PERFORMANCE ANALYSIS OF IEEE 802.11 DISTRIBUTED COORDINATION FUNCTION

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By

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CERTIFICATE

This is to certify that the dissertation titled ***"Performance Analysis of IEEE 802.11 Distributed Coordination Function"***, which is being submitted by **Mr. Pushpendra Patel** to the **School of Computer & Systems Sciences, Jawaharlal Nehru University, New Delhi,** in partial fulfillment of the requirements for the award of **Master of Technology in Computer Science & Technology** is a bonafide work carried out by him under the supervision of **Dr. D. K. Lobiyal.**

The matter embodied in the dissertation has not been submitted for the award of any other degree or diploma.

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DECLARATION

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I also mention that the subject matter of this dissertation has not been submitted by me elsewhere, in part or full for the award of any other degree or diploma.

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Dedicated to

My

Family

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ABBREVIATIONS

ACK	Acknowledgement
ADIDD	Adaptive Double Increment Double Decrement
AP	Access Point
BEB	Binary Exponential Back-off
BER	Bit Error Rate
BSS	Basic Service Set
CCK	Complementary Code Keying
CFP	Contention Free Period
CP	Contention Periods
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
DBPSK	Differential Binary Phase Shift Keying
DCF	Distributed Coordination Function
DIDD	Double Increment Double Decrement
DIFS	DCF Inter-Frame Spacing
DQPSK	Differential Quadrature Phase Shift Keying
DS	Distributed System
DSM	Distributed System Medium
DSSS	Direct Sequence Spread Spectrum
EIED	Exponential Increase Exponential Decrease
EIFS	Extended Inter-Frame Spacing
ELB	Exponential- Linear Back-off
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
GHz	Giga Hertz

GFSK	Gaussian Frequency Shift Keying
HR-DSSS	High-Rate Direct Sequence Spread Spectrum
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronic Engineers
IFS	Inter-Frame Spacing
IR	Infrared
ISM	Industrial, Scientific, and Medical
LAN	Local Area Network
LILD	Linear Increase Linear Decrease
LLC	Logical Link Control
MAC	Medium Access Control Layer
Mbps	Mega bits per second
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PC	Point Coordinator
PCF	Point Coordination Function
PHY	Physical Layer
PIFS	PCF Inter- Frame Spacing
PLCP	Physical Layer Convergence Procedure
PMD	Physical Medium Dependent Sublayer
QAM	Quadrature Amplitude Modulation
RC_4	Rivest Cipher 4
RTS/CTS	Request-To-Send/ Clear-To-Send
SIFS	Short Inter-Frame Spacing
SS	Station Services
STA	Station
WEP	Wired Equivalent Privacy
WLANs	Wireless Local Area Networks
WM	Wireless Medium

ABSTRACT

IEEE 802.11 is the only standard available in practice for wireless data communication for local area networks. Researchers have proposed various analytical models to evaluate the performance of IEEE 802.11, specially DCF mode for Ad-Hoc networks.

In the literature, various models and back-off algorithms have been suggested for the performance analysis of IEEE 802.11 DCF. However, these models and algorithms are specific in nature, and overcome only some problems of WLANs and ignore others. Therefore, the performance evaluation of these models remains a complex and challenging task. The models can be improved by considering issues that that are not addressed by existing models. To overcome these problems we proposed a Markov chain based model for the performance analysis of IEEE 802.11 DCF. Our model uses an Adaptive Double Increment Double Decrement (ADIDD) back-off algorithm which is based on number of competing stations and intensity of input traffic at any time step.

In this dissertation, we first evaluate the various analytical models, including the most common Bianchi's model, and back-off algorithms to improve the performance of IEEE 802.11 DCF in contention based networks. Secondly, we proposed a Markov chain model based on Adaptive DIDD (ADIDD) back-off algorithm to evaluate the performance of IEEE 802.11 DCF. Finally, we compare the proposed model with K. M. J. Khayyat *et al.* model.

The models are implemented through programs, written in MATLAB. The results of experiments are also plotted with the help of MATLAB. Experiments are performed for different network size of 4, 6, 8, 12, and 16 stations. The experiments produces encouraging results for our modified ADIDD back-off algorithm that optimize throughput, user access probability, and average delay when the number of stations is greater or equal to 8.

Chapter 1

Introduction

This chapter introduces the basic concept of IEEE 802.11 standard. A major section of this chapter covers physical layer and MAC layer specifications of IEEE 802.11. It also includes the problem statements and objectives of the dissertation. Finally, the organization of the dissertation is described.

1.1 Background

Wireless Local Area Networks (WLANs) are used for providing network services in substitution of wired network in situation where wired networks are very difficult to setup or are too expensive. Wireless local area networks have many problems like sharing the wireless medium, interference, security, quality of service etc. These problems raise the need for the optimum usage of the medium as bandwidth is a scarce resource in wireless. To overcome these problems various standards came into existence to fulfill these needs (e.g., IEEE 802.11 standard and the ETSI HIPERLAN standard).

During the past few years, IEEE 802.11 Wireless Local Area Networks (WLANS) are widely deployed in hotspots such as airports, libraries, restaurants, medical centers, hotels and other areas where people can simply access the Internet and wireless high-speed data services. In fact, the IEEE 802.11system has achieved worldwide acceptance within WLANS in a number of variety markets, particularly retail, manufacturing, and education, because of its easily installation, low cost, and high data transmission rates through 802.11a and 802.11b standards. Hence, due to tremendous growth, the performance evaluation of the supported protocols remains challenging.

The IEEE 802.11 standard [1] comes under the IEEE 802.x LAN standards. The IEEE 802.11 covers two networking layers for WLANs— the physical and data link layers. The physical layer corresponds to the OSI physical layer quite same, but the data link layer in IEEE 802.11 is divided into two sublayers— the Medium Access Control (MAC) and Logical Link Control (LLC) sublayers. The IEEE 802.11 specifications define Medium Access Control (MAC) and Physical Layer (PHY) sub layers for WLANs. The basic 802.11 standard supports three different physical layers: Infrared (IR) baseband PHY, a FHSS radio in the 2.4 GHz band, and a DSSS radio in the 2.4 GHz band. The IEEE 802.11 MAC uses two different access mechanisms; the primary access mechanism, called DCF and a centrally controlled access mechanism, called PCF. The DCF uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol with two access mechanisms: a two-way handshaking (DATA-ACK) called basic access mechanism and an optional four-way handshaking (RTS-CTS-DATA-ACK) called Request-to-Send/Clear-to-Send (RTS/CTS) access mechanism. Both the mechanisms resolve contention among wireless stations, and to verify successful transmissions.

1.2 IEEE 802.11 Standards

IEEE 802.11 was the first standard adopted by IEEE in 1997. It defines MAC layer and three physical layer specifications for wireless connectivity for fixed, portable and mobile stations within a geographical area. The three physical layers are an Infrared (IR) baseband, a Frequency Hopping Spread Spectrum (FHSS) radio in the 2.4 GHz band, and a Direct Sequence Spread Spectrum (DSSS) radio in the 2.4 GHz band.

IEEE 802.11a [2] operates in the 5 GHz unlicensed national information infrastructure band, delivering data up to 54 Mbps. It uses Orthogonal Frequency Division Multiplexing (OFDM) at the physical layer. This standard was ratified in 1999. IEEE 802.11 b [3] is an extension of IEEE 802.11 DSSS physical layer in the 2.4 GHz band. It operates in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band, delivering data up to 11 Mbps. It is popularly known as Wi-Fi (Wireless-Fidelity). This standard was also ratified in 1999, prior to IEEE 802.11a.

IEEE 802.11c standard was published in 1998, and used for bridging operations. IEEE 802.11d standard was published in 2001 with main aims are publishing definitions and requirements for enabling the operation of the IEEE 802.11 standards in countries that are not currently served by the standard. The IEEE 802.11e standard [4] is the extension of the current IEEE 802.11MAC.The purpose of IEEE 802.11e is to provide better security, efficiency. To increase the overall system performance IEEE 802.11e combined with physical layers of IEEE 802.11a & IEEE 802.11b. For example, transport of voice, audio and video over 802.11 wireless networks, video conferencing etc.

IEEE 802.11f standard was published in 2003, and deals with Access Points (APs) and distribution system which follow IEEE 802.11 standard. IEEE 802.11g standard [5] was published in 2003. It is an extension of IEEE 802.11b standard, with data rates up to 54 Mbps in the 5 GHz frequency band. This draft is based on CCK, OFDM, and PBCC technologies. IEEE 802.11h standard was published in 2003, and is supplementary standard of IEEE 802.11.

IEEE 802.11i standard deals with enhancing security in the IEEE 802.11 standard. IEEE 802.11j standard deals with enhancing the current IEEE 802.11 MAC physical layer protocol to additionally operate in newly available Japanese 4.9GHz and 5GHz bands. The objective of IEEE 802.11n standard is to achieve much higher throughputs at the MAC layer through the standardized modifications to the MAC and physical layers.

1.3 IEEE 802.11Architecture

There are two operation architectures defined in IEEE 802.11: Infrastructure Architecture and Ad-Hoc Architecture.

1.3.1 Infrastructure Architecture

In Infrastructure Architecture, the wireless network contains at least one AP, which is connected through existing wired network, and a set of wireless end stations. Access points can interact with wireless nodes as well as with the existing wired network. The mobile stations communicate with each other through APs. The functions of APs are comparable with base station in cellular networks.

This configuration of infrastructure is called a Basic Service Set (BSS). Two or more BSSs forming a single network, is known as an Extended Service Set (ESS). The distribution system which connects to this network is, almost always, an Ethernet LAN.

1.3.2 Ad-Hoc Architecture

Ad-Hoc Architecture is a set of 802.11 wireless stations that don't need any fixed infrastructure. Wireless stations directly communicate with each other without using an access point or any connection to wired network. The Ad-Hoc network can be easily deployed where fixed infrastructure based network is not possible. Ad-Hoc architecture is also known as peer-to-peer mode or an IBSS.

Ad-Hoc architecture (Mobile Ad-Hoc Networks) is used in battlefields, disaster affected areas, and wireless sensor networks etc.

1.4 IEEE 802.11 Service Set

IEEE 802.11 supports the following service set for WLANs: the Basic Service Set (BSS), the Extended Service Set (ESS), and the Independent Basic Service Set (IBSS).

1.4.1 Basic Service Set (BSS)

The set of stations that are associated with an AP is called a BSS. The stations present in the communication range of an AP are capable to communicate each others. The communication range of an AP is known as Basic Service Area (BSA). Fig. 1.1 represents the BSS.

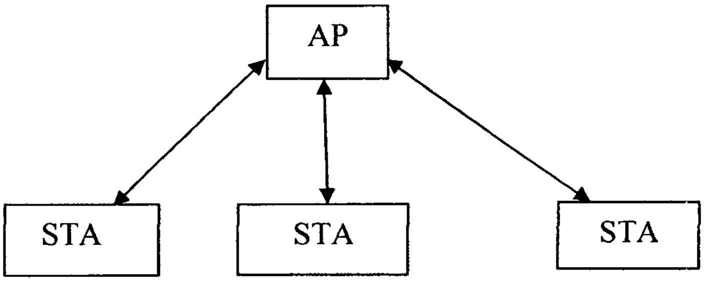


Fig. 1.1: Basic Service Set

1.4.2 Extended Service Set (ESS)

Extended Service Set (ESS) is a set of two or more basic service sets interconnected by a Distribution System (DS). In an extended service set traffic always flows through an AP. Fig. 1.2 represents the ESS.

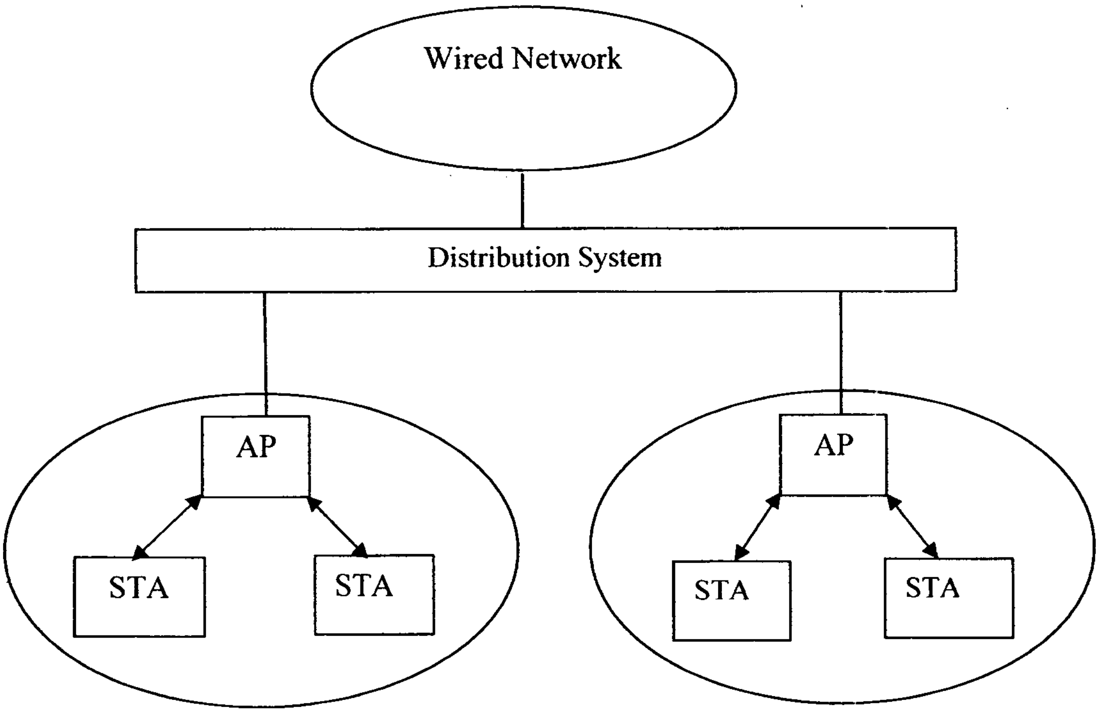


Fig. 1.2: Extended Service Set

1.4.3 Independent Basic Service Set (IBSS)

A Basic Service Set without an access point is called an Independent Basic Service Set, e. g., an Ad-Hoc LAN. At a particular time, one mobile station in the IBSS initiates the communication. Fig. 1.3 represents the IBSS.

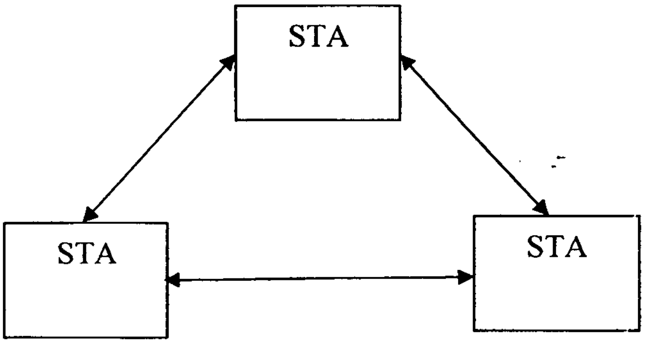


Fig. 1.3: Independent Basic Service Set

1.5 IEEE 802.11 Components

Various components of IEEE 802.11 include: station, station service, BSS, DS, and Distribution System Medium (DSM).

The medium which used for the WLAN is called wireless medium. In this dissertation, the terms "medium," and "channel," are used interchangeably. Any device that contains an IEEE 802.11 conformant MAC and PHY interface to the wireless medium is called station. In this dissertation, the terms "node," and "station," are used interchangeably. Station services include the services that support transport of MAC Service Data Units (MSDUs) between stations within a BSS.

The set of stations that are associated with a given AP is called a BSS, and the system used to interconnect a set of BSSs to form an ESS is known as DS. The medium used by DS is known as DSM, and according to IEEE 802.11 DSM is logically differ from WM.

1.6 IEEE 802.11Physical Layer

In 1997, the IEEE adopted first standard for WLANs, which includes three physical layers:

- Infrared (IR) physical layer
- Frequency Hopping Spread Spectrum (FHSS) radio physical layer
- Direct Sequence Spread Spectrum (DSSS) radio physical layer

In 1999 [6], two new physical layers based on radio technology were developed:

- 802.11a: Orthogonal Frequency Division Multiplexing (OFDM) radio physical layer
- 802.11b: High-rate Direct Sequence Spread Spectrum (HR-DSSS) radio physical layer

The physical layer is divided into two sublayers— Physical Medium Dependent sublayer (PMD) and Physical Layer Convergence Procedure (PLCP). While PMD handles encoding, decoding, and modulation of signals, the other provides a Service

Access Point (SAP), and a Clear Channel Assessment (CCA) carrier sense signal to the MAC layer.

1.6.1 Infrared (IR) Physical Layer

The infrared choice uses diffused (i.e., not line of sight) transmission at wavelengths in 850-950 nm range, at data rates of 1Mbps and 2 Mbps using pulse position modulation scheme. At 1 Mbps, Gray code encoding scheme is used. This scheme encodes a group of 4 bits into 16-bit codeword, which contains fifteen 0_s and a single 1. At 2 Mbps, the encoding scheme encodes 2-bit into a 4-bit codeword, containing only single 1, i. e. one of 0001, 0010, 0100, or 1000. Infrared option for physical layer is not popular due to its low bandwidth.

1.6.2 FSSS Physical Layer

Frequency Hopping Spread Spectrum (FSSS) is a simple technique in which available spectrum is divided into narrow band frequencies, like FDMA, and transmission switches across these narrow band frequencies allotted based on pseudo- random manner, unlike FDMA. Each frequency is used for a small amount of time, called the dwell time. The sender and receiver both know the sequence of these transmission frequencies, but for other nodes it is not known. FHSS uses 79 channels, each 1 MHz wide. The IEEE 802.11 standard provides 22 hop patterns or frequency shifts to choose from in the 2.4 GHz ISM band. The FHSS physical layer uses Gaussian Frequency Shift Keying (GFSK) modulation scheme, which encodes data as a series of frequency changes in a carrier. For 1 Mbps data rates, it uses 2-level Gaussian frequency shift keying modulation scheme, and for 2 Mbps data rates, it uses 4-level Gaussian frequency shift keying modulation scheme. It offers good resistance for multipath fading, and is relatively insensitive to radio interference. But the main drawback is its low bandwidth.

1.6.3 DSSS Physical Layer

The Direct Sequence Spread Spectrum (DSSS) transmission is an alternative spread spectrum technique that can be used to transmit a signal over a much wider frequency band. The DSSS technique divides the 2.4 GHz band into 14 channels; each channel is of 22 MHz bandwidth. Out of these 14 channels, the 11 adjacent channels overlap partially and remaining 3 channels do not overlap. Data is sent across one of the channel out of 14 channels without hopping to other channels. This produces noise in the channel. To reduce noise and number of re-transmissions each bit is transmitted as 11 chips, using Barker sequence {1, 0, 1, 1, 0, 1, 1, 1, 0, 0, 0}. It uses phase shift modulation for transmitting data at data rates 1 Mbps [using Differential Binary Phase Shift Keying (DBPSK) modulation scheme] and 2 Mbps [using Differential Quadrature Phase Shift Keying (DQPSK) modulation scheme].

1.6.4 OFDM Physical Layer

IEEE 802.11a uses Orthogonal Frequency Division Multiplexing (OFDM) to deliver data up to 54 Mbps in the wider 5 GHz ISM band. OFDM is a multicarrier transmission mechanism. In OFDM, 52 frequencies are used, out of them 48 for data and 4 for synchronization. In OFDM data is transmitted over multiple carriers. Each carrier is modulated at a low rate. The frequency spacing between the carriers is such that they are orthogonal to each other. A complex encoding scheme based on phase shift modulation is used for data speeds up to 18 Mbps, and Quadrature Amplitude Modulation (QAM) scheme for the data speeds above 18 Mbps. This technique has high-quality spectrum efficiency and good resistance to multipath fading.

1.6.5 HR-DSSS Physical layer

HR-DSSS uses 11 million chips/sec to obtain data rates upto 11 Mbps in the 2.4 GHz band. It is known as IEEE 802.11b. IEEE 802.11b supports data rates 1, 2, 5.5, and 11 Mbps. Phase shift modulation scheme is used for two slow data rates, and Walsh/Hadamard codes are used for two faster data rates. The operating speed of 802.11b is almost 11 Mbps. The speed of 802.11b is slower than 802.11a, but its range is about 7 times greater than 802.11a.

1.7 IEEE 802.11 MAC Sublayer

IEEE 802.11 specifications define MAC and PHY sublayers for WLANs. IEEE 802.11 MAC use two different access mechanisms; the primary access mechanism, called DCF and a centrally controlled access mechanism, called PCF. The DCF uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol with two access mechanism: Basic and RTS/CTS. Both the mechanisms resolve contention among wireless stations, and to verify successful transmissions. The PCF and DCF can coexist within one basic service set. IEEE 802.11 provides this facility by defining 4-different Inter-Frame Spacing (IFS). The IFS denotes the time interval between the transmissions of two successive frames. Different inter-frame spacing creates different priority levels for different types of traffic. Shorter IFS denote a higher priority. The four intervals are depicted in the figure 1.4.

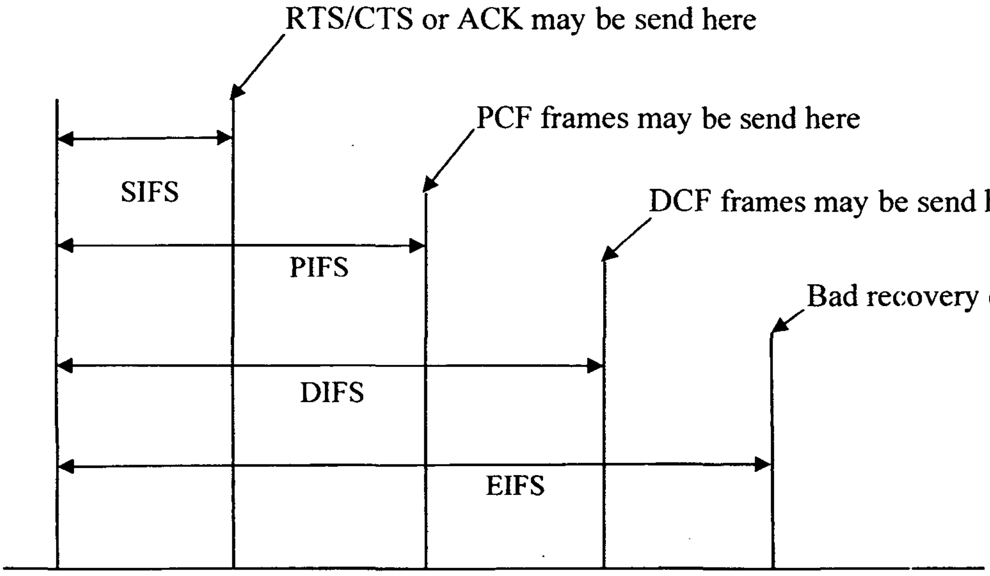


Fig. 1.4: Inter-Frame Spacing in IEEE 802.11

Short Inter-Frame Spacing (SIFS)

SIFS is the shortest among all IFSs. It is used for the highest priority transmissions, such as RTS/CTS frames and positive ACKs. These high priority transmissions can begin only after the channel is sensed idle for SIFS time period.

PCF Inter-Frame spacing (PIFS)

This is used for real time services. If after SIFS periods no station responds and a time of SIFS elapses, the base station may send a beacon frame or poll frame. This mechanism allows contention free operation.

DCF Inter-Frame Spacing (DIFS)

The DIFS is the minimum medium idle time for contention based services within a contention period. It is used for asynchronous data transfer within contention period.

Extended Inter-Frame Spacing

EIFS is the longest among all IFSs. It is used only when there is an error in frame transmission.

MAC Layer Services

The MAC layer provides various services. They are broadly categorize into two category: AP services and station services.

1.7.1 Access Point Services

Access point services include: association, re-association, disassociation, distribution, and integration.

In infrastructure networks, the identity and address of station is used for routing the packet by the AP. This is done through association, which enables the establishment of wireless link between wireless stations and APs. When a wireless station moves from one BSS to another BSS, then the re-association services are used by which the association is transferred from one AP to another.

The disassociation services are invoked by the station or the AP when the existing association is terminated due to nodes leaves the BSS or shut down. The distribution function is performed by DS through APs when the destination is in another BSS. Integration service, performed by portal, is invoked to provide logical integration between existing wired LANs and IEEE 802.11 LANs.

1.7.2 Station Services

The station services are provided by every station including APs. These include: authentication, de-authentication, privacy, and data delivery.

Authentication service is the process of providing station identity which takes place prior to a wireless station associating with an AP. Thus authentication provides security. De-authentication function is performed by base station to terminate existing authentication due to incorrect authentication settings or applied IP or MAC filters. The contents of messages may be encrypted by using WEP algorithm. The WEP option encrypts data before it is sent in the wireless medium, using a 40-bit encryption algorithm known as RC4. This prevents eavesdroppers from reading the messages. The primary service of MAC layer is to provide frame exchange between MAC layers. However, like Ethernet, the transmissions are not completely reliable, and the success of the transmission depends upon the algorithm used for collision avoidance, which main challenge before researchers.

1.7.3 Point Coordination Function (PCF)

Point Coordination Function (PCF) is used to implement real time services, like voice or video transmission. PCF is optional and provides contention free services. Special stations called Point Coordinators (PCs) are used to ensure that the wireless medium is provided without contention. Point coordinators reside in access points, so the PCF is restricted to infrastructure networks. This PC at the access point splits the time into super frame periods, which consists of alternating Contention Free Periods (CFPs) and Contention Periods (CPs). The PCF is a polled based service in which PC, polling master, will determine which station has the right to transmit data at any point of time. The IFS used by the PCF is smaller than the IFS of the frames transmitted by the DCF. Therefore, the point coordinated traffic will have higher priority access to the wireless medium when DCF and PCF are simultaneously in action. Special co-ordinations are required when there are multiple PCs with overlapping ranges

1.7.4 Distributed Coordination Function (DCF)

DCF is the basic access method based on CSMA/CA protocol. It is defined for asynchronous data transmissions. A station which has a frame queued for delivery, monitors the channel activity until an idle period equal to a DIFS is detected. Time immediately after an idle DIFS is slotted, and a station can transmit only at the beginning of each slot time. The duration of these slots is equal to the maximum time needed for a station to detect a packet from another station. This ensures that collision of frames would occur only if the exact same slot chosen by two or more stations. After sensing an idle DIFS, the station waits for a random amount of time dictated by Binary Exponential Back-off (BEB) algorithm, and then transmits its frame. The back-off time counter is decremented as long as the channel is sensed idle, frozen (stopped) when a transmission is detected on the channel, and reactivated when the channel is sensed idle for a period of DIFS. The station transmits when the back-off time reaches zero. At each frame transmission, the back-off time is uniformly chosen in the range $(0, W-1)$. The value of W is called contention window, and depends on the number of failed transmissions for the frame. At the first transmission attempt, W is set equal to a value *CWmin* called minimum contention (back-off) window. After each unsuccessful transmission, W is doubled, up to a maximum value $CWmax = 2^m\ CWmin$. The *CW* is reset to *CWmin* after a successful frame transmission or if the frames's retransmission limit is reached.

The DCF describes two techniques to transmit data packets: a two way handshaking (DATA-ACK) called basic access mechanism and an optional four way handshaking (RTS-CTS-DATA-ACK) called RTS/CTS mechanism.

Basic Access Mechanism

In this mechanism, a positive Acknowledgement (ACK) is sent to the sender of the original frame by the destination station (receiver). Explicit transmission of ACK is required due to the fact that in wireless medium sender of frame cannot alone determine whether the packet has been sent successfully or not. The ACK is immediately transmitted after SIFS time by the receiver of the frame. Since the SIFS (plus propagation delay) is shorter than a DIFS, therefore no other station is able to detect the wireless medium idle for a DIFS until the end of ACK. If the sender of frame does not receive the ACK within a defined time period (ACK_Time out), or it detects a transmission on the medium, it reschedules the frame transmission according to the given back-off algorithm. Fig. 1.5 represents the basic DCF access mechanism.

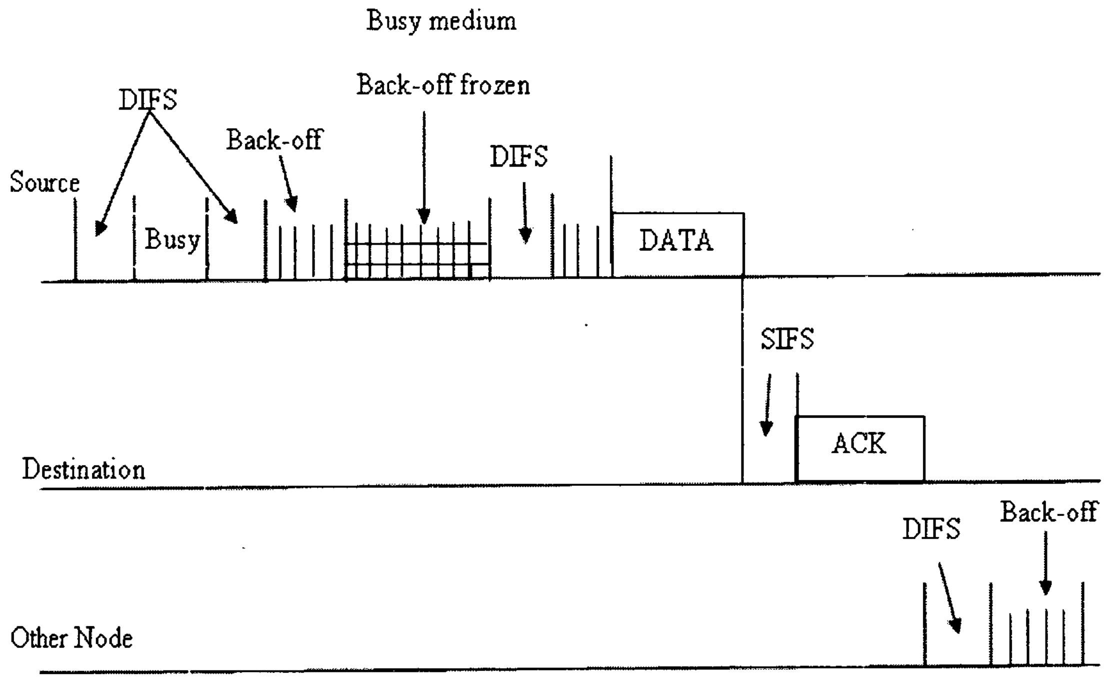


Fig. 1.5: IEEE 802.11 DCF with Basic Access Mechanism [7]

RTS/CTS Mechanism

RTS/CTS mechanism alleviates the hidden terminal problems. In this mechanism, before transmitting a frame, the sender sends a RTS frame to the receiver for the reservation of the channel. If the receiver is ready to receive the data frame, it sends a CTS frame.

In this mechanism, stations transmit data by using special short RTS/CTS frames before the transmission of an actual frame in order to minimize collision. A station that wants to transmit data frames first sends a RTS frame to the receiver. This frame includes the address of the receiver of the next data frames and the average time needed for data transmission. After waiting for SIFS period, immediately following the reception of RTS frame, if the receiver is ready to accept data frames, wait for SIFS period before sending a CTS frame to the sender. This CTS frame also contains the duration of data frames. All other stations which can hear RTS/CTS frame, will set their NAVs (Network Allocation Vectors) accordingly. The NAV is a timer that indicates the amount of time the medium will be reserved. After the successful transmission of RTS/CTS frame, sender waits for SIFS periods before sending frames. The receiver, received the frames, and waits for SIFS period before sending ACK to the sender. After this successful transmission, the NAV in each station is zero (unless the station in the intervening time heard some other RTS/CTS) and the process can repeat again. Fig. 1.6 represents the RTS/CTS mechanism.

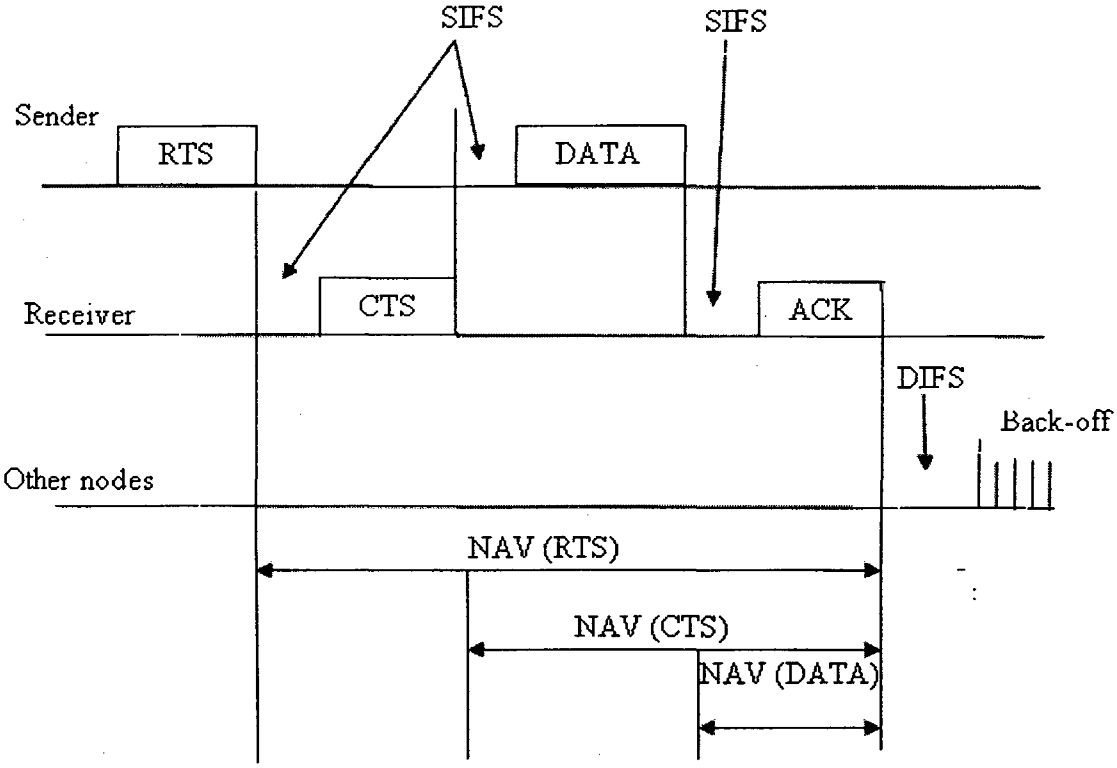


Fig. 1.6: IEEE 802.11 RTS/CTS Mechanisms

1.8 Motivation

In WLANs, the system throughput is highly depends on back-off algorithms and the number of contending stations for the wireless medium. Therefore, for the better performance of IEEE 802.11 DCF, the back-off algorithm is in accordance with the network conditions. Various back-off algorithms and models have been suggested for the performance analysis of IEEE 802.11 DCF. But these models and algorithms are specific in nature, and overcome only some problems of WLANs and ignore others. Therefore, models can be improved by considering issues that are not addressed by existing models.

1.9 Problem Statement and Objectives

The main drawback of IEEE 802.11 is the low performance of its MAC protocol in terms of throughput and access delay where network topology is dynamic, and congested. IEEE 802.11 DCF uses BEB algorithm for the resolution of contention among stations. The problem of binary exponential back-off algorithm is that when the number of contending stations increases, the number of collision may also increase due to sudden decrease in *CW* after every successful transmission. This adversely affects the performance of the network. Also, if the number of contending stations are not too many, the gradual decease in the contention window can lead to significant performance degradation as for most of time channel is idle.

In our work, we proposed to analyze the performance of IEEE 802.11 DCF by considering an adaptive back-off algorithm based on the traffic load and dynamic back-off window size. The proposed work sets the following objectives to meet the goal of the problem.

- ·Modification in the back-off algorithm, and proposing a Markov chain based model for IEEE 802.11 DCF.
- Evaluating its performance.
- Comparison with K. M. J. Khayyat *et al.* model [13].

1.10 Organization of the Dissertation

This dissertation consists of 5-chapters, which are organized as follows:

In chapter1, we introduce IEEE 802.11 for WLANs, and its various aspects like IEEE 802.11 standards, architectures, service set, components, physical layer, and MAC layer with its famous DCF. At the end of the chapter, problem statement with motivation and objectives are given.

Chapter 2 gives a critical analysis of various models related to our work, including most famous Bianchi's model for the performance analysis of IEEE 802.11 DCF.

Our proposed model for the performance analysis of IEEE 802.11 DCF has been explained in chapter 3.

In the chapter 4, experimental results for the performance analysis of IEEE 802.11 DCF using proposed model has been discussed. Further its comparative analysis with K. M. J. Khayyat *et al.* model has been also described.

Finally, we have summarized the work with prospective future enhancements in the chapter 5.

Chapter 2

Related work

In the previous chapter, we have discussed about the fundamentals of IEEE 802.11. This chapter discusses about various analytical models developed for the performance analysis of IEEE 802.11 DCF including the most common Bianchi's model. It also describes about various back-off algorithms for DCF.

2.1 Different Analytical Models of DCF

2.1.1 Bianchi's Model

The first analytical model [8] of DCF was proposed by Bianchi in 1998, with a final publication in IEEE Journal on Selected Areas in communication 2000 [9]. The main contribution of this model is the analytical calculation of saturation throughput in a closed form expression, assuming finite number of stations and ideal channel conditions.

Bianchi uses a two dimensional Markov chain [9]. Each state of this bi-dimensional Markov chain process is represented by *{s(t), b(t)}*, where *s(t)* is the stochastic process representing the back-off stage (*0, 1, 2, . . . ,m*) of a given station at time *t*, and *b(t)* is the stochastic process representing the back-off time counter of the station at time *t*. The key assumption of this model is that, at each transmission attempt, regardless of the number of retransmissions suffered, each frame collides with constant and independent probability *p*. For this Markov chain, the non null one step transition probabilities are given as follows:

$$\begin{array}{lll} P\{i, k|i, k+1\}=1 & k \in (0, W_i-2) & i \in (0,m) \\ P\{0, k|i, 0\}=(1-p)/W_0 & k \in (0, W_0-1) & i \in (0, m) \\ P\{i, k|i-1, 0\}=p/W_i & k \in (0, W_i-1) & i \in (1, m) \\ P\{m, k|m, 0\}=p/W_m & k \in (0, W_m-1) & \end{array} \qquad (2.1)$$

The first equation in (2.1) tells us that the back-off counter is decremented at the beginning of each slot time whether the medium is free or not. The second equation in (2.1) tells us that when back-off counter hits value *0* at time *t*, the station has a transmission. If transmission is successful, $s(t+1) = 0$, i. e., the back-off is reset to first stage, and $b(t+1) = k$ where k is uniformly chosen from 0 to $W_0 -1$. Similarly the third equation in (2.1) tells us that when back-off counter hits value 0 at time t, i. e. the station has a transmission. If transmission is unsuccessful, $s(t+1) = i$, if $s(t) = i-1$, i. e., the back-off is reset to next stage, and $b(t+1) = k$ where k is uniformly chosen from 0 to $W_i -1$. The last equation in (2.1) tells us that if $s(t) = m$ (i.e., if current back-off stage is the maximum attainable stage m), and counter hits 0, the station has a transmission. If frames collides in the channel then $s(t+1) = m$ (is still m), and $b(t+1) = k$ (counter reset) and k is uniformly chosen over 0 to W_m.

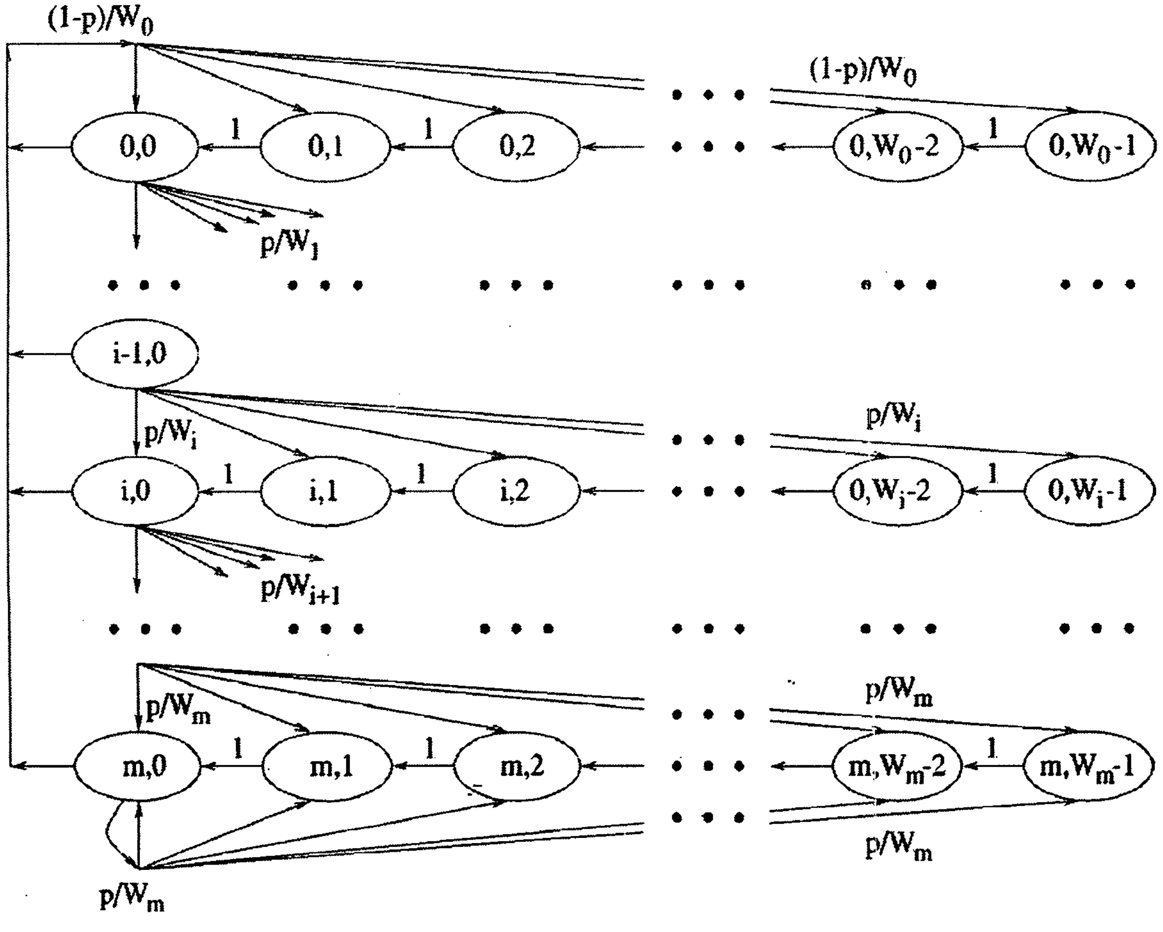


Fig. 2.1: Markov Chain Model for Back-off Window Size [9]

Let τ be the probability that a station transmits a frame in a randomly chosen slot. A frame sent by any station collides if at least one of the remaining *n-1* stations also transmits in the same slot. Therefore, *p* in terms of τ is given by:

$$p = 1-(1-\tau)^{n-1} \tag{2.2}$$

where *n* is the network size.

Let $b_{i,k} = Lim_{t\to\infty} P\{s(t) = i,\ b(t) = k\},\ i \in (0,\ m),\ k \in (0,\ W_i - 1)$ be the stationary distribution of the chain. Then,

$$\begin{array}{lll} b_{i-1,0} \cdot p = b_{i,0} & \to b_{i,0} = p^i\, b_{0,0} & 0 < i < m \\ b_{m,0} = p.(b_{m-1,0} + b_{m,0}) & \to b_{m,0} = \dfrac{p^m}{1-p} b_{0,0} & \end{array} \tag{2.3}$$

The first equation in (2.3) accounts for the fact that at steady state, any station will be in the back-off stage *i* (*0 < i <m*) if collision had occurred in the preceding stage. The second equation accounts for the fact that at steady state, a station will be in the final back-off stage if collision occurred either in m^{th} or $(m-1)^{th}$ stage.

Due to the chain regularity, for each $k \in (0,\ W_i - 1)$, $b_{i,k}$ is given as:

$$b_{i.k} = \frac{W_i - k}{W_i} . \begin{cases} (1-p)\sum_{j=0}^{m} b_{j,0} & i = 0 \\ p.b_{i-1,0} & 0 < i < m \\ p.(b_{m-1,0} + b_{m,0}) & i = m \end{cases} \tag{2.4}$$

The first equation in (2.4) accounts for the fact that at steady state a station will be in the initial back-off stage if frame is successfully transmitted while station was in any back-off stage. The back-off counter will be *k* with probability $(W_0 - k) / W_0$. The second and third equations in (2.4) are explained in the same line.

Using equation (2.3) and $\sum_{j=0}^{m} b_{j,0} = b_{0,0} / (1-p)$, equation (2.4) becomes

$$b_{i,k} = \frac{W_i - k}{W_I} b_{i,0} \qquad i \in (0, m) \quad k \in (0, W_i - 1) \tag{2.5}$$

Therefore, from equations (2.3) and (2.5) $b_{i,k}$ is expressed in terms of $b_{0,0}$ and p. The value of $b_{0,0}$ is calculated by summing all the probabilities that is equal to 1, as given below:

$$
\begin{aligned}
1 &= \sum_{i=0}^{m}\sum_{k=0}^{W_i-1} b_{i,k} \\
&= \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i-1} \frac{W_i-k}{W_i} \\
&= \sum_{i=0}^{m} b_{i,0} \cdot \frac{W_i+1}{2} \\
&= \frac{b_{0,0}}{2}\left[W\left(\sum_{i=0}^{m}(2p)^i + \frac{(2p)^m}{1-p}\right)+\frac{1}{1-p}\right] \\
&= \frac{b_{0.0}}{2}\left[\frac{(1-2p)(W+1)+pW\left(1-(2P)^m\right)}{(1-p)(1-2p)}\right]
\end{aligned}
\tag{2.6}
$$

Where $W_i = 2^i\ W$, W is the minimum contention window. From the above equation, we get

$$
b_{0.0} = \frac{2(1-p)(1-2p)}{(1-2p)(W+1)+pW\left(1-(2p)^m\right)}
\tag{2.7}
$$

Since any station transmits frame when its back-off time counter is equal to zero, whatever the back-off stage may be, therefore τ is given as:

$$
\begin{aligned}
\tau &= \sum_{i=0}^{m} b_{i,0} \\
&= \frac{b_{0,0}}{1-p} \\
&= \frac{2(1-2p)}{(1-2p)(W+1)+pW\left(1-(2p)^m\right)}
\end{aligned}
\tag{2.8}
$$

Equations (2.2) and (2.8) form a system of two non-linear equations that has a unique solution, and can be solved numerically for the values of p and τ.

Let P_{tr} denote the probability that there is at least one transmission in any considered slot time. Since $(1-\tau)^n$ is the probability that no station can transmits in the considered slot, therefore,

$$P_{tr} = 1-(1-\tau)^n \tag{2.9}$$

Let P_s denotes the probability of successful transmission on a channel. P_s is given by the probability that exactly one station transmits on the channel at a time, with the condition that there is at least one station which transmits frame. Therefore,

$$\begin{aligned} P_s &= \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} \\ &= \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \end{aligned} \tag{2.10}$$

The saturation throughput S, is defined as the ratio of average information payload transmitted in a slot time to the average duration of slot time. Therefore,

$$S = \frac{E[\mathit{payload\ information\ transmitted\ in\ a\ slot\ time}]}{E[\mathit{length\ of\ a\ slot\ time}]} \tag{2.11}$$

Where,

E [payload information transmitted in a slot time]

= Prob. of successful transmission in the slot. E [payload of packet]

= $P_{tr}\,P_s\,E[p]$

And,

E [length of a slot time]

= E [idle time] + E[success time] + E[collision time]

$$= (1-P_{tr})\sigma + P_{tr}\,P_s\,T_s + P_{tr}(1-p_S)T_c$$

Here T_s is the average successful transmission time, T_c is the average collision time, and σ is the average duration of an empty slot time. Therefore,

$$S = \frac{P_S P_{tr} E[p]}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s) T_s} \tag{2.12}$$

Let H= PHY_{hdr} + MAC_{hdr} be the packet header, and δ be the propagation delay. Then T_c and T_s can be calculated for the basic transmission mode as:

$$\begin{aligned} T_s^{bas} &= H + E[P] + SIFS + \delta + ACK + DIFS + \delta \\ T_c^{bas} &= H + E[P^*] + DIFS + \delta \end{aligned} \tag{2.13}$$

where $E[P^*]$ is the expected length of longest collided packet payload.

For the RTS/ CTS mode, T_s and T_c can be calculated as:

$$\begin{aligned} T_s^{rts} &= RTS + SIFS + \delta + CTS + SIFS + \delta + H + E[P] + SIFS + \delta + ACK + DIFS + \delta \\ T_c^{rts} &= RTS + DIFS + \delta \end{aligned} \tag{2.14}$$

Performance Evaluation

Bianchi's model shows that the throughput for the basic access scheme depends on the number of stations in the network. In most of the cases, throughput decreases with increase in the network size. But for the RTS/CTS scheme the throughput impairment does not occur when network size increases. The throughput for the basic access scheme highly depends on *W,* whereas for the RTS/CTS scheme throughput is almost independent of $W \leq 64$ and $n \leq 50$. An advantage of RTS/CTS scheme is that the throughput is less sensitive to the transmission probability τ despite of the fact that the maximum throughput achievable by the basic access scheme is very close to that is achievable by the RTS/CTS scheme.

Limitations

The model given by Bianchi for IEEE 802.11 DCF has gained worldwide acceptance due to its simplicity. However, it has some limitations as described in [1]. These are as follows:

1. Bianchi's model excludes the performance analysis of networks under finite load conditions, which is an important practical circumstances in WLANs. It consider only saturated condition.

2. Bianchi's model does not consider the loss of frames due to channel conditions and consider only packet collision.

3. Bianchi's model decreases the back-off counter at the beginning of each slot time, and does not consider whether the channel is idle or not. Therefore, decrementing the back-off value by a station is not according to the IEEE 802.11 DCF standard [1].

Frame Delay Analysis

P. Chatzimisios *et al.* [10] uses the Bianchi' model to calculate the average frame delay in successful transmission of the frame, for both basic and RTS/CTS mechanism. In [10], all the assumptions and notations are same as in [9]. Average frame delay, $E[D]$, is given by:

$$E[D] = E[X].\ E[slot] \tag{2.15}$$

where E[X] is the expected number of slot times for a successful frame transmission, and is calculated as follows:

Let, d_i = average number of slot times that is delayed in the i^{th} back-off stage

and, q_i = probability to reach in the i^{th} back-off stage

therefore,

$$E[X] = \sum_{i=0}^{m} d_i \times q_i \tag{2.16}$$

In the i^{th} back-off stage, a station can choose any back-off value from $(0,\ W_i\text{-}1)$ with the probability $1/W_i$. Therefore, the value of d_i $(0 \leq i \leq m)$ is given by

$$\begin{aligned} d_i &= \sum_{k=0}^{W_i-1} (W_i - k) \times \frac{1}{W_i} \\ &= \frac{1}{W_i} \times \frac{W_i (W_i + 1)}{2} \\ &= \frac{W_i + 1}{2} \end{aligned} \tag{2.17}$$

Since on every frame collision, a station goes into the next back-off stage and remains in the last back-off stage until the successful transmission occurs. Therefore, the value of q_i $(0 \leq i \leq m)$ is given by

$$\begin{aligned} q_i &= \begin{cases} p^i & i \in (0, m-1) \\ p^m + p \times p^m + p^2 \times p^m + \ldots\infty & i = m \end{cases} \\ &= \begin{cases} p^i & i \in (0, m-1) \\ \dfrac{p^m}{1-p} & i = m \end{cases} \end{aligned} \tag{2.18}$$

Using equations (2.17) and (2.18), equation (2.16) becomes

$$\begin{aligned} E[X] &= \sum_{i=0}^{m} q_i \times \frac{W_i + 1}{2} \\ &= \sum_{i=0}^{m-1} p^i \times \frac{W_i - 1}{2} + p^m \times \frac{W_m + 1}{2} \\ &= \frac{(1-2p)(W+1) + pW\left(1 - (2P)^m\right)}{1(1-p)(1-2p)} \end{aligned} \tag{2.19}$$

Experimental results of this model show that for the RTS/CTS mechanism average delay is lower than the basic access mechanism for the large size network.

2.1.2 Models Related to Bianchi's model

Many researchers extended (modified) the Bianchi's model directly or indirectly to remove the shortcomings of the model through finite retransmission attempts [11], or freezing back-off counter during busy periods [12], or assuming finite load conditions (unsaturated condition) [13].

H. Wu *et al.* [11] modified Bianchi's model by introducing a limit on the number of retransmissions and maximum size of contention window. But they assumed ideal channel conditions.

E. Ziouva and T. Antonakopoulos [14], and M. Ergen and P. Varaiya [12], extended Bianchi's model by taking into account freezing of the back-off counter during busy time periods, with ideal channel condition.

P. Chatzimisios *et al.* [15] and Q. Ni *et al.* [16] extended Wu's model [11] for basic access method by adding transmission failure due to errors. These models assume saturated condition; i. e. there is always a frame ready for transmission in each station's queues. In [16] ACK frame loss due to errors is considered, while in [15] it is not considered. Analytical results of [15] demonstrate that performance of the protocol strongly depends on the Bit Error Rate (BER). When BER increases, throughput decreases while the frame drop probability increases.

K. Szczypiorski and J. Lubacz [17] extended Bianchi's model [9] taking into account finite number of retransmissions, maximum size of contention window, impact of transmission errors and freezing of back-off counter during busy periods. The proposed model [17] has good precision in both error free and error prone mediums. When the number of stations increases in the network to share the medium, the freezing the back-off counter off has good impact on throughput assessment. But this model is for saturated condition, and applies only for basic access mechanism.

In [18], Adaptive Minimum Contention Window with Binary Exponential Back-off Algorithm (AWBEB algorithm) based on Double Increment Double Decrement (DIDD) was proposed but for ideal and saturated channel. This algorithm gives 30- 40 percent more throughput than DCF for a small sized networks, and 10-20 percent more throughput when stations in the network become larger.

N. Wattanamongkhol *et al.* [19] extended the Bianchi's model by proposing a DIDD back-off algorithm. This model improves the performance (saturation throughput) of basic access mechanism significantly at high load. But for RTS/CTS mechanism, this improvement is marginal. At light loads, negative effect is experienced. Limitations of the model are same as that of Bianchi's model.

G. Sun and B. Hu [20] extended the Bianchi's model by considering the back-off suspension during the busy periods. Simulation results of the model show that without considering the back-off suspension, the current major models estimated the saturation delay performance of the IEEE MAC protocol.

I.Tinnirello *et al.* [21] extended the Bianchi's model by considering the correlation between consecutive channel slots. This model does not consider freezing back-off state explicitly.

In the literature, some investigations have been done on finite load models for the performance analysis of IEEE 802.11 DCF [22-27]. However, decrementing of back-off value by a station is according to [1] in these models.

P. P. Pham *et al.* [22] extended the Bianchi's model [9] by considering the finite load condition (unsaturated condition) and finite number of retransmissions. In this model, a new idle state is assumed for the situation when the station's queue is empty after either a successful transmission or maximum retransmissions attempt. Simulation results show that the model strongly reveals the behavior of IEEE 802.11 in terms of channel throughput and frame delay. But this model uses ideal channel conditions; i. e. hidden terminal problems and channel errors are not considered.

S. L. Yong *et al.* [23] proposed a model by extending the Bianchi's model [9] for unsaturated conditions. In this model, a new idle state is assumed for the situation when the station's queue is empty after a successful transmission, and a frame is discarded after *m* failed retransmissions. This model also considers the hidden terminal problem. This model shows that the maximum throughput is obtained well before the saturation, when the network size is large. But in this model channel errors are not considered.

In [27], a Markov model has been proposed by considering the limited load. In this model a new state, called post–back-off, for each back-off stages is added. This new state is accounts for the case when there are no packets for transmission. This model predicts that peak throughput occurs prior to saturation. But, decrementing of back-off counter is not considered in this model according to [1].

2.1.3 K. M. J. Khayyat *et al.* Model [13]

This model is based on Markov chain for analyzing the performance of the IEEE 802.11 DCF. This model considers non saturated condition, finite number of retransmission attempts, and freezing of back-off counter during the busy periods. The most important outcome of this model is that it gives a relation between the number of stations and the initial size of contention window for the evaluating the performance of a network.

This model analyzes the effect of initial back-off window size on the performance of DCF. It gives optimum performance in terms of throughput, user access probability, and delay when the initial back-off window size is equal to the number of users. However, this model does not consider RTS/CTS mechanism and uses the binary exponential back-off algorithm. Therefore, throughput of the network decreases when the number of contending stations increases

Khalid M. J. Khayyat and F. Gebali [28] extended the model [13] by considering all levels of traffic and finite retransmission attempts. This model considers RTS/CTS mechanism. It shows that throughput and user access probability have better values than the basic access model over most of the input traffic range. The model also shows low delay and small average energy over most of the input traffic range when RTS/CTS mechanism is used. But this model is designed only for BEB algorithm.

Khalid M. J. Khayyat and F. Gebali [29] extended the model [13] for wireless ad-hoc networks by considering the channel bit error rates and a non-ideal channel environment. In this model, a frame is retransmitted under two situations either a collision occurs or a frame is received in error. In the case of channel error (2nd situation), frame is retransmitted without doubling the back-off window. This model gives optimum throughput, user access probability, average delay, and average energy when the bit error rate is low. But the model considers basic access mechanism and BEB algorithm, only.

2.2 Models for Back-off Algorithm

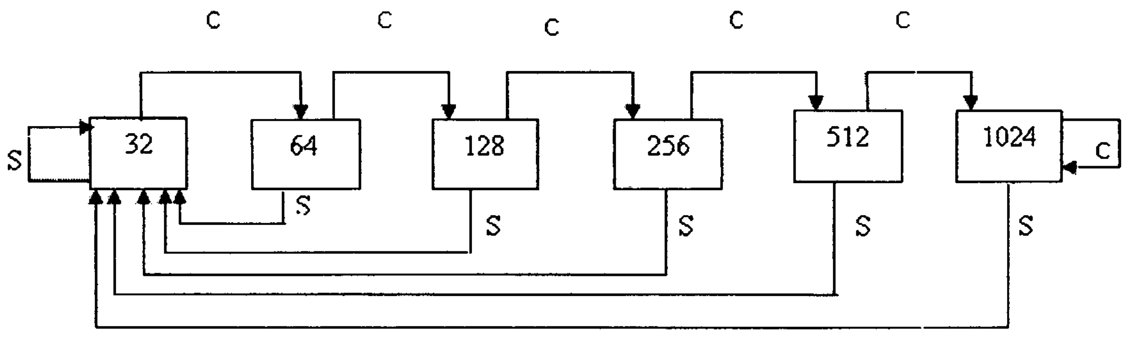
In the previous sections of this chapter we have discussed about various analytical models for the performance analysis of IEEE 802.11 DCF. This section discusses explicitly about the some back-off algorithms used in the performance analysis of IEEE

802.11 DCF. The selection of proper back-off algorithm is extremely important as it truly reflects the capacity to resolve contention among nodes, and enhances the total performance of the system. In the absence of proper selection of back-off algorithm, the system performance degrades rapidly. Some important back-off algorithms are discussed below.

2.2.1 BEB Algorithm

IEEE 802.11 DCF is based on a CSMA/CA and it uses BEB algorithm, to minimize the packet collisions due to multiple simultaneous transmissions [9]. In this algorithm, after each unsuccessful transmission contention window W is doubled up to a maximum value of $CW_{max} = 2^m * CW_{min}$ where m is the maximum number of back-off stages. Once it reaches the maximum back-off value, it will remain this maximum value until a successful transmission occurs. After a successful transmission, the *CW* is reset to initial value. The pseudo code for BEB algorithm is given below:

```
if collision
    $CW_{new} = min\ (CW_{old} * 2,\ CW_{max})$
if transmission success
    reset CW to $CW_{min}$
```



C: collision S: successful transmission

Fig. 2.2: Markov chain model for the BEB algorithm

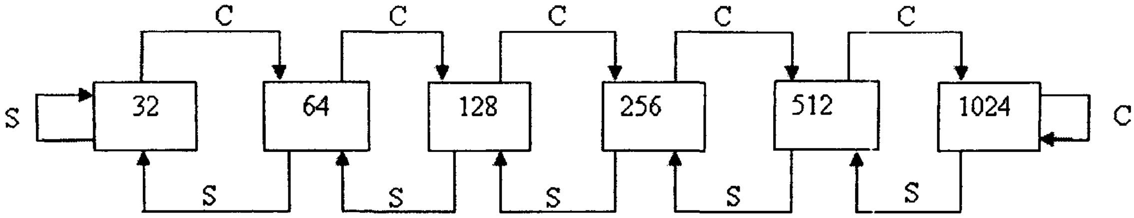
$(CW_{min} = 32,\ CW_{max} = 1024)$

Since in this algorithm *CW* is reset to the initial value after a successful transmission, therefore chance of packet collision increases when there is large number of stations contending for the channel. Therefore, there is another algorithm called DIDD that solves the problem.

2.2.2 DIDD Algorithm

Authors of [18] Suggests a simple and effective contention window resetting algorithm, named Double Increment Double Decrement (DIDD), to improve the performance of IEEE 902.11 DCF in heavy contention based network. In this algorithm after each unsuccessful transmission contention window W is doubled up to a maximum value $CW_{max} = 2^m * CW_{min}$ where m is the maximum number of back-off stages. After a successful transmission, the *CW* becomes half of the current *CW*. The pseudo code for DIDD algorithm is given below:

```
if collision
    $CW_{new} = min (CW_{old} * 2, CW_{max})$
if transmission success
    $CW_{new} = max (CW_{old} /2, CW_{min})$
```



C: collision S: successful transmission

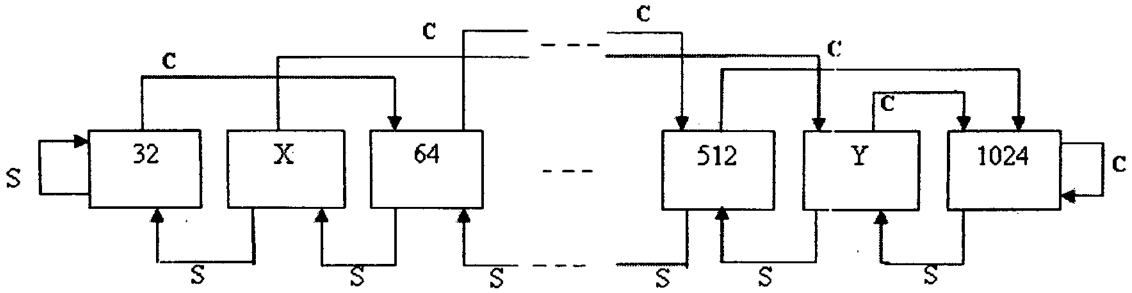
Fig. 2.3: Markov chain model for the DIDD algorithm
($CW_{min} = 32$, $CWmax = 1024$)

This algorithm improves the throughput and decreases the collision probability by slowing down the speed with which *CW* return to minimum value. However, this algorithm does not work well when there is small number of stations in the network. Therefore, there is another algorithm called EIED was proposed to solve this problem.

2.2.3 EIED Algorithm

A number of modifications have been suggested for the baseline BEB algorithm [30]. EIED is a quite flexible back-off algorithm with a number of adaptable parameters like network load, packet length, etc. In this algorithm, a station sets the new contention window as CW_{old} multiplied by the parameter r_i, increments back-off factor after each unsuccessful transmission. After each successful transmission, the new value of *CW* is given by CW_{old} divided by the parameter r_d, where r_d is the decrement back-off factor. The pseudo code for EIED algorithm is given below:

```
if collision
    $CW_{new} = min (CW_{old} * r_i, CW_{max})$
if transmission success
    $CW_{new} = max (CW_{old} / r_d , CW_{min})$
```



C: collision S: successful transmission $X=32\times 2^{1/2}$, $Y= 512\times 2^{1/2}$

Fig. 2.4: Markov chain model for the EIED algorithm

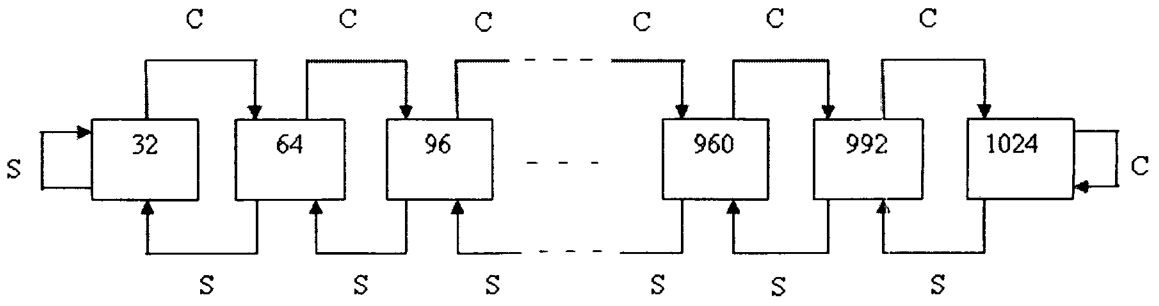
($r_i = 2$, $r_d = 2^{1/2}$, $CW_{min}=32$, $CW_{max}=1024$)

Simulation results in [30] show that the EIED algorithm is better than BEB and DIDD algorithms in both the situations whether there is large number of competing stations or few competing stations. However, this algorithm does not work well when there are too many competing stations.

2.2.4 LILD Algorithm

This algorithm is an improvement of the MIMD algorithm [31]. MIMD algorithm increases and decreases the contention window multiplicatively. Whereas, LILD algorithm increases and decreases the contention window linearly. The pseudo code for LILD algorithm is given below:

```
if collision
    $CW_{new} = min\ (CW_{old} + CW_{min},\ CW_{max})$
if transmission success
    $CW_{new} = max\ (CW_{old} - CW_{min},\ CW_{min})$
```



C: collision S: successful transmission

Fig. 2.5: Markov chain model for the LILD algorithm

$(CW_{min} = 32,\ CW_{max} = 1024)$

This algorithm works well for the large number of competing stations because the contention window size varies gradually.

2.2.5 ELB Algorithm

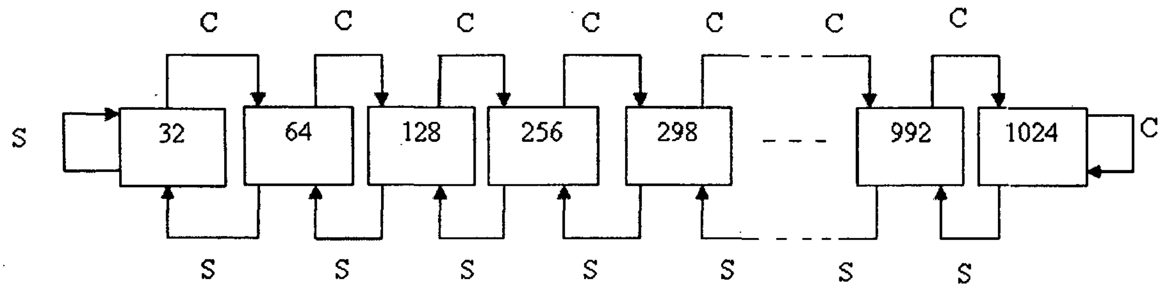
This algorithm [32] combines the advantages of both the EIED and LILD to adjust it under different wireless network loads. Firstly, this algorithm set a threshold contention window ($CW_{Threshold}$) based on the current network conditions, as indicated by the number of consecutive collisions, to find out whether the competitive wireless stations are low or high. If the contention window size is smaller than or equal to this threshold, at light network load, the contention window is setup exponentially, otherwise it is setup linearly. The pseudo code for ELBA is given below [32]:

1. ELBA CW decrease procedure (after each successful transmission)

```
if ($W_{i-1} = CW_{min}$)
    $W_i = CW_{min}$
elseif ($W_{i-1} <= CW_{Threshold}$)
    $W_i = W_{i-1}/2$
elseif ($W_{i-1} <= CW_{max}$)
    $W_i = W_{i-1} - CW_{min}$
```

2. ELBA CW increase procedure (after each transmission collision)

```
if ($W_{i-1} <= CW_{Threshold}$)
    $W_i = W_{i-1} * 2$
elseif ($W_{i-1} < CW_{max}$)
    $W_i = W_{i-1} + CW_{min}$
elseif ($W_{i-1} = CW_{max}$)
    $W_i = CW_{max}$
```



C: collision S: successful transmission

Fig. 2.6: Markov chain model for the ELB algorithm

($CW_{min} = 32$, $CW_{max} = 1024$, $CW_{threshold} = 256$)

The numerical results in [32] show that the ELBA improves the system throughput and collision rates than the BEB, EIED and LILD under both type of networks, i.e., heavy load or light load.

Chapter 3

Proposed Model and its Mathematical Analysis

In the previous chapter we have studied various analytical models for the performance analysis of IEEE 802.11 DCF. Despite of their own strengths and weakness, these models are quite helpful in understanding of the performance metrics. As the BEB algorithm is not suited for networks under heavy traffic load, we extended the model [13] by using an Adaptive DIDD (ADIDD) back-off algorithm in place of BEB algorithm to resolve the contention among the stations.

3.1Model Description

A DCF station can be either in idle state or back-off state or transmitting state. The current state of a user depends only on its previous (just before the current) state, following Markovian property [33]. A collision occurs only when two or more stations send frames in the same slot time, i.e., only frame collision are taken into consideration. DCF mechanism with ADIDD algorithm is used to access the medium. In ADIDD algorithm, a station doubles up its contention window after each collision, upto a maximum value, of $CW_{max} = 2^m CW_{min}$, where m is the maximum number of collisions experienced by the station during the back-off procedure. After each successful transmission contention window is reduced to half, if the station has a frame for transmission, otherwise it goes into the idle state.

Assumptions

The assumptions for the model are the same as in [13].

1. All network stations N are in radio contact with each other, i.e., there are no hidden terminal or capture problems.
2. The contention slot period is equal to the time step t.
3. When an idle station receives a packet for transmission, the probability to issues request to transmit a frame in a time step is equal to a.
4. The length of all MAC frames are fixed and requires n time steps for its transmission.

v. During the back-off periods, station freezes its back-off counter when the channel is busy and decreases its back-off counter by one for each time step when the channel is free.

vi. Certain error control protocols are used to remove the noise from the channel.

3.2 State Transition Diagram for the Model

Fig. 3.1 shows a Markov transition for the transmission states of a tagged station. In the figure, p is the probability of frame collision, f is the probability that channel is free, and s (s = input traffic/ total number of competing stations) is the probability that a station has a another frame for transmission after successful frame transmission. The probabilities α_i is given by

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

where W_i is the size of ith stage back-off window.

The back-off states are represented by the sets B_i $(0 \leq i \leq m)$;

$$B_i = \{B_{i,0} \quad B_{i,1} \quad \dots \quad B_{i,W_i-1}\} \tag{3.2}$$

The transmission states are represented by the sets T_i $(0 \leq i \leq m)$

$$\mathrm{T_i = \{T_{i,0} \quad T_{i,1} \quad \dots \quad T_{i,n-1}\}} \tag{3.3}$$

In the steady state, applying the Markov chain to first set of back-off states B_0 in Fig. 3.1, gives

$$\begin{aligned} B_{0,W_0-1} &= B_{0,W_0-1} \times (1-f) + I\,a\,\alpha_0 + (T_{1,n-1} + T_{0,N-1}) \times ((1-p)s\,\alpha_0) \\ &= \frac{1}{f}\left[I\,a\,\alpha_0 + (1-p)s\,\alpha_0 \times (T_{0,n-1} + T_{1,n-1})\right] \end{aligned}$$

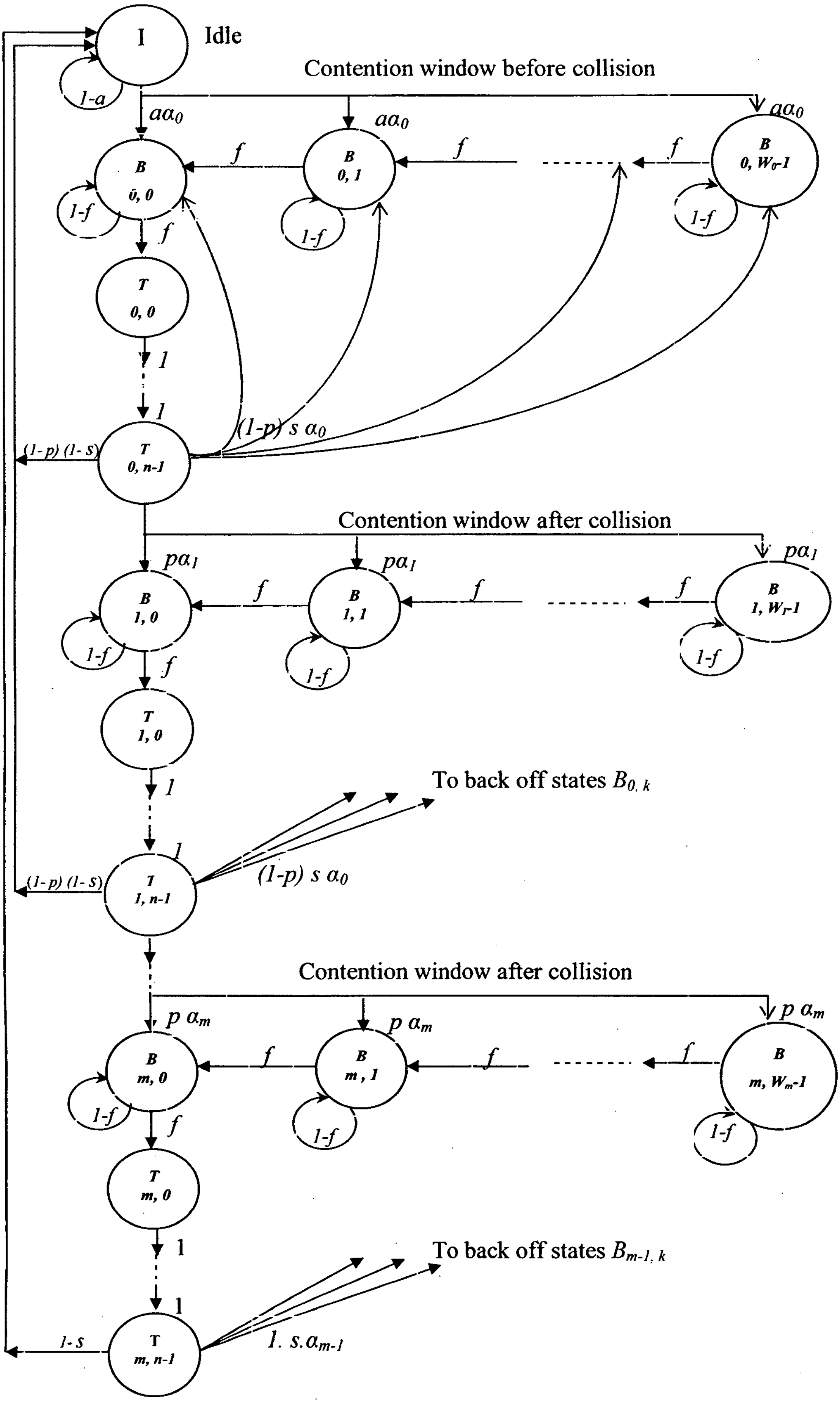


Figure 3.1: State Transition Diagram

$$
\begin{aligned}
B_{0,W_0-2} &= B_{0,W_0-2}\times(1-f)+B_{0.W_0-1}\times f+I\,a\alpha_0+(1-p)s\alpha_0\times(T_{0,n-1}+T_{0,n-1}) \\
&= \frac{2}{f}\left[I\,a\alpha_0+(1-p)s\alpha_0\times(T_{0,n-1}+T_{1,n-1})\right] \\
&= \frac{W_0-(W_0-2)}{f}\alpha_0\left[I\,a+(1-p)s\alpha_0\times(T_{0,n-1}+T_{1,n-1})\right]
\end{aligned}
$$

Similarly, for $0 \le k \le W_0\text{-}1$, we have

$$
B_{0.k} = \frac{W_0-k}{f}\left[I\,a\alpha_0+(1-p)s\alpha_0\times(T_{0,n-1}+T_{1,n-1})\right] \tag{3.4}
$$

A station starts to send frame at back-off stage 0 when its back-off counter reaches zero and channel is free at that time step. Therefore, the probability that a station starts sending at back-off stage 0 is given by

$$
\begin{aligned}
T_{0,0} &= B_{0,0}\times f \\
&= I\,a+(1-p)s\times(T_{0,n-1}+T_{0,n-1})
\end{aligned} \tag{3.5}
$$

From the state transition diagram in Fig. 3.1, it is clear that all transmission states in set T_i $(0 \le i \le m)$ are equal. Therefore, for $0 \le i \le m$, we have

$$
T_{i,0} = T_{i,1} = T_{i,2} = \ldots \quad = T_{i,n-1} \tag{3.6}
$$

In the steady state, applying the flow balance to the second set of back-off states B_1 in Fig. 3.1, gives

$$
\begin{aligned}
B_{1,W_1-1} &= B_{1,W_1-1}\times(1-f)+T_{0,n-1}\,p\alpha_1+T_{2,n-1}(1-p)s\alpha_1 \\
&= \frac{1}{f}\alpha_1\left[T_{0,n-1}\,p+T_{2,n-1}(1-p)s\right]
\end{aligned}
$$

$$
\begin{aligned}
B_{1,W_1-1} &= B_{1,W_1-2}\times(1-f)+B_{1,W_1-1}\times f+T_{0,n-1}\,p\alpha_1+T_{2,n-1}(1-p)s\alpha_1 \\
&= \frac{2}{f}\alpha_1\left[T_{0,n-1}\,p+T_{2,n-1}(1-p)s\right] \\
&= \frac{W_1-(W_1-2)}{f}\alpha_1\left[T_{0,n-1}\,p+T_{2,n-1}(1-p)s\right]
\end{aligned}
$$

Similarly, for $0 \leq k \leq W_1\text{-}1$, we have

$$B_{1,k} = \frac{W_1 - k}{f}\alpha_1\left[T_{0,n-1}\,p + T_{2,n-1}(1-p)s\right] \tag{3.7}$$

A station starts to sending frames at back-off stage *1* when its back-off counter reaches zero and channel is free at that time step. Therefore, the probability that a station starts to send at back-off stage *1* is given by

$$\begin{aligned} T_{1,0} &= B_{1,0} \times f \\ &= T_{0,n-1}\,p + T_{2,n-1}(1-p)s \end{aligned} \tag{3.8}$$

Similarly for $0 < i < m\text{-}1$ and $0 \leq k \leq W_i\text{-}1$, we have

$$B_{i,k} = \frac{W_i - k}{f}\alpha_i\left[T_{i-1,n-1}\,p + T_{i+1,n-1}(1-p)s\right] \tag{3.9}$$

$$T_{i,0} = T_{i-1,n-1}\,p + T_{i+1,n-1}(1-p)s \tag{3.10}$$

In the steady state applying the flow balance to the back-off states B_{m--1} in Fig. 3.1 gives the following equations. Further in the m^{th} back-off stage, it does not matter whether a packet collides or not, because after *m* failed attempts, sender returns to the idle state.

$$\begin{aligned} B_{m-1,W_{m-1}-1} &= B_{m-1,W_{m-1}-1} \times (1-f) + T_{m-2,n-1}\,p\alpha_{m-1} + T_{m,n-1}\,s\alpha_{m-1} \\ &= \frac{1}{f}\alpha_{m-1}\left[T_{m-2,n-1}\,p + T_{m,n-1}\,s\right] \end{aligned}$$

$$\begin{aligned} B_{m-1,W_{m-1}-2} &= B_{m-1,W_{m-1}-2} \times (1-f) + B_{m-1,W_{m-1}-1} \times f + T_{m-2,n-1}\,p\alpha_{m-1} + T_{m,n-1}\,s\alpha_{m-1} \\ &= \frac{2}{f}\alpha_{m-1}\left[T_{m-2,n-1}\,p + T_{m,n-1}\,s\right] \\ &= \frac{W_{m-1} - (W_{m-1} - 2)}{f}\alpha_{m-1}\left[T_{m-2,n-1}\,p + T_{m,n-1}\,s\right] \end{aligned}$$

Similarly, for $0 \leq k \leq W_{m-1}-1$, we have

$$B_{m-1,k} = \frac{W_{m-1}-k}{f}\alpha_{m-1}\left[T_{m-2,n-1}\,p + T_{m,n-1}\,s\right] \tag{3.11}$$

Therefore, $$T_{m-1,0} = B_{m-1,0} \times f = T_{m-2,n-1}\,p + T_{m,n-1}\,s \tag{3.12}$$

In the steady state, applying the flow balance to last set of back-off states B_m in Fig. 3.1, gives

$$\begin{aligned} B_{m,W_m-1} &= B_{m,W_m-1} \times (1-f) + T_{m-1,n-1}\,p\,\alpha_m \\ &= \frac{1}{f}\alpha_m\left[p\,T_{m-1,n-1}\right] \end{aligned}$$

$$\begin{aligned} B_{m,W_m-2} &= B_{m,W_m-2} \times (1-f) + B_{m,W_m-1} \times f + p\alpha_m\,T_{m-1,n-1} \\ &= \frac{2}{f}\alpha_m\,p\,T_{m-1,n-1} \\ &= \frac{W_m-(W_m-2)}{f}\alpha_m\,p\,T_{m-1,n-1} \end{aligned}$$

Similarly, for $0 \leq k \leq W_m-1$, we have

$$B_{m,k} = \frac{W_m-k}{f}\alpha_m\,p\,T_{m-1,n-1} \tag{3.13}$$

Therefore, $$T_{m,0} = B_{m,o} \times f = pT_{m-1,n-1} \tag{3.14}$$

The above probabilities ($B_{i,j}$ & $T_{i,j}$) can be calculated for a particular value of m. In our experiment, we have used m = 3. Therefore, from equation (3.14), we get

$$T_{3,0} = pT_{2,n-1} \tag{3.15}$$

From the equation (3.12), we get

$$\begin{aligned} T_{2,0} &= pT_{1,n-1} + sT_{3,n-1} \\ &= \frac{p}{1-ps} \times T_{1,n-1} \end{aligned} \tag{3.16}$$

From the equation (3.10), we obtain

$$T_{1,0} = \frac{p(1-ps)}{1-ps(2-ps)} \tag{3.17}$$

From the equation (3.5)

$$\begin{aligned} T_{0.0} &= Ia + s(1-p) \times (T_{0.n-1} + T_{1,n-1}) \\ &= Ia + s(1-p) \times \left[T_{0,n-1} + \frac{p(1-ps)}{1-ps(2-p)} \times T_{0,n-1} \right] \\ &= \frac{1-ps(2-p)}{(1-s)-2ps(1-s-p+ps)} \times Ia \end{aligned} \tag{3.18}$$

Using D = $(1- s) - 2\,p\,s\,(1- p - s + p\,s)$, and considering the equation (3.6), the transmission probabilities $T_{i,j}$ ($o \le j \le n\text{-}1$) are calculated as:

$$\begin{aligned} T_{0,j} &= \frac{1-ps(2-p)}{D} \times Ia \\ T_{1,j} &= \frac{p(1-ps)}{D} \times Ia \\ T_{2,j} &= \frac{p^2}{D} \times Ia \\ T_{3,j} &= \frac{p^3}{D} \times Ia \end{aligned} \tag{3.19}$$

Now, putting the values of $T_{i,j}$, $0 \le i \le 3$ & $0 \le j \le n\text{-}1$, in the equations (3.9), the value of $B_{i,k}$, $0 \le i \le 3$ & $0 \le k \le W_i\text{-}1$ are as follows :

$$
\begin{aligned}
B_{0,k} &= \frac{W_0 - k}{W_0 \times f} \times \frac{(1 - ps(2 - 4s + p))}{D} \times I\,a \\
B_{1,k} &= \frac{W_1 - k}{W_1 \times f} \times \frac{(p - p^2 s)}{D} \times I\,a \\
B_{2,k} &= \frac{W_2 - k}{W_2 \times f} \times \frac{p^2}{D} \times I\,a \\
B_{3,k} &= \frac{W_3 - k}{W_3 \times f} \times \frac{p^3}{D} \times I\,a
\end{aligned}
\qquad (3.20)
$$

Similarly for any other value of m, the probabilities $B_{i,j}$ and $T_{i,j}$ can be calculated.

Since the sum of all the probabilities is equal to one. Therefore, we have

$$I + \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} B_{i,k} + \sum_{i=0}^{m} \sum_{j=0}^{n-1} T_{i,j} = 1 \qquad (3.21)$$

Substituting the value of $B_{i,k}$ and $T_{i,j}$ in the above equation, we can obtain the value of I as a function of probabilities f and p.

3.3 Estimation of the Probabilities f and p

Since the idle state probability (I) is a function of the probabilities f and p, which depend on the state probabilities $B_{i,k}$ and $T_{i,j}$. Therefore to estimate the user states (I, B, and T) from the above highly non-linear system of equations, we use iterative technique. The related probabilities f and p for a given traffic level can be determined as follows:

A station starts to sending frame when its back-off counter reaches zero and channel is free at that time step. Therefore, the probability q that a station starts to send at a time step is represented by

$$q = \sum_{i=0}^{m} f \times B_{i,0} = \sum_{i=0}^{m} T_{i,0} \qquad (3.22)$$

The probability r that a station is not sending at a time step is given by

$$r = I + \sum_{i=0}^{m} \sum_{k=1}^{W_i - 1} B_{i,k} + (1 - f) \sum_{i=0}^{m} B_{i,0} \tag{3.23}$$

For a given station channel is free when remaining *N-1* stations are not sending. Therefore, the probability *f* that the channel is free at a given time step is given by

$$f = r^{N-1} \tag{3.24}$$

A collision occurs when two or more stations send at the same time step. Therefore, the collision probability p (according to binomial distribution) is given by

$$p = \sum_{k=2}^{N} {}^{N}C_k \, q^k \, r^{N-k} \tag{3.25}$$

3.4 Performance Metrics

We have considered three performance metrics for evaluating the performance of our model. They are– throughput, user access probability, and average delay.

The throughput, *Th*, is average number of successfully transmitted frames per contention slot. Therefore, throughput is estimated as

$$\begin{aligned} Th &= (1 - p) N \sum_{i=0}^{m} \sum_{j-0}^{n-1} T_{i,j} \\ &= (1 - p) N n \sum_{i=0}^{m} T_{i,0} \end{aligned} \tag{3.26}$$

The average input traffic (N_a) to the system is denoted by

$$N_a = N \times a \tag{3.27}$$

The average acceptance probability for a given station, i.e., user access probability, p_a, is the probability that a station is competent to access the channel when it is ready to send. Therefore, p_a is the ratio of frames transmitted through the system to the total number of arriving frames in one time step [34, 35]. Therefore, we have

$$p_a = \frac{Th}{N_a} \tag{3.28}$$

The delay occurs in frame retransmission due to channel errors or frame collisions. Since the expected number of failures before first success (with success probability p_a) follows geometric distribution, therefore the average number of frame retransmissions, n_a, is given by

$$\begin{aligned} n_a &= \sum_{i=0}^{\infty} i\left(1-p_a\right)^i p_a \\ &= \frac{1-p_a}{p_a} \end{aligned} \tag{3.29}$$

Chapter 4

Experimental Results

In the previous chapter, we have discussed the mathematical analysis of our proposed model for the performance analysis of IEEE 802.11 Distributed Coordination Function (DCF). The next important issue is implementation and computation of results. In this chapter experimental results of the proposed model comparing with the model [13] are given.

4.1 Simulation and Experiments

To simulate the model, we have written programs in MATLAB. The various input parameters used for performance evaluations of the models are given below:

Parameter	Meaning	Values
a	Probability that an idle station issues a request for transmission of a frame during a time step	$0 \leq a < 1$
s	Probability that a station, after successful transmission of a frame, has another frame for transmission	$s = a$
N	Total number of stations	4, 6, 8, 12, 16
N_a	Input traffic	$N \times a$
n	Total number of time steps required for transmission of a frame	4
m	Maximum number of collisions	3
W_0	Initial contention window size	16, 32, 64, 128, 256

Table 4.1: Parameter values used for performance analysis

The performance of the proposed model, corresponding to various level of input traffic, is measured with the help of the following metrics:

Throughput (frame / time step)
User access probability, p_a
Average delay, n_a

The throughput, *Th*, is the average number of successfully transmitted frames per time step.

The average acceptance probability for a given user, i.e, user access probability, p_a, is the probability that a station is competent to access the channel when it is ready to send.

Average delay is defined as the total number of frame retransmissions before the successful transmission of a frame.

4.1 Results and Analysis

This section discusses the results obtained from the proposed model using ADIDD back-off algorithm and from the model given in [13] using BEB algorithm. Experimental results obtained in terms of throughput, user access probability, and average delay for different input traffic are represented in the form of graphs using MATLAB. Experimental results are divided into following three categories.

4.1.1 Effect of Initial Back-off Window on Throughput

To show the effect of initial back-off window on throughput for to two back-off algorithms, we varied W_0 and N.

Fig. 4.2.1(a) shows the throughput versus input traffic for the cases when m = 3, n = 4, N = 4, and the initial back-off window (W_0) taking values as 16, 32, 64, 128. It is observed from the figure that the BEB algorithm gives better throughput than the ADIDD back-off algorithm for the most values of input range.

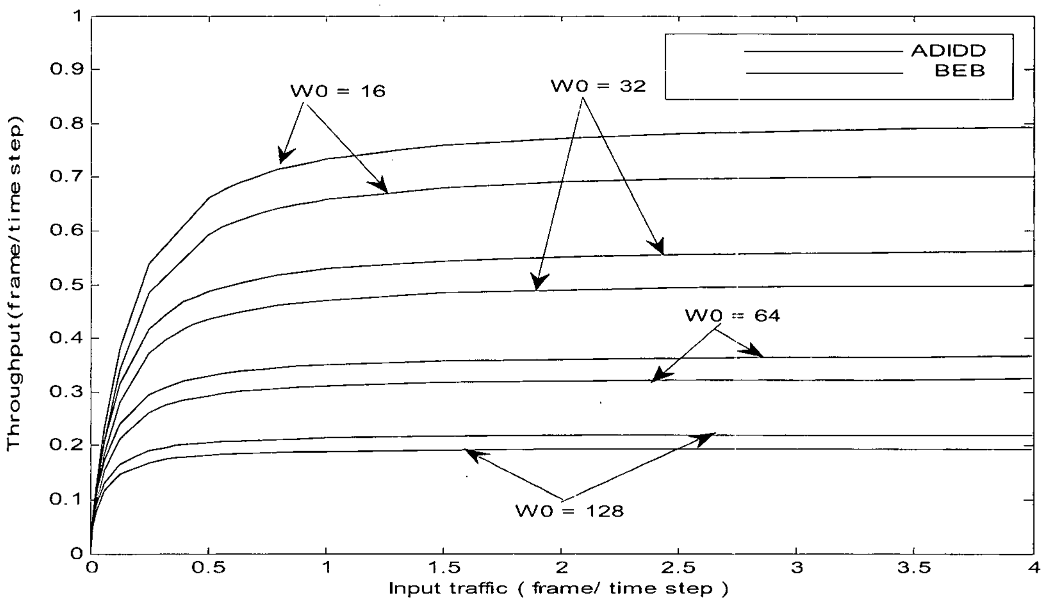


Fig. 4.2.1(a): Throughput versus input traffic for N = 4

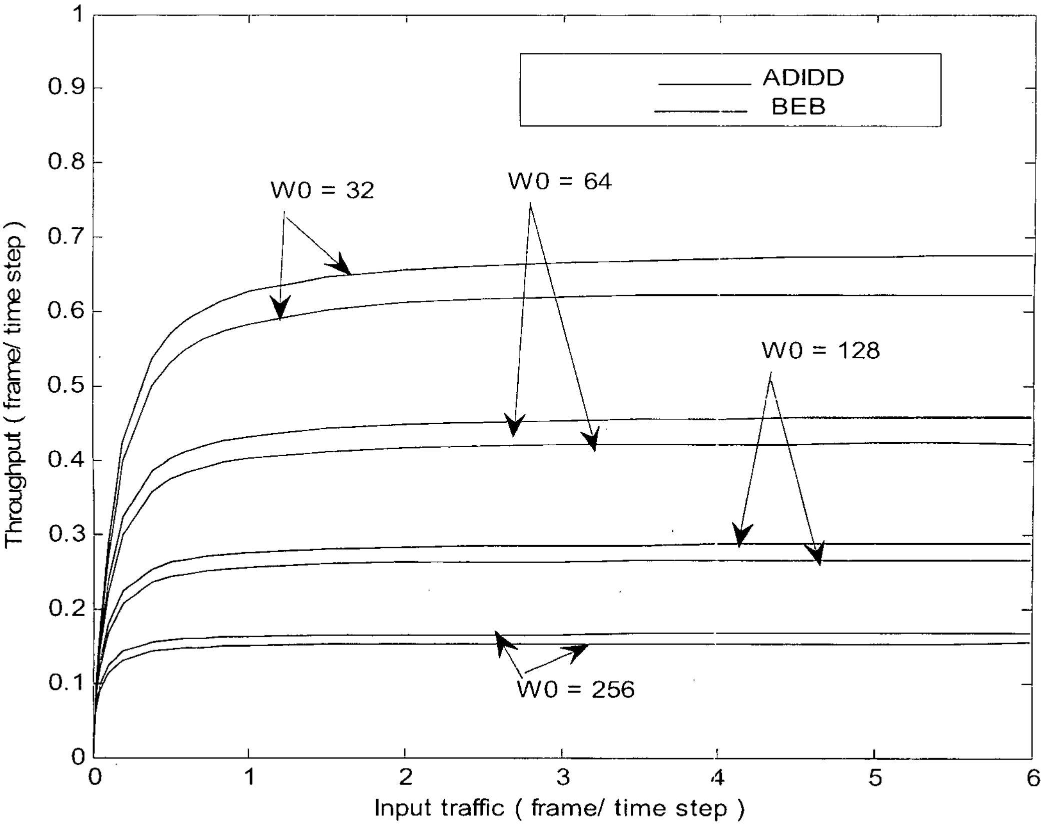


Fig 4.2.1(b): Throughput versus input traffic for N = 6 .

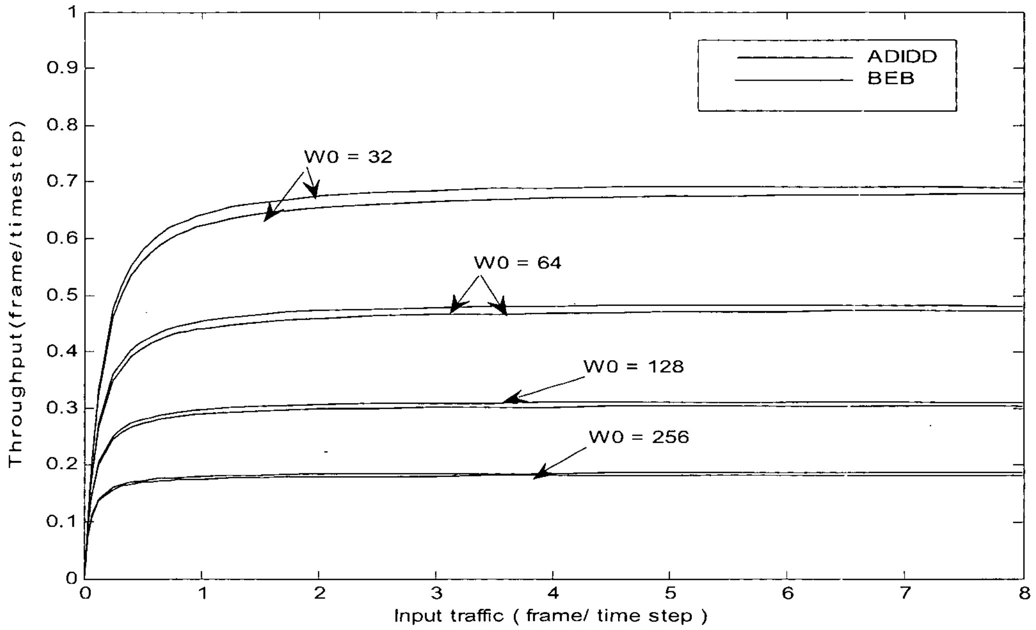


Fig. 4.2.1(c): Throughput versus input traffic for N = 8

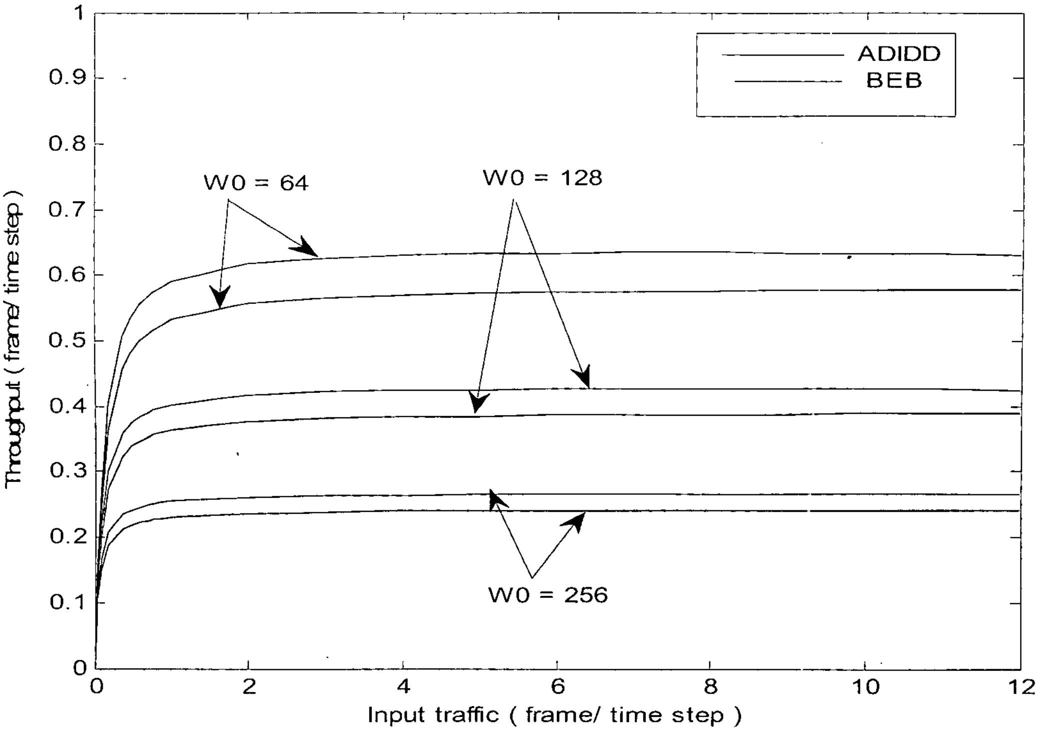


Fig. 4.2.1(d): Throughput versus input traffic for N = 12

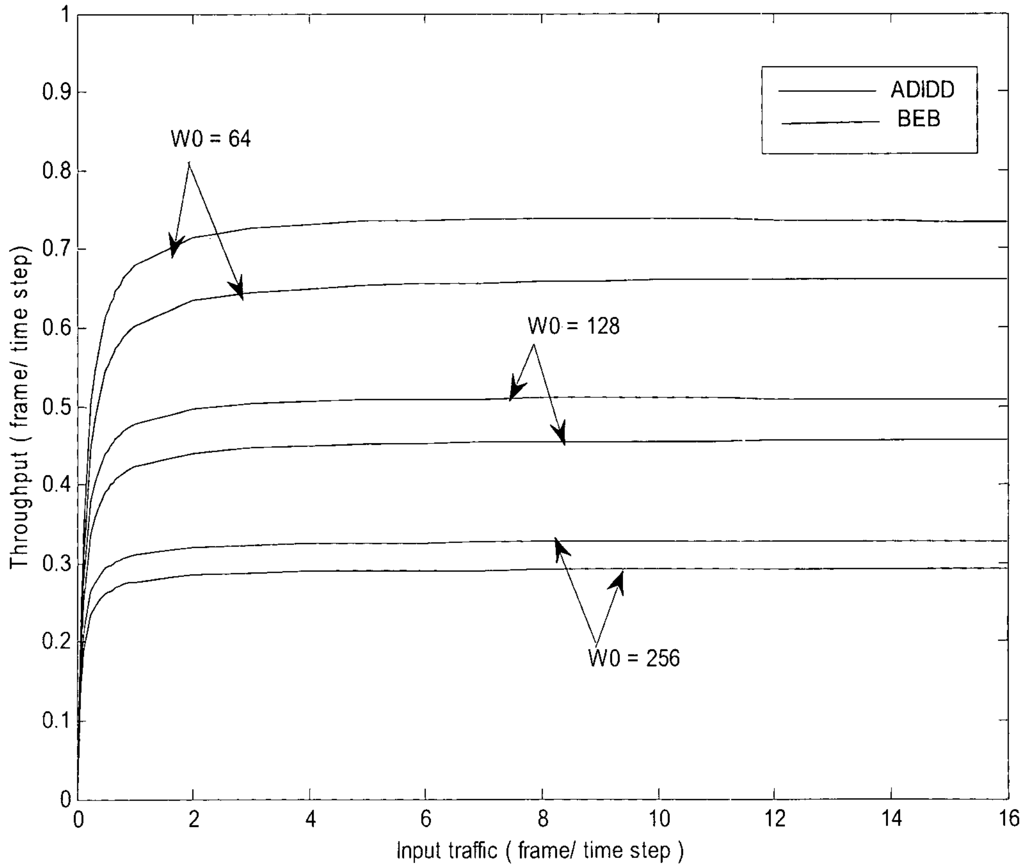


Fig 4.2.1(e): Throughput versus input traffic for N = 16

Fig. 4.2.1(b) shows that the throughput versus input traffic for the cases when m = 3, n = 4, N = 6, and the initial back-off window (W_0) taking values as 32, 64, 128, 256. It is observed from the figure that the BEB algorithm gives better throughput than the ADIDD back-off algorithm for the most of the input values. But, the performance of ADIDD back-off algorithm also improves.

Fig. 4.2.1(c) shows the throughput versus input traffic for the cases when m = 3, n = 4, N = 8, and the initial back-off window (W_0) taking values as 32, 64, 128, 256. It is observed from the figure that the ADIDD back-off algorithm gives better throughput than the BEB algorithm for most of the input values. However, the differences in throughput for these two back-off algorithms are negligible for higher values of W_0.

Fig. 4.2.1(d) shows the throughput versus input traffic for the cases when m = 3, n = 4, N = 12, and the initial back-off window (W_0) taking values as 64, 128, 256. It is observed from the figure that the ADIDD back-off algorithm gives better throughput than the BEB algorithm for most of the input values.

Fig. 4.2.1(e) shows the throughput versus input traffic for the case when m = 3, n = 4, N = 16, and the initial back-off window (W_0) taking values as 64, 128, 256. It is observed from the figure that the ADIDD back-off algorithm gives better throughput than the BEB algorithm for most of the input values, with remarkable performance.

Therefore, from the above figures, we conclude that when $N \geq 8$, the ADIDD back-off algorithm gives better throughput than the BEB algorithm for most of the values of input range.

4.1.2 Effect of Initial Back-off Window on User Access Probability

To show the effect of initial back-off window on user access probability, for two back-off algorithms, we varied W_0 and N.

Fig. 4.2.2(a) shows the user access probability versus input traffic for the cases when m = 3, n = 4, N = 4, and the initial back-off window (W_0) taking values as 16, 32, 64, 128. It is observed from the figure that the BEB algorithm gives better user access probability than the ADIDD back-off algorithm for most of the input values.

Fig. 4.2.2(b) shows the user access probability versus input traffic for the cases when m = 3, n = 4, N = 6, and the initial back-off window (W_0) taking values as 32, 64, 128, 256. It is observed from the figure that the BEB algorithm gives better user access probability than the ADIDD back-off algorithm for most of the input values. However, the performance of the ADIDD back-off algorithm improves.

Fig. 4.2.2(c) shows the user access probability versus input traffic for the cases when m = 3, n = 4, N = 8, and the initial back-off window (W_0) taking values as 32, 64, 128, 256. It is observed from the figure that the user access probabilities for these back-off algorithms are almost equal for most of the input values, for higher values of W_0.

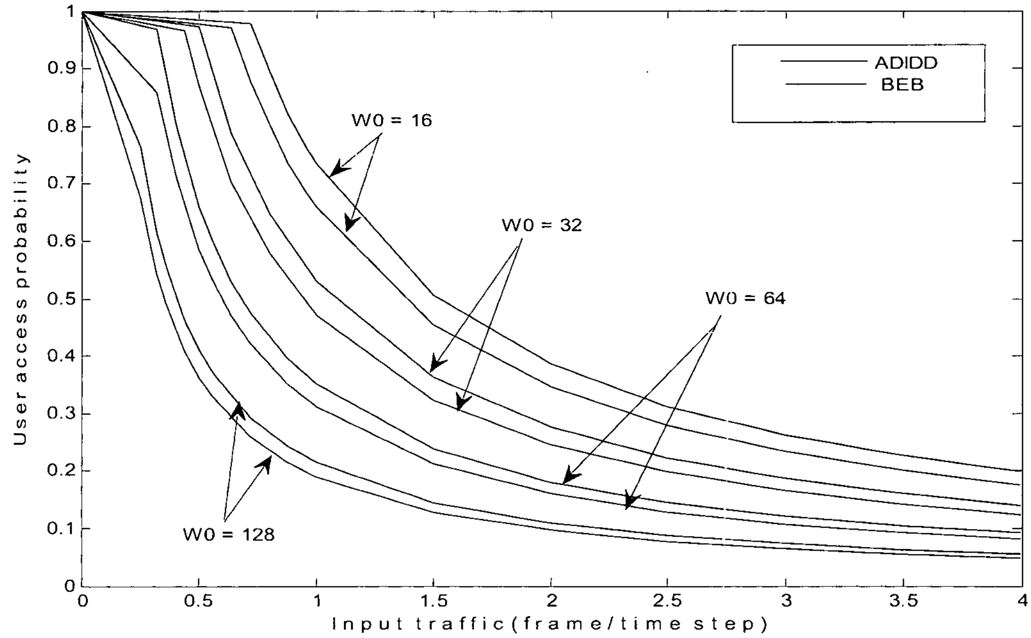


Fig. 4.2.2(a): User access probability versus input traffic for N = 4

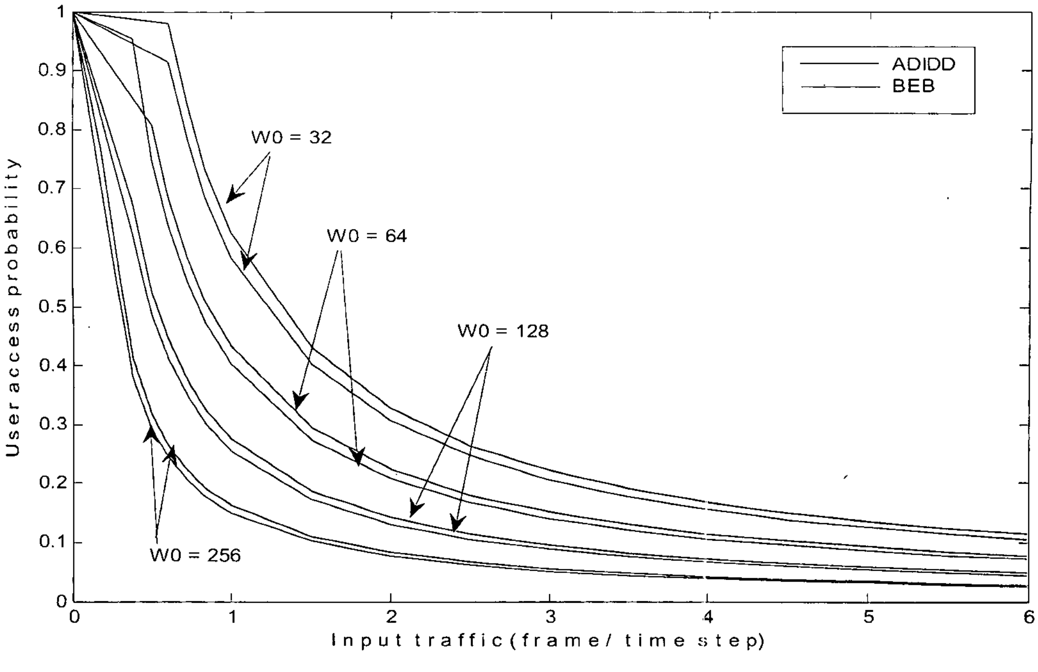


Fig. 4.2.2(b): User access probability versus input traffic for N = 6

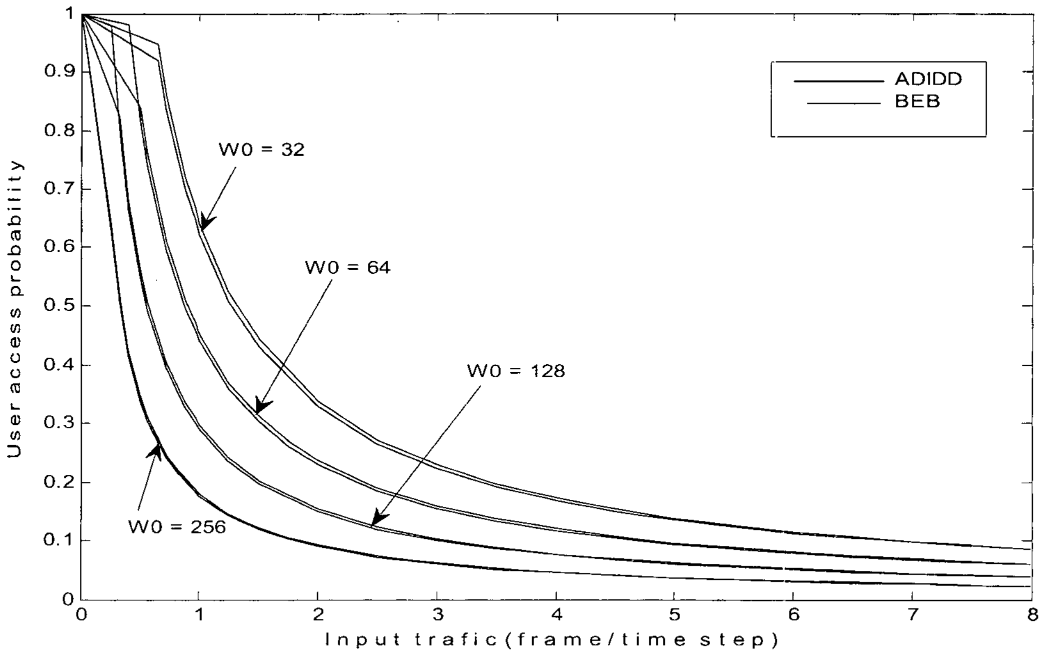


Fig. 4.2.2(c): User access probability versus input traffic for N = 8

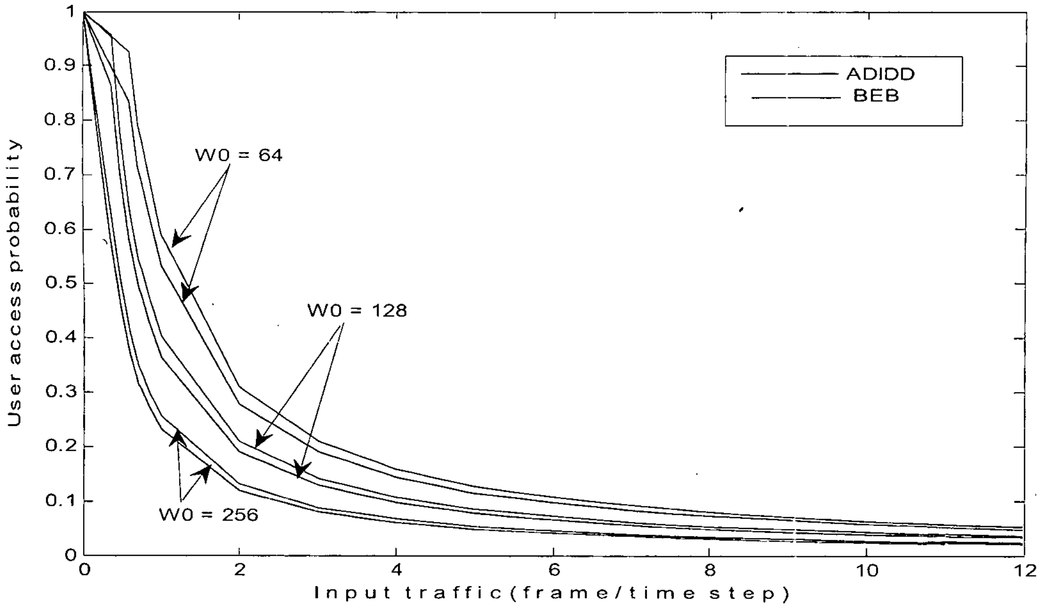


Fig. 4.2.2(d): User access probability versus input traffic for N = 12

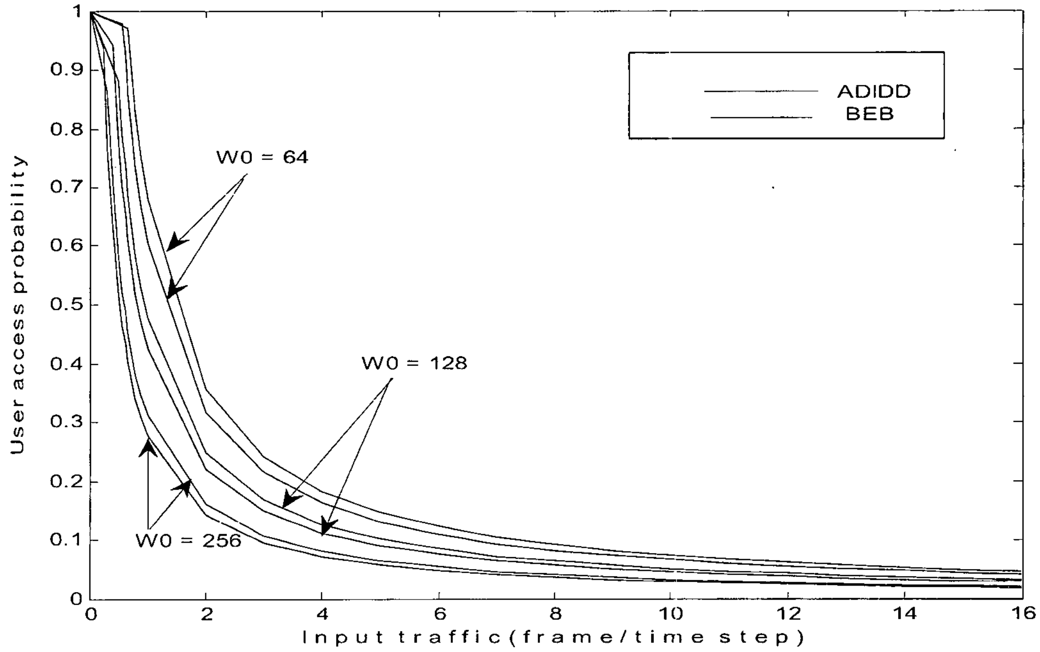


Fig. 4.2.2(e): User access probability versus input traffic for N = 16

Fig. 4.2.2(d) shows the user access probability versus input traffic for the cases when m = 3, n = 4, N = 12, and the initial back-off window (W_0) taking values as 64, 128, 256. It is observed from the figure that the ADIDD back-off algorithm gives better user access probability than the BEB algorithm for most of the input values.

Fig. 4.2.2(e) shows the user access probability versus input traffic for the cases when m = 3, n = 4, N = 16, and the initial back-off window (W_0) taking values as 64, 128, 256. It is observed from the figure that the ADIDD back-off algorithm gives better user access probability than the BEB algorithm for most of the input values.

Therefore, from the above figures, we conclude that when N ≥ 8, the ADIDD back-off algorithm gives better user access probability than the BEB algorithm for most of the input values.

4.1.3 Effect of Initial Back-off Window on Average Delay

To show the effect of initial back-off window on average delay, for two back-off algorithms, we varied W_0 and N. Average delays are represented on Log. Scale.

Fig. 4.2.3(a) shows the average delay versus input traffic for the cases when m = 3, n = 4, N = 4, and the initial back-off window (W_0) taking values as 16, 32, 64, 128. It is observed from the figure that the BEB algorithm gives lower average delay than the ADIDD back-off algorithm for most of the input values.

Fig. 4.2.3(b) shows the average delay versus input traffic for the cases when m = 3, n = 4, N = 6, and the initial back-off window (W_0) taking values as 32, 64, 128, 256. It is observed from the figure that the BEB algorithm gives lower average delay than the ADIDD back-off algorithm for most of the input values. However, the performance of the ADIDD back-off algorithm improves.

Fig. 4.2.3(c) shows the average delay versus input traffic for the cases when m = 3, n = 4, N = 8, and the initial back-off window (W_0) taking values as 32, 64, 128, 256. It is observed from the figure that average delays for these back-off algorithms are almost equal for most of the input values for higher values of W_0.

Fig. 4.2.3(d) shows the average delay versus input traffic for the cases when m = 3, n = 4, N = 12, and the initial back-off window (W_0) taking values as 64, 128, 256. It is observed from the figure that the ADIDD back-off algorithm gives lower average delay than the BEB algorithm for most of the input values.

Fig. 4.2.3(e) shows the average delay versus input traffic for the cases when m = 3, n = 4, N = 16, and the initial back-off window (W_0) taking values as 64, 128, 256. It is observed from the figure that the ADIDD back-off algorithm gives lower average delay than the BEB algorithm for most of the input values.

Therefore, from the figures, we conclude that when $N \geq 8$, the ADIDD back-off algorithm gives better performance, in terms of average delay, than the BEB algorithm for most of the input values.

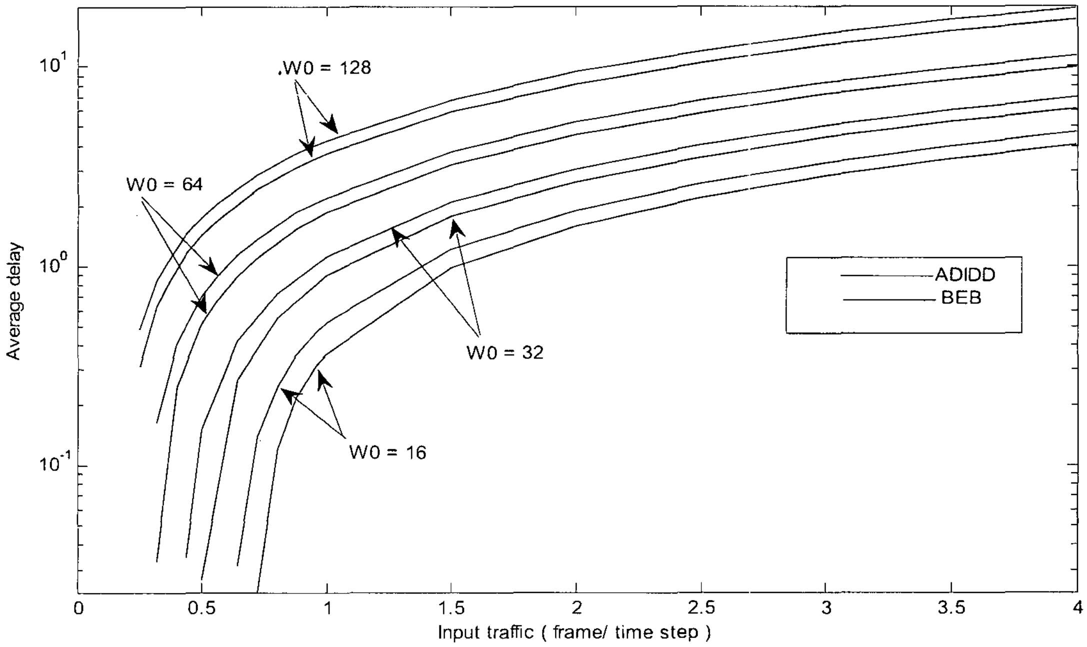


Fig. 4.3.3(a): Average delay versus input traffic for N = 4

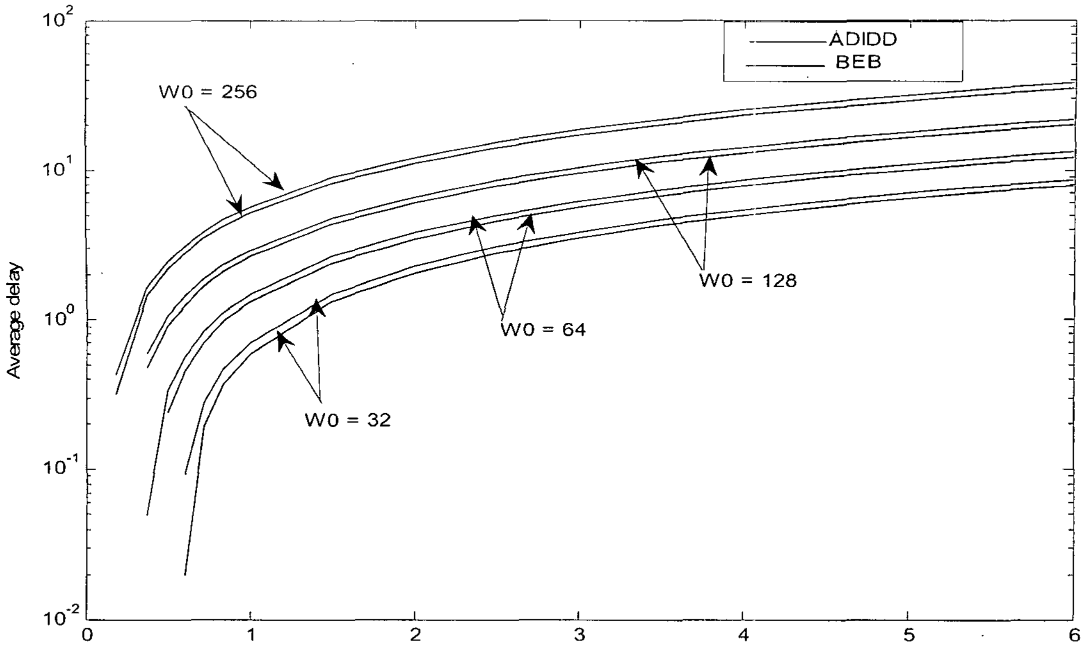


Fig. 4.2.3(b): Average delay versus input traffic for N = 6

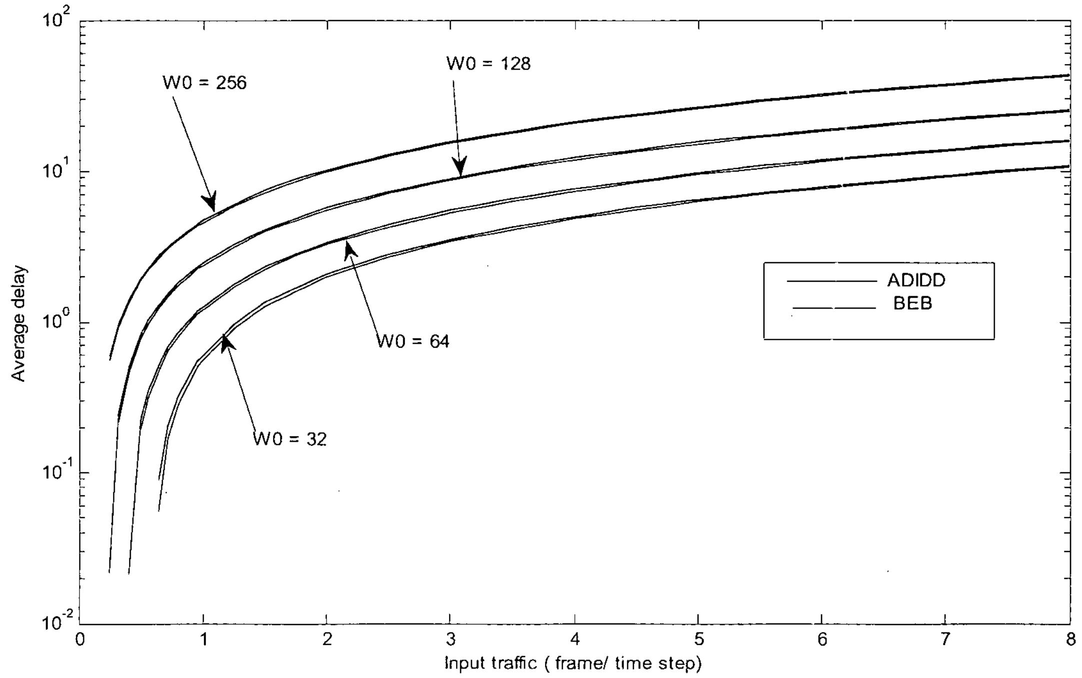


Fig. 4.2.3(c): Average delay versus input traffic for N = 8

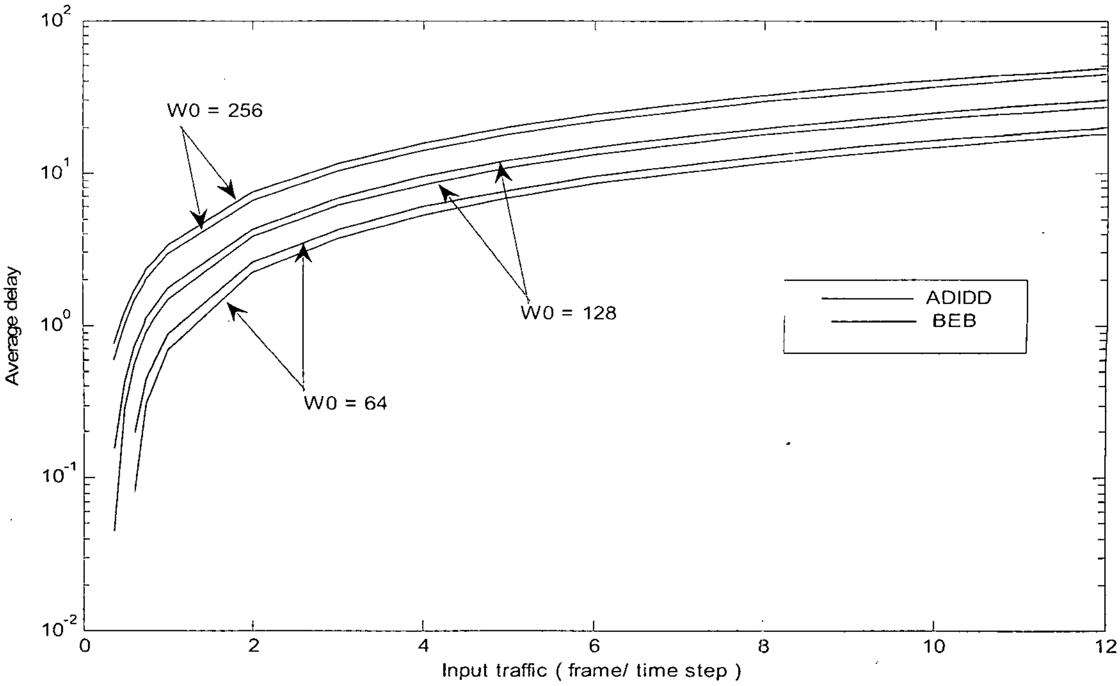


Fig. 4.2.3(d): Average delay versus input traffic for N = 12

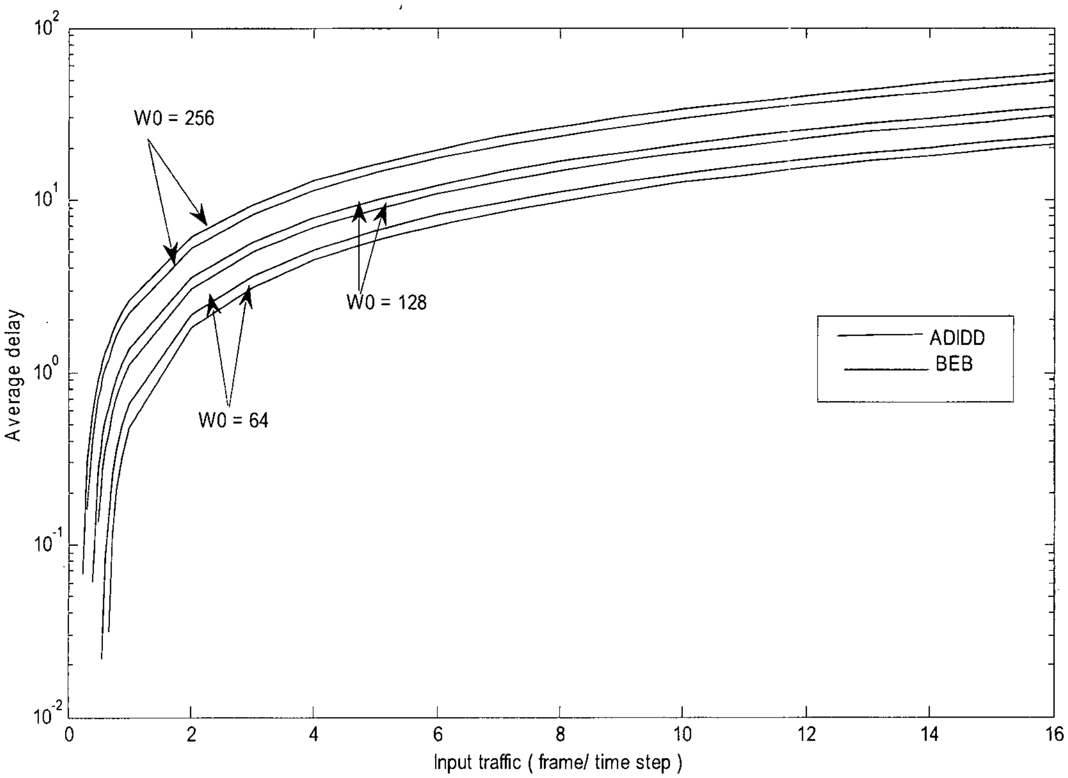


Fig. 4.2.3(e): Average delay versus input traffic for N = 16

Chapter5

Conclusion and Future Work

5.1 Conclusions

In the dissertation, we have presented a simple analytical model for the performance analysis of IEEE 802.11 DCF protocol under non-saturated conditions, using a Markov chain model. This model can be used to analyze the performance of DCF due to adaptive back-off algorithm (ADIDD back-off algorithm), finite retransmission attempts, and freezing of back-off counter. Using the developed model, we compared the efficiency of our model with the model given by K. M. J. Khayyat *et al* [13].

The results of experiment show that the proposed model has better performance in terms of throughput, user access probability, and average delay for most of the input values when the number of competing stations is greater or equal to 8. This is because in the BEB algorithm after a successful transmission, CW is reduced to CW_{min}. Therefore, the probability that more than one station uses the same slot is high in the situation when the number of competing stations is large. To reduce collisions in congested network, our modified ADIDD back-off algorithm will not change CW of a successful station to CW_{min} directly but it divides CW of the successful station by 2. That is why our modified ADIDD back-off algorithm reduces collisions, and thus improving the throughput, user access probability, and average delay when the number of competing stations is greater or equal to 8. However, for the small number of stations the performance of the ADIDD back-off algorithm is lower than the BEB algorithm [13] in terms of throughput, user access probability, and average delay. This reverse performance in the ADIDD back-off algorithm can be explained as follows. When the number of competing stations is small (≤ 8), the probability that at least one stations uses a slot time is very low, i.e., maximum times these slots are remain idle. Therefore, decreasing the CW of a successful station to CW_{min} directly will reduce the number of idle slots and thus improving system performance in terms of throughput, user access probability, and average delay.

5.2 Future Work

In the future, we will extend our dissertation work for the performance analysis of IEEE 802.11 DCF by considering the other parameters which were not considered in this model. The possible extensions are given below:

- Design RTS/CTS based model
- Design model by considering BERs
- Design model for other suitable adaptive back-off algorithm

We can also extend the Bianchi's model [9] by considering the parameters:

- Adaptive back-off algorithm
- Finite number of retransmissions
- Non-saturated conditions

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