2 = 32$, $n_1 = 4$, $n_2 = 8$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.

Figure 6.6(b) is an expanded view of Figure 6.6 (a). The effect of class 2 traffic is illustrated.

Figure 6.7 (a) shows the terminal access probability versus the input traffic of class1 when $N_2 = 16$, $w_2 = 32$, $n_2 = 4$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes. Figure 6.7(b) is an expanded view of Figure 6.7 (a). The effect of class 1 traffic is illustrated.

Comparing Figures 6.6 and 6.7 we note that the terminal access probability of class1 is higher than the terminal access probability of class2. Moreover, from one hand, the effect of class2 traffic on terminal access probability for class1 is small compared with the effect of class 1 traffic on the terminal access probability for class 2. One the other hand, the effect of class1 traffic on terminal access probability for class2 is significantly affect the terminal access probability of class2 against the traffic variation of class1. For example, by increasing the traffic of class1 from 0.1 to 0.9, the terminal access probability of class2 decreases by about 22.4%. Figure 6.7(b) explain this in more details.

Figure 6.8 (a) shows the average number of frame retransmissions versus the input traffic of class1 when $N_1 = 16$, $w_1 = 16$, $n_1 = 4$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes. Figure 6.8(b) is an expanded view of Figure 6.8 (a). The effect of class 2 traffic is illustrated.

Figure 6.9 (a) shows the average number of frame retransmissions versus the input traffic of class1 when $N_2 = 16$, $w_2 = 32$, $n_2 = 4$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes. Figure 6.9(b) is an expanded view of Figure 6.9 (a). The effect of class 1 traffic is illustrated.

Comparing Figures 6.8 and 6.9 we note that the average number of frame retransmissions of class1 is smaller than the average number of frame retransmissions of class2. Moreover, from one hand, the effect of class2 traffic on average number of frame retransmissions for class1 is small compared with the effect of class 1 traffic on the average number of frame retransmissions for class 2. One the other hand, the effect of class1 traffic on average number of frame retransmissions for class2 is significantly affect the average number of frame retransmissions of class2 against the traffic variation of class1. For example, by increasing the traffic of class1 from 0.1 to 0.9, the average number of frame retransmissions of class2 increases by about 43.4%. Figure 6.9(b) explain this in more details.

Figure 6.10 (a) shows the average energy versus the input traffic of class1 when $N_1 = 16$, $w_1 = 16$, $n_1 = 4$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes. Figure 6.10(b) is an expanded view of Figure 6.10 (a). The effect of class2 traffic is illustrated.

Figure 6.11 (a) shows the average energy versus the input traffic of class1 when $N_2 = 16$, $w_2 = 32$, $n_2 = 4$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes. Figure 6.11(b) is an expanded view of Figure 6.11 (a). The effect of class1 traffic is illustrated.

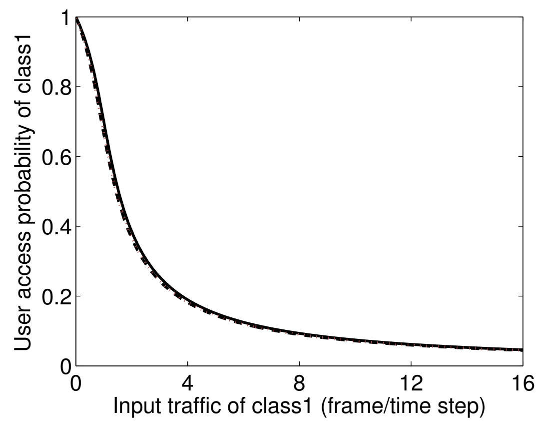
Comparing Figures 6.10 and 6.11 we note that the average energy of class1 is higher than the average energy of class2. Moreover, from one hand, the effect of class2 traffic on average energy for class1 is small compared with the effect of class1 traffic on the average energy for class2. One the other hand, the effect of class1 traffic on average energy for class2 is significantly affect the average energy of class2 against the traffic variation of class1. For example, by increasing the traffic of class1 from 0.1 to 0.9, the average energy of class2 increases by about 13.2%. Figure 6.11(b) explain this in more details.

6.3 Chapter Summary

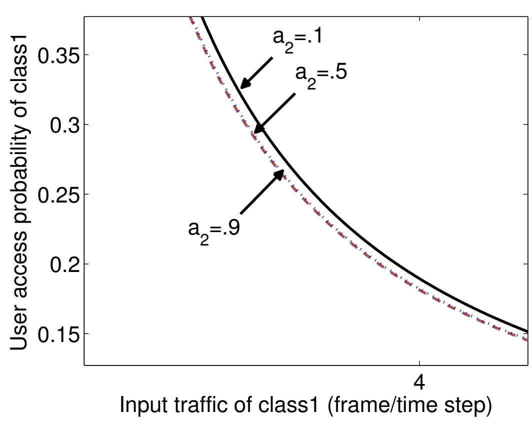
Using the developed model, results illustrate the protocol performance dependence on the QoS. For the low-priority case, throughput degrades and frame delay increases. In addition, we analyzed the effects of the AIFS and backoff window size on the performance of wireless ad hoc networks. We demonstrated that setting AIFS and backoff window size equal to the number of terminals gives optimum performance in terms of throughput, terminal access probability, delay, and energy.

We proposed a realistic model for wireless ad hoc networks with accurate consideration of QoS. This model can be used to analyze the performance of ad hoc networks due to changes of backoff strategies, finite retransmission attempts, adjustment of the AIFS counter, and freezing of the backoff counter. Our work becomes important and meaningful since it predicts ad hoc protocol performance very accurately considering QoS. Using the developed model, results illustrate that protocol performance strongly depends on the AIFS. When AIFS increases, throughput degrades and frame delay as well as average energy increase.

With realistic protocol modelling, any improvement to protocol parameters can be modelled and analyzed. This work can be extended to include RTS/CTS mechanisms, adaptive backoff based on the traffic load, and dynamic backoff window size adjustment.

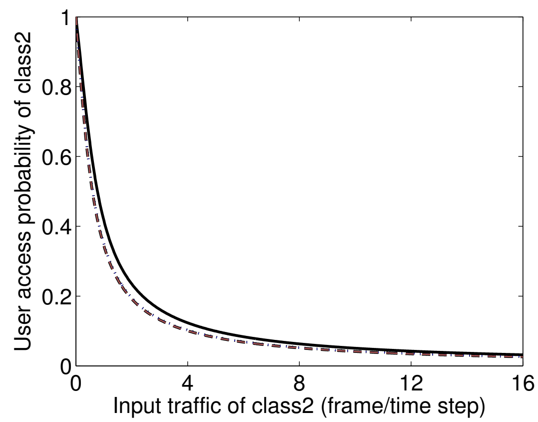


(a)

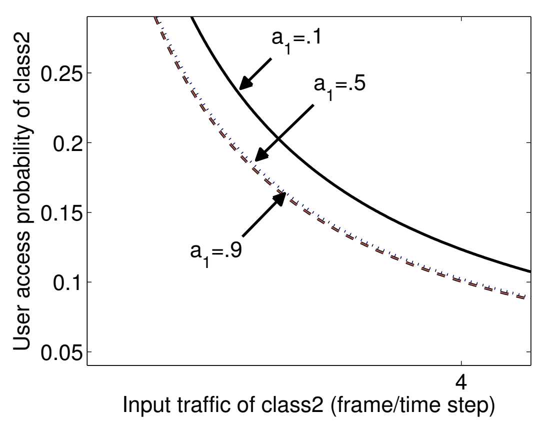


(b)

Figure 6.6: Terminal access probabilities for class1 versus input traffic of class1. (a) Full range. (b) Limited range. The solid line is the terminal access probability when the $a_2 = 0.1$, the dotted line is the terminal access probability when the $a_2 = 0.5$, and the dashed line is the terminal access probability when the $a_2 = 0.9$. In case when $N_1 = 16$, $N_2 = 16$, $w_1 = 16$, $w_2 = 32$, $n_1 = 4$, $n_2 = 8$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.

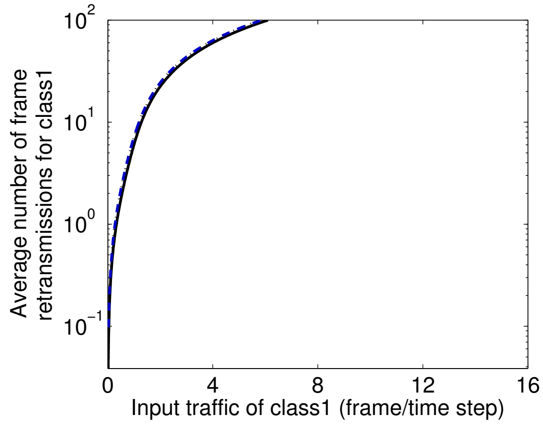


(a)

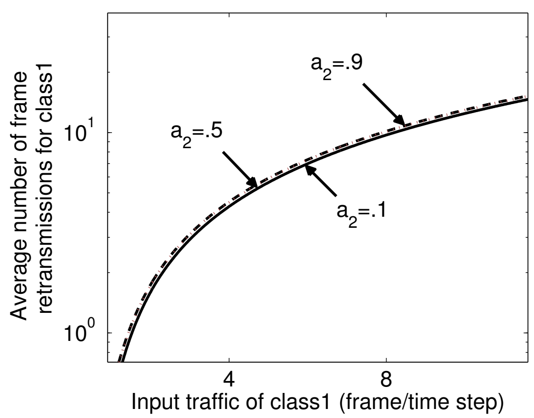


(b)

Figure 6.7: Terminal access probabilities for class2 versus input traffic of class2. (a) Full range. (b) Limited range. The solid line is the terminal access probability when the $a_1 = 0.1$, the dotted line is the terminal access probability when the $a_1 = 0.5$, and the dashed line is the terminal access probability when the $a_1 = 0.9$. In case when $N_1 = 16$, $N_2 = 16$, $w_1 = 16$, $w_2 = 32$, $n_1 = 4$, $n_2 = 8$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.

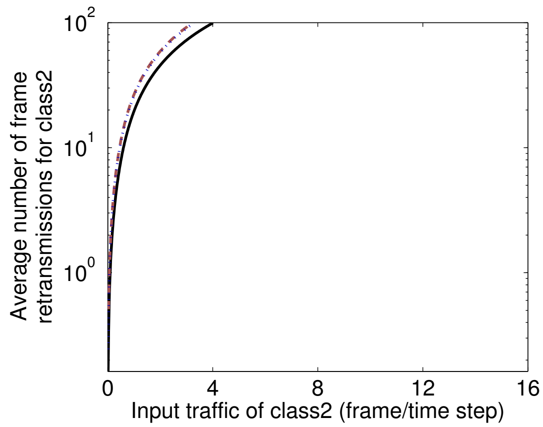


(a)

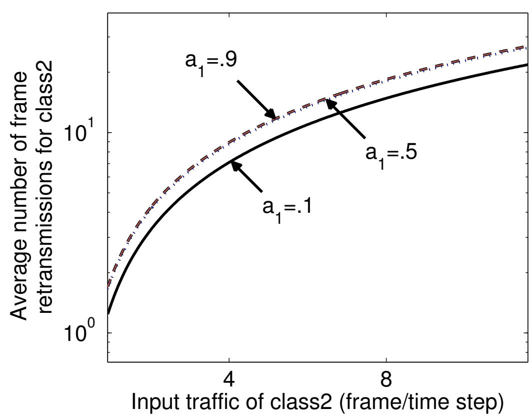


(b)

Figure 6.8: Average number of frame retransmissions for class1 versus input traffic of class1. (a) Full range. (b) Limited range. The solid line is the average number of frame retransmissions when the $a_2 = 0.1$, the dotted line is the average number of frame retransmissions when the $a_2 = 0.5$, and the dashed line is the average number of frame retransmissions when the $a_2 = 0.9$. In case when $N_1 = 16$, $N_2 = 16$, $w_1 = 16$, $w_2 = 32$, $n_1 = 4$, $n_2 = 8$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.

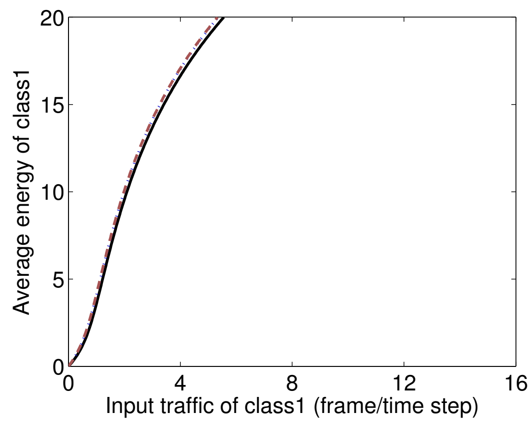


(a)

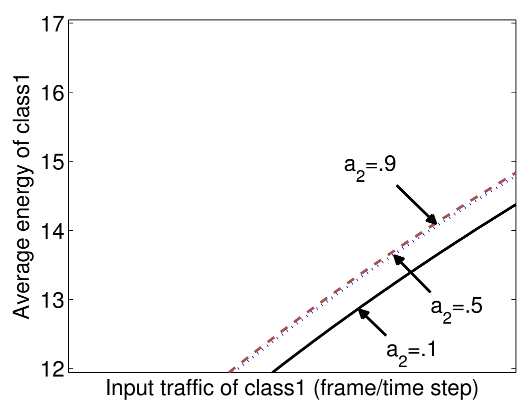


(b)

Figure 6.9: Average number of frame retransmissions for class2 versus input traffic of class2. (a) Full range. (b) Limited range. The solid line is the average number of frame retransmissions when the $a_1 = 0.1$, the dotted line is the average number of frame retransmissions when the $a_1 = 0.5$, and the dashed line is the average number of frame retransmissions when the $a_1 = 0.9$. In case when $N_1 = 16$, $N_2 = 16$, $w_1 = 16$, $w_2 = 32$, $n_1 = 4$, $n_2 = 8$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.

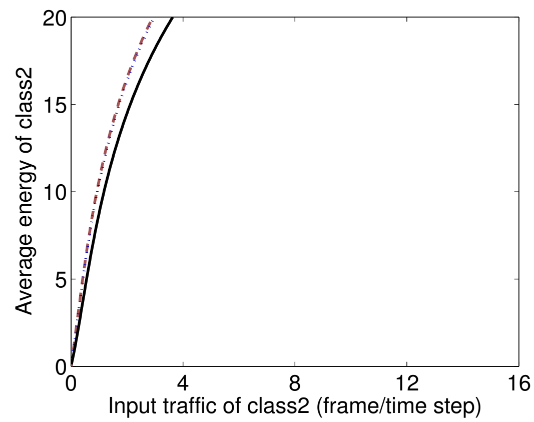


(a)

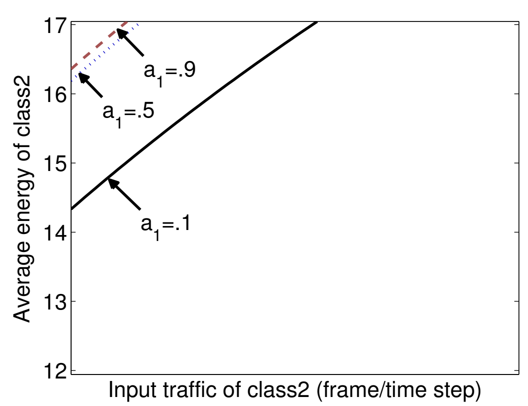


(b)

Figure 6.10: Average energy for class1 versus input traffic of class1. (a) Full range. (b) Limited range. The solid line is the average energy when the $a_2 = 0.1$, the dotted line is the average energy when the $a_2 = 0.5$, and the dashed line is the average energy when the $a_2 = 0.9$. In case when $N_1 = 16$, $N_2 = 16$, $w_1 = 16$, $w_2 = 32$, $n_1 = 4$, $n_2 = 8$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.



(a)



(b)

Figure 6.11: Average energy for class2 versus input traffic of class2. (a) Full range. (b) Limited range. The solid line is the average energy when the $a_1 = 0.1$, the dotted line is the average energy when the $a_1 = 0.5$, and the dashed line is the average energy when the $a_1 = 0.9$. In case when $N_1 = 16$, $N_2 = 16$, $w_1 = 16$, $w_2 = 32$, $n_1 = 4$, $n_2 = 8$, $n_3 = 7$, and the frame size $L_F = 512$ Bytes.

Chapter 7

Contributions and Future Work

Here, we conclude this dissertation with the major contributions of this dissertation. As well, we suggest directions for future research.

7.1 Contributions

We summarize the contributions of this dissertation as follow.

7.1.1 Two-Way Handshaking Mechanism Investigation

In the first contribution, we present a Markov chain analysis for studying the performance of the IEEE 802.11 DCF. We propose a model that considers all levels of traffic and finite retransmission attempts and supports an arbitrary backoff strategy. The performance analyses in [9, 33–35, 39] are limited to saturated traffic conditions. Their models are only for backoff strategies that do not consider transmission states. Our model more realistically and flexibly studies the behaviour of a two-way handshaking mechanism. This work has been published by Khayyat and Gebali [58].

7.1.2 Optimizing the Backoff Strategy

In the second contribution, our model allows us to optimize the backoff strategy to improve system throughput. In previous work [9, 33–35, 39], the initial contention window was fixed and equal to 128 time steps. We found that the most important parameter affecting the performance of binary exponential backoff is the initial backoff window size. Our results show that the probability of frame collision can be reduced when the initial backoff window size equals the number of terminals. Thus, the throughput of the system increases and, at the same time, the delay to transmit successfully the frame is reduced. This work has been published by Khayyat and Gebali [58].

7.1.3 Four-Way Handshaking Mechanism Investigation

Our third contribution is to develop a four-way handshaking model. We also compare our model to a two-way handshaking mechanism. Results show that a four-way handshaking mechanism is better in terms of throughput, average number of retransmissions, and energy. The works presented in [52–54] add RTS/CTS as a duration in obtaining the performance estimate of the RTS/CTS mechanism. In the present work, we add the RTS state in the transmitting statesto provide more realistic results. Our work becomes important and meaningful since it predicts ad hoc protocol performance very accurately considering the RTS frame. Using the developed model, we derived analytical results, which illustrate that protocol performance strongly depends on the four-way handshaking mechanism. This work has been published by Khayyat and Gebali [59].

7.1.4 Channel Noise Model at MAC Layer

Our fourth contribution lies in proposing a model that takes channel errors into account and in verifying that using a NAK message in wireless ad hoc networks achieves better system performance. Due to channel errors, the receiver sends a ACK/NAK and, hence, the sender can retransmit using the same backoff window size. The works presented in [60–63] are limited to retransmission of a frame only if a collision or error occurs after doubling the backoff window size. Our results show that a cross-layer model has a better performance under BER conditions. We also evaluated the effect of frame error probability on the throughput, access probability, and average number of retransmissions. This work has been published in [87].

7.1.5 Quality of Service Support Model

Finally, we proposed a model that takes the QoS into account. In doing so, we verified that using a AIFS duration and minimum backoff window size in wireless ad hoc networks could achieve better system performance. Our model for class 1 high-priority traffic has better performance than does the model for class 2 low priority traffic. As well, we evaluated the effect of QoS on the throughput, access probability, average number of retransmissions, and average energy. This work has been submitted for publication [88].

7.2 Directions for Future Work

This research work can be extended to include adaptive backoff based on the traffic load and dynamic backoff window size adjustment. A dynamic backoff algorithm is a new algorithm for the backoff window scheme that improves the exponential approach used currently in the IEEE 802.11 protocol. The dynamic backoff algorithm uses supervised learning neural networks to adapt the backoff parameters according to network conditions and service constraints.

In addition, in the future this research work can be extended to accommodate external challenges for newer technologies such as WiMAX and Long Term Evolution, LTE; where LTE is not a replacement for Universal Mobile Telecommunications System (UMTS), but rather an update to the UMTS technology that will enable it to provide significantly faster data rates for both uploading and downloading. It is believed that 802.l1e will stay significant and may be complementary to WiMAX and LTE, for mobile networks.

Bibliography

[1] "IEEE 802.11 WG, Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications," 1999.

[2] "IEEE 802.11 WG, Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications," 2003.

[3] "ANSI/IEEE Std 802.11e, Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements," November 2005.

[4] "IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks– Specific requirements, Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications." June 2007.

[5] Y. Yan, H. Cai, and S.-W. Seo, "Performance analysis of IEEE 802.11 wireless mesh networks," in *Proceedings of the IEEE International Conference on Communications, ICC'08.*, May 2008, pp. 2547–2551.

[6] A. Abdrabou and W. Zhuang, "Stochastic delay guarantees and statistical call admission control for IEEE 802.11 single-hop ad hoc networks," *IEEE Transactions on Wireless Communications,*, vol. 7, no. 10, pp. 3972–3981, October 2008.

[7] H.-W. Tseng, A.-C. Pang, C.-F. Kuo, and S.-T. Sheu, "Efficient and fast retransmission for wireless networks," *Transactions on Computer Communications*, vol. 29, pp. 2964–2974, September 2006.

[8] F. Cali, M. Conti, and E. Gregori, "IEEE 802.11 protocol: Design and performance evaluation of an adaptive backoff mechanism," *IEEE Journal on Selected Areas in Communications, J-SAC'2000.*, vol. 18, no. 19, pp. 1774–1786, September 2000.

[9] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, March 2000.

[10] H. Zhai, Y. Kwon, and Y. Fang, "Performance analysis of IEEE 802.11 MAC protocols in wireless LANs: Research articles," *Wireless Communication Mobile Computer*, vol. 4, pp. 917–931, December 2004.

[11] L. Kleinrock and F. Tobagi, "Packet switching in radio channels: Part i carrier sense multiple-access modes and their throughput-delay characteristics," *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1400–1416, December 1975.

[12] H. S. Chhaya and S. Gupta, "Performance modeling of asynchronous data transfer methods of IEEE 802.11 MAC protocol," *Wireless Networks*, vol. 3, pp. 217–234, 1997.

[13] K. C. Huang and K.-C. Chen, "Interference analysis of nonpersistent CSMA with hidden terminals in multicell wireless data networks," in *In Proc. IEEE PIMRC*, Toronto, Canada, 1995, pp. 907–911.

[14] X.-Y. Li, *Wireless Ad Hoc and Sensor Networks : Theory and Applications.* 32 Avenue of the Americas, NY: Cambridge University Press, 2009.

[15] P. Serrano, A. Banchs, P. Patras, and A. Azcorra, "Optimal configuration of 802.11e EDCA for real-time and data traffic," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 5, pp. 2511–2528, June 2010.

[16] B.-J. CHANG, Y.-H. LIANG, and J.-W. CHU, "Performance analyses of high-efficiency EDCA for reducing contention collision and increasing throughput in QoS-based IEEE 802.11e wireless networks," *Information Science and Engineering*, vol. 26, pp. 1991–2007, November 2010.

[17] K. How, M. Ma, and Y. Qin, "A MAC-Layer QoS provisioning protocol for cognitive radio networks," *Wireless Personal Communications*, pp. 1–20, 2011.

[18] R. Geng, L. Guo, and X. Wang, "A New Adaptive MAC Protocol with QoS Support Based on IEEE 802.11 in ad hoc Networks," *Computers and Electrical Engineering*, pp. 1–9, July 2010.

[19] L.-C. Wang, A. Chen, and D. S. Wei, "A cognitive MAC protocol for QoS provisioning in ad hoc networks," *Physical Communication*, vol. 3, no. 2, pp. 105–118, 2010.

[20] R. Geng, Z. Li, and L. Song, "AQMP: An adaptive QoS MAC protocol based on IEEE802.11 in ad hoc networks," in *Proceedings of the 5th International Conference on Wireless Communications, Networking and Mobile Computing, 2009, WiCom '09.*, September 2009, pp. 1–4.

[21] K. Liu, X. Xing, and D. Wang, "A distributed QoS-guaranteed multiple access protocol for mobile ad hoc networks," in *Proceedings of the 6th IEEE International Conference on Consumer Communications and Networking Conference, CCNC'09.*, January 2009, pp. 1–5.

[22] B. Kuan, "IEEE 802.11e channel utilization: Performance modelling and management," Ph.D. dissertation, University Malaya, Kuala Lumpur, December 2009.

[23] F. Gebali, "IEEE 802.11 Wireless Protocol: User Performance Using Discrete-Time Markov Chains," in *The 46th IEEE International Midwest Symposium on Circuits and Systems*, vol. 1, Cairo, Egypt, December 2003, pp. 459–462.

[24] F. Gebali, *Computer Communication Networks: Analysis and Design*, 3rd ed. Victoria, B.C, Canada: Northstar Digital Design, Inc, 2005.

[25] F. Gebali, *Analysis of Computer and Communication Networks.* New York,NY: Springer, 2008.

[26] H. Chhaya and S. Gupta, "Throughput and fairness properties of asynchronous data transfer methods in the IEEE 802.11 MAC protocol," in *Proceeding of the 6th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC'95.*, vol. 2, September 1995, pp. 613–617.

[27] T.-S. Ho and K.-C. Chen, "Performance analysis of IEEE 802.11 CSMA/CA medium access control protocol," in *Personal, Indoor and Mobile Radio Communications, 1996. PIMRC'96., Seventh IEEE International Symposium on*, vol. 2, Oct. 1996, pp. 407 –411 vol.2.

[28] G. Bianchi, L. Fratta, and M. Oliveti, "Performance Evaluation and Enhancement of the CSMA/CA MAC Protocol for 802.11 Wireless LANs," in *Proceedings of the annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Taipei, Taiwan, 1996, pp. 392–396.

[29] G. Bianchi, "IEEE 802.11 Saturation Throughput Analysis," *IEEE Communications Letters*, vol. 2, no. 12, pp. 318–320, December 1998.

[30] P. Chatzimisios, V. Vitsas, and A. Boucouvalas, "Throughput and delay analysis of IEEE 802.11 protocol," in *Proceeding of the 5th IEEE International Workshop on Networked Appliances*, October 2002, pp. 168–174.

[31] G. Wang, Y. Shu, L. Zhang, and O. Yang, "Improving DCF in IEEE 802.11 wireless LAN," in *Canadian Conference on Electrical and Computer Engineering, CCECE '03*, vol. 2, May 2003, pp. 919–922.

[32] H. Su and P. Qiu, "IEEE 802.11 distributed coordination function: performance analysis and protocol enhancement," in *Proceedings of the 18th International Conference on Advanced Information Networking and Application, AINA'04.*, vol. 2. IEEE Computer Society, March 2004, pp. 335–338.

[33] E. Ziouva and T. Antonakopoulos, "CSMA/CA performance under high traffic conditions: Throughput and delay analysis," *Computer Communications*, vol. 25, no. 3, pp. 313–321, 2003.

[34] Y. Xiao and G. Bianchi, "Modeling saturation performance of the IEEE 802.11 MAC," in *Wireless Communications and Mobile Communications WCMC'03.*, September 2003.

[35] M. Ergen, B. Dunbar, and P. Varaiya, "Throughput analysis of an extended service set in 802.11," in *proceedings of the 2004 IEEE Global Telecommunications Conference, (GLOBECOM '04).*, vol. 2, Dallas, TX, USA, December 2004, pp. 1040–1045.

[36] C. H. Foh and J. Tantra, "Comments on IEEE 802.11 saturation throughput analysis with freezing of backoff counters," *IEEE Communications Letters*, vol. 9, no. 2, pp. 130–132, February 2005.

[37] G. Bianchi and I. Tinnirello, "Remarks on IEEE 802.11 DCF performance analysis," *IEEE Communication Letters*, vol. 9, no. 8, pp. 765–767, August 2005.

[38] I. Tinnirello, G. Bianchi, and Y. Xiao, "Refinements on IEEE 802.11 distributed coordination function modeling approaches," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 3, pp. 1055–1067, March 2010.

[39] H. Wu, Y. Peng, K. Long, S. Cheng, and J. Ma, "Performance of reliable transport protocol over IEEE 802.11 wireless LAN: Analysis and enhancement," in *Proceedings of the twenty-first annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM'02*, vol. 2, New York, NY, USA, June 2002, pp. 599–607.

[40] F. Cali, M. Conti, and E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit," *IEEE/ACM Trans. Networking*, vol. 8, no. 6, pp. 785–790, December 2000.

[41] Q. Ni, I. Aad, and C. Barakat, "Modeling and Analysis of Slow CW Decrease for IEEE 802.11 WLAN," in *14th IEEE Proceedings on Indoor and Mobile Radio Communications*, vol. 2, 2003.

[42] A. Banchs and X. Perez, "Providing Throughput Guarantees in IEEE 802.11 Wireless LAN," in *Wireless Communications and Networking Conference, WCNC'02.*, vol. 1, Orange Country Convention Center, Orlando, FL, USA, March 2002, pp. 130–138.

[43] Y. Xiao, "A Simple and Effective Priority Scheme for IEEE 802.11," *IEEE Communications Letters*, vol. 7, no. 2, pp. 70–72, February 2003.

[44] I. Tinnirello, G. Bianchi, and L. Scalia, "Performance Evaluation of Differentiated Access Mechanisms Effectiveness in 802.11 Networks," in *47th Annual IEEE*

Global Telecommunications Conference (GLOBECOM 04), vol. 5, Dallas, TX, USA, 29 November–3 December 2004, pp. 3007–3011.

[45] G. D. Celik, G. Zussman, W. F. Khan, and E. Modiano, "MAC for networks with multipacket reception capability and spatially distributed nodes," *IEEE Transactions on Mobile Computing*, vol. 9, pp. 226–240, February 2010.

[46] P. Karn, "MACA: a new channel access method for packet radio," in *Proceedings of the 9th Canadian Radio Relay League (CRRL) and American Radio Relay League (ARRL) on Special Interest Group on Data Communication, SIGCOMM'94.*, September 1990, pp. 134–140.

[47] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: a media access protocol for wireless LANs," in *Proceedings of the conference on Communications architectures, protocols and applications on Special Interest Group on Data Communication, SIGCOMM'94.* New York, NY, USA: ACM Press, October 1994, pp. 212–225.

[48] K. Xu, M. Gerla, and S. Bae, "How Effective Is the IEEE 802.11 RTS/CTS Handshake in Ad Hoc Networks," in *Proceedings of the IEEE conference on Global Telecommunications, GLOBECOM'02 .*, vol. 1, November 2002, pp. 72–76.

[49] K. Xu, M. Gerla, and S. Bae, "Effectiveness of RTS-CTS handshake in IEEE 802-11 based ad hoc networks," *Elsevier Transactions on Ad Hoc Networks 1*, pp. 107–123, 2003.

[50] H. Zhai, J. Wang, X. Chen, and Y. Fang, "Medium access control in mobile ad hoc networks: challenges and solutions," *Wireless Communications and Mobile*

Computing Transactions on Special Issue on Ad Hoc Wireless Networks, vol. 6, no. 2, pp. 151–170, 2006.

[51] C. K. Ho and J.-P. M. G. Linnartz, "Successive-Capture analysis of RTS/CTS in ad hoc networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 1, pp. 213–223, January 2008.

[52] Y. Chen, Q.-A. Zeng, and D. P. Agrawal, "Analytical Modeling of MAC Protocol in ad hoc Networks: Research Articles," *ACM Transactions on Wireless Communications and Mobile Computing*, vol. 8, no. 1, pp. 45–59, 2008.

[53] H. Ju and I. Rubin, "The effect of disengaging RTS/CTS dialogue in IEEE 802.11 MAC protocol," in *Proceedings of the International Conference on Wireless Networks*, Las Vegas, NV, USA, June 2003, pp. 632–638.

[54] H. Ju, I. Rubin, and Y. Kuan, "An Adaptive RTS/CTS Control Mechanism for IEEE 802.11 MAC Protocol," in *Proceedings of the IEEE Conference on Vehicle Technology*, vol. 2, Jeju, Korea, April 2003, pp. 1469–1473.

[55] N. Choi, Y. Seok, and Y. Choi, "Multi-channel MAC protocol for mobile ad hoc networks," in *Proceeding of the 58th IEEE on Vehicular Technology Conference, VTC'03.*, vol. 2, October 2003, pp. 1379–1382.

[56] H. Zhai, J. Wang, Y. Fang, and D. Wu, "A dual-channel MAC protocol for mobile ad hoc networks," in *Proceeding of the IEEE on Global Telecommunications Conference Workshops, GlobeCom'04.*, 29 November-3 December 2004, pp. 27–32.

[57] S.-C. Lo and C.-W. Tseng, "A novel multi-channel MAC protocol for wireless ad hoc networks," in *Proceeding of the 65th IEEE on Vehicular Technology Conference, VTC'07.*, April 2007, pp. 46–50.

[58] K. M.-J. Khayyat, F. Gebali, and E. Abdel-Raheem, "Performance analysis of the IEEE 802.11 DCF," in *Proceedings of the IEEE International Symposium on Signal Processing and Information Technology (ISSPIT 2007)*, Cairo, Egypt, December 2007, pp. 653–657.

[59] K. M.-J. Khayyat and F. Gebali, "Analytical modelling and performance analysis for wireless ad-hoc networks using four-way handshaking mechanism," in *Canadian Conference on Electrical and Computer Engineering, CCECE '09.*, St. John's, NL, Canada, May 2009, pp. 318–322.

[60] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "Influence of channel BER on IEEE 802.11 DCF," *IEEE Electronics Letters*, vol. 39, no. 23, pp. 1687–1689, November 2003.

[61] P. Chatzimisios, V. Vitsas, and A. C. Boucouvalas, "On Improving Performance for IEEE 802.11 Wireless LANs under Congested and Error-Prone Environments," in *Proceedings of the 24th International Association of Science and Technology for Development, IASTED, conference on Internet and Multimedia Systems and Applications, IMSA'06 .* Anaheim, CA, USA: ACTA Press, February 2006, pp. 177–182.

[62] J.-M. Lee, S. H. Han, H. S. Park, and W. H. Kwon, "Performance Analysis of the IEEE 802.11 DCF with Time-Varying Channel Environments," *IEICE Transaction Communcation Letters*, vol. E88B, no. 9, pp. 3784–3787, September 2005.

[63] A. Samhat, Z. Altman, and B. Fourestie, "Performance analysis of the IEEE 802.11 DCF with imperfect radio conditions," in *Proceedings of the Second International Conference on Wireless and Mobile Communications, ICWMC'06.*, Bucharest, Romania, July 2006, pp. 27–32.

[64] Y. Chang, C. Lee, and J. Copeland, "Goodput Enhancement of VANETs in Noisy CSMA/CA Channels," *Journal on IEEE Selected Areas in Communications*, vol. 29, no. 1, pp. 236–249, January 2011.

[65] Y. Xiao, "A simple and effective priority scheme for IEEE 802.11," *IEEE Transaction on Communications Letters*, vol. 7, no. 2, pp. 70–72, February 2003.

[66] Y. Xiao, "IEEE 802.11e: QoS provisioning at the MAC layer," *IEEE Transaction on Wireless Communications*, vol. 11, no. 3, pp. 72–79, June 2004.

[67] Z.-N. Kong, D. Tsang, B. Bensaou, and G. Deyun, "Performance Analysis of IEEE 802.11e Contention-Based Channel Access," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 10, pp. 2095–2106, December 2004.

[68] H. Zhu and I. Chlamtac, "Performance analysis for IEEE 802.11e EDCF service differentiation," *IEEE Transactions on Wireless Communications*, vol. 4, no. 4, pp. 1779–1788, July 2005.

[69] J. Hui and M. Devetsikiotis, "Performance analysis of IEEE 802.11e EDCA by a unified model," in *Proceedings of the IEEE Global Telecommunications Conference, GLOBECOM'04.*, vol. 2, December 2004, pp. 754–759.

[70] Z. Tao and S. Panwar, "Throughput and delay analysis for the IEEE 802.11e enhanced distributed channel access," *IEEE Transactions on Communications*, vol. 54, no. 4, pp. 596–603, April 2006.

[71] I. Inan, F. Keceli, and E. Ayanoglu, "Saturation throughput analysis of the 802.11e enhanced distributed channel access function," in *Proceedings of the IEEE International Conference on Communications, ICC '07.*, June 2007, pp. 409–414.

[72] J. W. Tantra, C. H. Foh, I. Tinnirello, and G. Bianchi, "Analysis of the IEEE 802.11e EDCA under statistical traffic," in *Proceedings of the 2006 IEEE International Conference on Communications ICC'06.*, Istanbul, Turkey, June 2006, pp. 546–551.

[73] G. Bianchi, I. Tinnirello, and L. Scalia, "Understanding 802.11e Contention-Based Prioritization Mechanisms and Their Coexistence with Legacy 802.11 Stations," *IEEE Network*, vol. 19, no. 4, pp. 28–34, July-August 2005.

[74] J. Liu and Z. Niu, "Delay analysis of IEEE 802.11e EDCA under unsaturated conditions," in *Proceedings of the IEEE Wireless Communications and Networking Conference, WCNC '07.*, March 2007, pp. 430–434.

[75] D. Gao, J. Cai, C. H. Foh, C.-T. Lau, and K. N. Ngan, "Improving WLAN VoIP capacity through service differentiation," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 1, pp. 465–474, January 2008.

[76] C. Kelley, *Iterative Methods for Linear and Nonlinear Equations.* Society for Industrial and Applied Mathematics, SIAM, 1995.

[77] C. He and J. C. Mitchell, "Analysis of the 802.11i 4-way handshake," in *Proceedings of the the ACM Workshop on Wireless Security, WiSe04.*, Philadelphia, Pa, USA, October 2004, pp. 43–50.

[78] F. D. Rango, D. C. Lentini, and S. Maranoi, "Static and dynamic 4-way handshake solutions to avoid denial of service attack in Wi-Fi protected access and IEEE 802.11i," in *Proceedings of the European Association for Signal Processing, EURASIP Journal on Wireless Communications and Networking.*, vol. 2, April 2006, pp. 1–19.

[79] Z. Bai and Y. Bai, "4-way handshake solutions to avoid denial of service attack in ultra wideband networks," in *Third International Symposium on Intelligent Information Technology Application, IITA'09.*, vol. 3, November 2009, pp. 232–235.

[80] F. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part ii–the hidden terminal problem in carrier sense multiple-access and the busy-tone solution," *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1417–1433, December 1975.

[81] A. A. Bertossi and M. A. Bonuccelli, "Code assignment for hidden terminal interference avoidance in multihop packet radio networks," *IEEE/ACM Transactions on Networks*, vol. 3, pp. 441–449, August 1995. [Online]. Available: http://dx.doi.org/10.1109/90.413218. Last accessed: August 2007.

[82] J. Proakis, *Digital Communications*, 4th ed. New York: McGraw Hill, 2001.

[83] A. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *Transactions on IEEE Communications*, vol. 45, no. 10, pp. 1218–1230, October 1997.

[84] A. Goldsmith, *Wireless Communications*, 1st ed. New York: Cambridge University Press, 2005.

[85] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication.* The Edinburgh Buliding, Cambridge CB2 8RU, UK: Cambridge University Press, 2005.

[86] G. J. M. Janssen, P. A. Stigter, and R. Prasad, *Mobile communications: advanced systems and components.* Berlin: Springer, 1994.

[87] K. M.-J. Khayyat and F. Gebali, "Cross-layer modeling of wireless ad hoc networks in the presence of channel noise," in *Proceedings of the IEEE GLOBECOM 2009 on Ad Hoc, Sensor and Mesh Networking, GC AHSN'09.*, Honolulu, Hawaii, December 2009, pp. 1–6.

[88] K. M.-J. Khayyat and F. Gebali, "Modelling Quality of Service of Wireless Ad-Hoc Networks using EDCA," *Submitted to IEEE Transactions on Communications*, January 2011.