Quality of Service Support with Error Control Protocol in Wireless Local Area Networks

by

Abdelsalam Bubaker Amer

BSc, The Higher Institute of Electronics,
Bani-Walid, Libya 1988
M.Eng., University of Victoria,
Victoria, BC, Canada 1999

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Supervisory Committee

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

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

Abstract

This dissertation discusses some techniques to improve the medium access control in infrastructure multi channel wireless local area networks. Medium Access Control protocols (MAC) coordinate the stations and resolve the channel contentions so that scarce radio resources are shared fairly and efficiently amongst participating users. We propose different models to improve the medium access control performance. The models deal with improving the channel access and allocation. By proposing some backoff strategies for the collided users to retransmit, the performance is improved. A comparison amongst the proposed models is shown.

We also investigate the quality of service provisioning in infrastructure-based wireless local area networks medium access control. We propose a multiple class traffic model to support quality of service. This model is a cross-layer model as we consider the error in the transmitted state. We also propose models for uplink channel utilizations for data channel transmissions that can be applied to different WLANs. Finally, we propose an integrated model that deals with error in both the request and data transmissions. That model applies in the single class and quality of service support models we develop.

In this dissertation, we propose four techniques to improve the medium access control frame utilization by developing four backoff strategies to reduce the collision on the request channels. We propose a cross-layer model for the error control protocol. We propose another model for uplink channel utilization for data transmission in one class of traffic. We also propose a quality of service support model so high priority users get better performance compared to low priority class traffic. Furthermore, we propose cross-layer design for data transmission to guarantee safe data delivery to the receiver for the QoS model. Finally, we propose a model for uplink channel utilization in the QoS model. This model can be applied to different WLANs standards. This model also includes the channel error in both the request and data channels.

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List of Abbreviations

ACH	Access feedback CHannel
ACK	Acknowledgment
AIFS	Arbitrary InterFrame Space
AP	Access Point
ARQ	Automatic Repeat and reQuest
ASCII	American Standard Code for Information Interchange
AWGN	Additive White Gaussian Noise
BCH	Broadcast CHannel
BE	Best Effort
BEB	Binary Exponential Backoff
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BWA	Broadband Wireless Access
DCD	Downlink Channel Descriptor
CDMA	Code Division Multiple Access
CID	Connection IDentifier
CFP	Contention Free Period
CP	Contention Period
CS	Convergence Sublayer
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
DCF	Distributed Coordination Function
DiL	Direct Link phase
DL	Down Link

DLC	Data Link Control
EDCA	Enhanced Distribution Channel Access
ETSI	European Telecommunications Standard Institute
FCH	Frame CHannel
FEC	Forward Error Correction
HCF	Hybrid Coordination Function
HIPERLAN	HIgh PERformance Local Area Network
IE	Information Element
IP	Internet Protocol
MAC	Medium Access Control
MAC CPS	MAC Common Part Sublayer
WLAN	Wireless Local Area Network
MT	Mobile Terminal
nrPS	Non real time Polling Service
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDU	Protocol Data Unit
PHY layer	PHYsical layer
PPP	Point-to-Point Protocol
QAM	Quadrature Amplitude modulation
QoS	Quality of Service
QPSK	Quaternary Phase Shift keying
RCH	Random CHannel
RLC	Radio Link Control
RTS\CTS	Request To Send \Clear To Send
RTG	Receiver Transmitter turnaround Gap

rPS	Real time Polling Service
SDMA	Space Division Multiple Access
SDU	Service Data Unit
SINR	Signal Interference Noise Ratio
SNR	Signal to Noise Ratio
SS	Subscriber Station
SSCS	Service-Specific Convergence Sublayer
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TTG	Transmitter receiver Turnaround Gap
TXOP	Transmission Opportunity
UCD	Uplink Channel Descriptor
UL	Up Link
USG	Unsolicited Grant Service
WiMAX	Wireless Microwave
WPAN	Wireless Personal Area Network

List of Symbols

D	Access Delay
D_1	Access delay for high priority class
D_2	Access delay for low priority class
D_{data}	Average delay for data channels
$D(i)_{data}$	Average delay for class i data channels
E_a	Average nergy
E_{a1}	Average energy for high priority class
E_{a2}	Average energy for low priority class
E_{data}	Average energy for data channels
$E(i)_{data}$	Average energy for class i data channels
L	Data transmission channels
L_1	Data transmission channels for class one
L_2	Data transmission channels for class two
N	Total Number of users
N_{ave}	Average Number of users
NP	Number of packets
N_t	Average Number of Retransmissions
N_{1a}	Average Number of users from high priority class
N_{2a}	Average Number of users from low priority class
N_{t1}	Average number of retransmissions for high priority class
N_{t2}	Average number of retransmissions for low priority class
P	Transition matrix
P_a	Acceptance Probability
$P_{a(net)}$	Net acceptance probability for single class
Pa_{data}	Acceptance probability for data channels

p_{1a}	Acceptance probability for high priority class
p_{2a}	Acceptance probability for low priority class
$P_{a(net)i}$	Net acceptance probability for class i
$Pa(i)_{data}$	Acceptance probability for class i data channels
Th	Throughput
Th_1	Throughput for high priority class
Th_2	Throughput for low priority class
Th_{data}	Data channels throughput for single class
$Th(i)_{data}$	Data channels throughput for class i
a	Arrival probability
b	Number of bits in single class model
$b1$	Number of bits in the request packet
$b2$	Number of bits in the data packets
c	Retransmission probability
$c1$	Retransmission probability for high priority class
$c2$	Retransmission probability for low priority class
e	Average Error
$e1$	Average error in request channels
$e2$	Average error in data channels
k	RCH channels
k_{max}	Maximum allocated channels
k_1	High priority class allocated channels
k_2	Low priority class allocated channels
l	Packet priority probability
m	Weight factor to split the random access channels
n	Number of bits

$n1$	Number of bits in request packets
$n2$	Number of bits in data packets
s	State vector
s_i	Idle state
s_t	Transmission state
s_c	Collided state
x	Probability that a user selects a free channel
x_1	Probability that a user from high priority class selects a free channel
x_2	Probability that a user from low priority class selects a free channel
y	Probability that a user selects a busy channel
y_1	Probability that a user from high priority class selects a busy channel
y_2	Probability that a user from low priority class selects a busy channel
η	Efficiency
ϵ	Bit Error Rate
η_1	Efficiency for high priority class
η_2	Efficiency for low priority class
η_U	Uplink channel utilization for single class
η_{Ui}	Uplink channel utilization for class i
τ	Average requests access delay
τ_{data}	Average delay for data channels

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Abdelsalam Bubaker Amer, Victoria, BC, Canada

Dedication

To my parents, brothers and sisters

To my family, wife and kids.

Chapter 1

Introduction

Wireless Local Area Networks (WLANs) attracted big attention in research in the past decades. WLANs such as WiMAX [2], [3], [4], IEEE802.11x [5] and Hiperlan\2 [6], [7] have similarities in the Physical layer as they all employe OFDM as their modulation scheme. The limited resources in WLANs lead to several problems that effect the system performance. These problems affect the performance of the system such as throughput, acceptance probability, energy and delay. Quality of Service (QoS) is another issue the WLANs is lacking in away or another. Differentiating the users and/or the applications into classes so that certain users and/or application get better priorities over the others. The uplink channel utilization in WLANs is another issue to be tackled. Single channel WLANs standard such as IEEE802.11a has its uplink channel mostly utilized, however, multiple channel have less uplink channel utilization. The wireless channel might be in error and that affects the access or the data transmission. In this work we studied the channel error over the MAC layer in both the request channel and data transmission channel.

1.1 Wireless Medium Access Control Protocol

The medium access control (MAC) protocol coordinates the nodes in a network and resolves the contention among their accessing the shared medium so that the resources are shared fairly and efficiently [8]. Wireless access can be classified into three categories [9]: random access, guaranteed access and hybrid access protocols. Random access protocols are distributed contention-based protocols that are quite suitable for networks with stations carrying durst traffic. Protocols like Aloha [10] , slotted Aloha [11] and CSMA [12] are examples of these protocols. To avoid collisions, random backoff algorithms are used (e.g. Binary exponential backoff) have been added to these protocols. A widely used protocol is CSMA/CA. This protocol is the basis of WLANs and Wireless Personal Area Networks (WPANs). This protocol does not require a central controller and is simple to implement. The main disadvantage is the channel idle periods and frame collisions are wasting the channel bandwidth. Guaranteed access protocols are contention-free protocols with which stations access the channel via polling or scheduling. Thus, certain QoS provisioning is provided. The overhead when the polled stations have no need to use the medium wastes the channel bandwidth. The Hybrid access protocol normally combines the advantages of the random access and guaranteed access protocols to achieve flexibility, efficiency and QoS [9]. In the hybrid protocol each station sends a request, using random access protocol to the central controller (e.g. the base station or the access point) indicating the time and bandwidth required for future transmission. Once the request received the admission control scheme decides whether to grant it or not. In the original scheme, the controller allocates time slots and notifies the requesting stations of the start time and the assigned duration. Hybrid MAC protocols are normally deployed in infrastructure-based networks to support a variety of delay-sensitive traffic with satisfactory QoS provisioning.

This dissertation focuses on how to utilize the MAC frame to get better performance in the infrastructure-based WLAN, investigates the backoff strategy that users could adapt to retransmit, and studies quality of service assurance and a cross-layer design protocol that packet error is minimized. We also studied the uplink channel utilization for data transmission for the single class and the quality of service support models. Furthermore, we studied the request mechanism and data transmission channels for the single class and quality of service support models. We study several factors that give better MAC performance. We also study the QoS provisioning. The developed models have the merit that can be applied to different wireless standards.

1.2 Problem Statement

This dissertation focuses on developing some algorithms to get better utilization of the medium access control frame and to provide quality of service to certain traffic classes.

Contention could happen at anytime when many users are requesting access to the MAC frame. Collisions result when two or more users are requesting access on the same random access channel. Users adopt a backoff algorithm to request access in another time. One of the well-known backoff algorithms is the binary exponential backoff algorithm. However, the exponential growth of the backoff window will lead to significant delay. Therefore, other alternatives have to be proposed in order to resolve the contention on the random access phase and as a result we can get better utilization of the MAC frame.

Quality of service support to certain class of users and/or application is another issue. Different quality of service support models have been proposed but a general model that can be applied in different wireless standard is not been developed. Therefore, a general model that can be used in various WLANs is a challenge.

Channel error is another challenge in wireless local area networks. If the channel is noisy due to interference or suffer fading due to path loss and shadowing, data packet may be received in error. These packets have to be retransmitted. The retransmission process increases the delay. Different models have been proposed but many of them have pros and cons. Most of these models reduce one problem but leave another problem unsolved.

Uplink channel utilization for data transmission is another challenge in WLANs. In a cross-layer dialogue between the two lower layers certain assumptions have to be made in order this dialogue to be established. These assumptions are bit error rate, channel type, coding scheme etc.

1.3 Contributions

This section presents our contributions.

First, we proposed a Markov chain model for backoff strategy investigation. In this contribution, we proposed four backoff strategy models for the random access channel. We varied the number of requesting channels (channels that users send their request for access the MAC) and compared the proposed models. We enhanced this model by introducing the channel error in the transmission state. This is a cross-layer model since it takes into consideration the channel error. This work has been published in [13] and [14].

Second, we developed a model for the uplink channel utilization for data transmission. We applied our backoff models and our cross-layer model on this proposed model. The uplink channel utilization is evaluated and also the net acceptance probability for several WLANs. This work has been published in [15].

We enhanced this model by studying the impact of data transmission channels in the uplink. This work has been published in [16]. Furthermore, this model is extended to consider the error in the request channels. Users may not get access due to collision and channel error. This work has been submitted to [17]

Third, we proposed a quality of service support model in the medium access control frame. In this model we split traffic into two classes. We allocate number of random access channels for each class. The traffic is classified as high priority traffic and low priority traffic. We demonstrated that the quality of service is guarantee to the high priority class. The performance metrics show that high priority traffic get better acceptance probability. This model is extended as a cross-layer model. In this model we applied our proposed backoff strategy. Also, we applied our error control model for safe data delivery to the receiver. The collided users can retransmit adapting one of our developed backoff strategy models. Once, the resources are granted to the users, users can transmit their data on the allocated bandwidth. The users retransmit the corrupted data several times until positive acknowledgment has received or stop retransmitting and the channel declared noisy. This work has been published in [18] and [19].

Fourth, we developed a cross-layer model for the uplink channel utilization in the quality of service support model. We applied backoff strategy model and the error control model on this model. The impact of different parameters are studied. This work has been published in [15]. We also developed a model for request mechanism and data transmission channels. This work has been submitted to [20]. We enhanced this model to take into account the error in the request channels. Users may not granted access due to either collision or error in the request channels. We considered this issue and we developed a model to consider the error in the request channels. This work has been submitted to [21]

1.4 Dissertation Organization

This dissertation is organized as follows;

Chapter 2 gives some literature review for MAC protocols in wireless LANS, backoff algorithms, error control, QoS and channel utilizations.

Chapter 3 proposes a single class model for a user. In this model a number of random access channels are allocated in the random access phase. Different backoff strategy models are developed for the collided users retransmissions. Collided users adopt one of the proposed backoff strategy in order to get access. A cross-layer model is developed in this chapter as well. We showed the performance of our proposed models. We showed in our models which backoff strategy perform better in the low and heavy loads.

Chapter 4 proposes a single class model for uplink channel utilization, request mechanisms and data transmission channels. In this chapter we developed a model for uplink channel utilization. We applied that to different wireless standards such us IEEE802.11x, IEEE802.16 and Hiperlan 2. In this chapter we also include our developed model for request mechanism and data transmission. We also in included the channel error in the request and data channels.

Chapter 5 proposes a quality of service support (QoS) model. Through the modeling using discrete-time Markov chain analysis, we show that a quality of service can be provided to certain class of traffic. Even if the packet priority probability is higher in low priority users still the acceptance probability for high priority traffic is higher. We also show that the backoff strategy can be applied to this model. Moreover, cross-layer model is proposed in this chapter as well.

Chapter 6 proposes a quality of service support model for uplink channel utilization. In this chapter the quality of service support model has been extended where we can study the data transmission and evaluate the uplink channel utilization for WLANs with single channel such IEEE802.11a and with multiple channel access such as IEEE802.16 or Hiperlan 2. In this chapter we also present our developed model for request mechanism and data transmission with the quality of service support.

Chapter 7 summarizes this dissertation, states our contributions, and suggests directions for future research.

Chapter 2

Random Access Wireless Local Area Networks and Quality of Service: Review

This chapter reviews work related to this dissertation, including random access schemes applied in wireless local area networks, backoff strategy, and error control protocol. It also reviews the related work regarding the quality of service algorithms that had been applied in wireless networks and channel utilization.

This chapter is organized as follows. IEEE802.16 (WiMAX) standard will be reviewed, Section 2.1 reviews the random access in the wireless LANs. Section 2.2 reviews the resource allocations in WLANs. Backoff algorithms are reviewed in Section 2.3. Error control is reviewed in Section 2.4. Section 2.5 reviews some quality of service models that been applied to the wireless local area networks. It also discusses some methods error control protocols. Channel utilization is reviewed in Section 2.6. Proposed solution are presented in 2.7. Section 2.8 Summarizes the chapter.

2.1 Random Access in Wireless Local Area Networks

In the high performance radio access networks, a number of random access channels can be used for mobile stations to transmit their bandwidth requests in contention mode via random access channels. Several schemes have been proposed to get better utilization in the medium access control frame and to reduce the contention on the random access channels. The contention on the random access channels can be reduced by some backoff stages such as the binary exponential backoff algorithm. However, the delay in the retransmission may be longer. Some wireless standards do not specify a specific algorithm to be used. Hence, different algorithms can be used to resolve the contention. In [22], [23] Gyung-Ho et al. proposed a model for random channel allocation. In this model, he proposed an adaptive random channel allocation. The AP schedular in centralized wireless LAN(e.g. Hiperlan 2) controls the number of random access channels in one MAC frame according to the transmission results of the previous MAC frame. The AP increases the random channels of the next MAC frame by as many as collided random access channels and decreases them by successful access attempts with a weight factor. When there is no access attempt in the previous MAC frame, the AP reduces the number of random access channels by one. In [24] and [25] Choi et al. proposed an algorithm that provides an adaptive random access and resource allocation. This algorithm provides both access control and efficient resource allocation. Moreover, this algorithm provides priority services to the MTs. The AP controls the number of random access channels allocated to the current frame by using both access probability and estimated number of MTs accessed at previous MAC frame. Then, the AP broadcasts the access probability for the access control of MTs, and each MT does access attempt based on this access probability. Hyun-Ho et al. in [26], proposed and algorithm that provide effective access control and resource allocation based on service priority. The priority service can be controlled by the

AP or the MTs. If the priority provided by the AP then it is Centralized Priority-controlled Access (CPA). If the priority is controlled by the MTs, then it is Distributed Priority-controlled Access (DPA). You-Chang Ko in [27], proposed an algorithm for collision reduction using m-ary split algorithm. In this algorithm the random access channels are split into two groups. First group is for the new arriving request. The second group is for the collided random channels. For each collided random channel the algorithm allocates two random channel in the next MAC frame. You-Chang in [28] studied the throughput in the MAC protocol taking into account the guard timing space which give more accurate throughput. In [29], Liu et.al proposed a multiple access control protocol. In this protocol, the packet transmission can be scheduled according to the exact number of active mobile terminals determined by the self-organizing algorithm, and adjust the number of packets sending by one node in one frame properly. Xaio in [30] reviewed the enhanced distributed admission control algorithm for enhanced distributed channel access in IEEE802.11e. This algorithm is evaluated for video streams in terms of throughput, delay and transmission limit coverage. Benelli in [31], investigated the multiple access with fixed and variable frames in slotted aloha.

2.2 Resource Allocation in Wireless Local Area Networks

The scarce resources in the wireless local area networks may lead to contention. Certain algorithms are needed in order to resolve contention for these resources. Several algorithms have been proposed for better resource allocations. In [32], Magin et al. proposed a dynamic resource allocation scheme for WLANs. In this scheme, the allocation takes advantage from coexistence of connections that have different QoS tolerances. When errors happen due to channel noise or fading, the bandwidth allocated to connection with low QoS requirements could be reduced and assigned to the connection with more stringent QoS requirements to perform retransmissions. In [33] Jones, proposed an allocation scheme based on the lowest interference the channel encounters. Lenzini in [34] and [35], proposed a model to manage the bandwidth for different types of traffic. Delicado in [36] proposed a class-based allocation mechanism for delay sensitive traffic in WLANs. He proposed a bandwidth allocation protocol which distinguished five types of connections with different QoS requirement. In [37], Sonia et al. proposed a model to specify high rules which aim to control pre-reservation and reservation of resources in a coherent and concerted way. In [38], Michael et al. proposed a downlink resource allocation scheme in the MAC level for OFDMA system based on IEEE 802.16. In [39], Koja proposed a distributed resource allocation algorithm where users control the service rates to their neighbors. Resource allocation (bandwidth) had also been tackled in [40], [41], [42] for WLANs. The bandwidth has been divided into different categories based on the type of traffic and accordingly the admission control. To get better MAC utilization a space division multiple access has been proposed in [43]. The performing algorithms provide better capacity. In [44], random access control mechanism using traffic load in aloha and CSMA for EDGE has been proposed. The idea is to limit the number of transmissions and retransmissions at high traffic loads in order to minimize the collisions while keeping the system stability. Cross-layer modeling of capacity in wireless networks has been proposed in [45]. In this work, cross-layer modeling has been proposed in the presence of two types of flows.

2.3 Backoff in Wireless Local Area Networks

In random access system where users compete to gain access to the MAC frame collisions may take place when two or more terminals try to access the same slot/channel. A widely used collision resolution protocol is the binary exponential backoff (BEB). This algorithm is used in ethernet and WLANs. In [46], [47] the exponential backoff algorithms was discussed for its performance and analyzed for slotted aloha protocol. The collision resolution is also discussed in [48] in the context of Space Division Multiple Access (SDMA) and using the m-ary splitting algorithm where the AP allocates two random access channels for each collided request [27]. In IEEE802.11 the EDCF coordinates the access to the channel. In [49], the throughput and delay have been evaluated. The approach relied on the elementary conditional probability rather than on the bidirectional Markov chain as in the former proposals. In [50] a model for IEEE802.11 DCF with RTS/CTS was developed. Also with the RTS\CTS the performance of the MAC frame has been improved. In [51] the issue of coexistence between the IEEE802.11e and IEEE802.11a is addressed.

2.4 Error Control

One of the major challenges in wireless networks is to provide fast and reliable communications. Transmitted data may be corrupted due to interference, noise etc. To increase the apparent quality of communication channel there are two approaches, either Forward Error Correction (FEC) or Automatic Repeat Request (ARQ). FEC employs error correcting codes to combat bit errors by adding redundancy to information packets before they are transmitted. This redundancy is used by the receiver to detect and correct errors. ARQ only has error detection capability and has no attempt to correct any packets received in error. Instead, the packets received in error have to be retransmitted. FEC techniques are associated with unnecessary overhead that reduces the throughput when the channel is error free. ARQ leads to variable delays which are not acceptable for real time services. Different techniques that combine the two schemes called Hybrid ARQ have been developed in [52], [53], [54] and [55]. Enhanced Hybrid ARQ has been proposed in [56] and applied for WiMAX. This scheme follows the multi-channel stop-and wait. This scheme proactively reacts to poor channel conditions. It sends multiple copies of the same data burst over the subsequent channels available to a subscriber station (SS) based on the feedback on the channel conditions. As a result, under noisy condition it reduced the time to successfully transmit data burst. A fast retransmission ARQ scheme for real-time traffic has been proposed by Afonso in [57]. This scheme is intended to reduce the delay introduced by the retransmissions. An overview of error control schemes for networks has been presented in [58]. The authors reviewed FEC for Block coding, Code shortening, code puncturing, code selection and interleaving. In ARQ, stop-and-wait, selective repeat and Go-back-N are discussed. Finally he discussed the hybrid error control. In [59] Lodewijik proposed a scheme for BER estimation in wireless channel based on the statistical analysis of the soft output of the receiver only.

2.5 Quality of Service Models in Wireless Local Area Networks

Quality of Service provisioning challenges are shown in Fig. 2.1 [1].

the challenges are handling time-varying network conditions, adapting to varying application profile and managing link layer resources. As shown in Fig. 2.1, a summary of these challenges are stated. Handling time-varying network conditions is one of the current challenge in WLANs. The two different factors related to network condition impact the experienced QoS are: channel conditions and network load. Varying channel conditions occur in WLANs because of propagation loss, multipath effects, and interference. Channel conditions can lead to retransmissions and dropped packets, and thereby increase latency while degrading throughput. The second factor is the network load (i.e. number of contending nodes in the network). Since WLANs

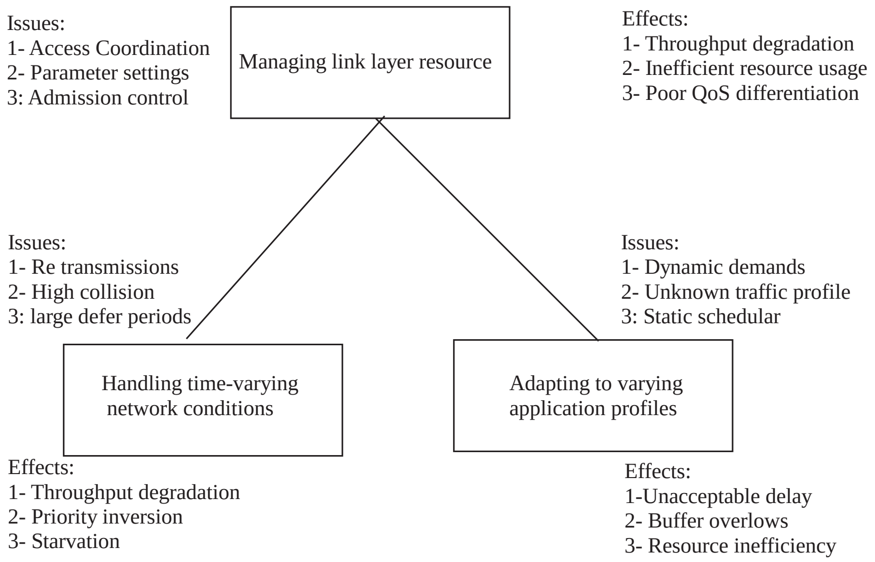


Figure 2.1: Challenges in providing QoS in Wireless Local Area Networks [1]

use shared channel access mechanism, the load of the network directly affects each node's performance. In order to meet the QoS requirements for various application, it is necessary to deploy QoS provisioning mechanism. In [60], [61] and [62] a QoS-aware resource request mechanism has been proposed. Also, a framework is proposed for different types of traffic to provide QoS. In [63] and [64] the throughput has been increased while the channel has some interference. In [65] and [66] a differentiated service priority mechanism to support QoS in WLANs have been proposed.

A survey on Internet QoS was done in [67] and [68]. The authors provided an overview of the various QoS mechanisms described the major QoS protocols and classifies them into broader signaling categories. A comparison based on their individual characteristics was shown. In [69] a centralized MAC protocol with QoS support was proposed. In this protocol, in the presence of the AP, the network operation within a superframe is divided in two phases namely, Contention Period (CP) and Contention free period (CFP). In the CP, all the station follow the DCF and in the CFP the AP has the control over the network. Distributed mechanism for QoS in WLANs was discussed in [70]. QoS support in IEEE802.16 also has been discussed in [71], [72], [73] and [74]. These proposals introduced a packet scheduling algorithms and admission control policy. Another algorithm applies space division multiple access (SDMA) MAC scheduling. The latter algorithms dealt with the performance evaluations of the IEEE802.16 MAC for QoS Support. In these two proposals, different types of traffic are generated and the evaluations are based on the effectiveness of the MAC to deal with sensitive traffic and Best effort traffic (BE). Emerging the contention based and contention free centrally controlled channel mechanism were discussed in [75] and [76]. In these two proposals, the MAC frame can operate in these two mechanisms. The MAC is hybrid coordination function (HCF). This type of MAC can support QoS. The HCF defines two medium access mechanism, contention-based channel access and controlled channel access includes polling. Contention-based channel access is referred to an EDCA, controlled channel access as HCF controlled channel access (HCCA). In IEEE802.11e, there maybe still two phases of operation in the superframe (CP and CFP). The EDCA is used in the CP only, while the HCCA is used in both phases. Enhancement of the QoS provisions is proposed in [77]. In this proposal, a single hop and multihop scenarios are considered. The focus was on the EDCA which manages the QoS through users traffic priority. IEEE802.11e provides priority-based service differentiation EDCA mechanisms. Three traffic priority mechanisms are included in EDCA to provide QoS differentiation: Backoff contention window (CW) priority, arbitrary interframe space (AIFS) and transmission opportunity (TXOP) limit.

2.6 Channel Utilization

The channel in WLANs is the broadcast medium and it is shared amongst users. During a simultaneous transmission by two or more users, transmission may be corrupted. This process is called collision. MAC is designed to reduce the collision. MAC protocols can coordinate the access to the medium from different users at different times. Some WLANs have only one access channel such IEEE802.11x. In IEEE802.11x carrier sense multiple access with collision avoidance (CSMA/CA) is used as a MAC protocol. Distributed coordination function (DCF) is the fundamental MAC protocol in IEEE802.11. IEEE802.11e supports QoS and it also uses DCF. The main drawback in DCF is that the packets have to spend additional time in their MAC buffer during the backoff process. The channel utilization and the throughput are reduced as a result of that. There are several attempts to improve the channel utilization. In [78] a protocol was proposed to reduce the time spent by the packet in the backoff process to improve the throughput. In [79] authors find out the reason for the channel utilization degradation is the backoff assignment algorithm. When the number of nodes increases in the carrier sensing zone, the channel utilization decreases. They proposed a model to improve the channel utilization by a better backoff-state assignment algorithm. Channel utilization measurement in WLAN has been proposed in [80]. The overhead such as RTS/CTS also reduces channel utilization. Hence, in [81] authors proposed a method for frames aggregation to improve the channel utilization. The data frame can aggregate the ACK and as a result the channel utilization is improved. Another way to improve the channel utilization has been proposed in [82]. The idea is that, the contention window size for each station is properly selected to reflect the relative weight among data traffic flows to achieve fairness and to reflect the number of contending station for the wireless medium. In [83] a simple protocol is proposed to achieve maximum channel utilization in IEEE802.11n using the basic DCF. The proposed MAC uses the frame aggregation. With the frame aggregation, they can aggregate as many small user frames as possible into a large frame until the maximum aggregated frame size is reached. Because the MAC overhead is reduced, throughput is boosted.

2.7 Proposed Solutions to Problems

In this chapter we have discussed and reviewed several problems in WLANs. These problems are related to contention on the resources, error control and QoS support. These proposals provided some improvements in one aspect and leave the other unsolved. Most of the proposed models proposed for contention resolution adapted either BEB algorithm or probability backoff. However, BEB has the tendency of the exponential growth of its contention window which leads to a delay and that reflects on the performance of the MAC frame. Probability backoff also does not give any QoS support and do not differentiate amongst users or type of traffic. We proposed four backoff models for collided users. We applied these models to QoS support models which we developed. Our proposed model, besides their simplicity provide QoS. Moreover, our models can combine the requests and the allocation for users in the same MAC frame. In terms of QoS, proposed models usually allocate certain bandwidth for certain class of users or traffic and some models do not consider the channel error on top of the physical layer. However, our proposed models consider the channel error and they are cross-layer models since we consider the channel error as the wireless channel is prone to error due to noise and fading. Furthermore, we considered the request channels might be in error. Users may not get access due to two reasons, either collision or channel error which is not considered in a unified model. In our models we considered that case into account where users may not get access due to these two reasons. We also investigated the wireless channel utilization in a single and multi channel wireless standards. Hence, we proposed cross-layer models for wireless channel that take into consideration, collisions, channel error and QoS support. These proposed models deal with single class and QoS support models in single and multichannel wireless networks.

2.8 Chapter Summary

This chapter explored the challenges in the wireless networks for random access and channel allocation. It also gives background in the some backoff strategies adapted in the randan access. Furthermore, some quality of service issues been revised and some drawbacks have been highlighted. Moreover, we showed some error control protocol approached which have been applied in wireless networks. In the random channel allocation there are different ways were used, however, some of them have complexity in the algorithm flows and some of them have the restrictions that these algorithms have to be applied to one wireless standard. Quality of service models also, have the tendency that only the classification should be applied to users or applications. From our study, we get the motive that we can develop some models that can be applied to different wireless networks use the random access. Our proposed models for the backoff strategies have the flexibility to be used in different wireless networks. Also, our proposed quality of service models can be used in different wireless networks and have different parameters to be adjusted so that a better performance can be approached.

Chapter 3

Backoff Strategies Investigation

This chapter presents the first contribution of this dissertation. We proposed different backoff strategies for the collided users. We use a Markov chain model for random access channel allocation. Furthermore, we enhanced our developed model by error control protocol for data transmission where the data might be in error.

This chapter is organized as follows. Section 3.1 defines the system model under study. Section 3.2 presents our constant backoff probability model, its analysis and results. Section 3.3 presents our proposed backoff model (two-valued backoff probability model) and its results. Section 3.4 and Section 3.5 present the proportional backoff probability model and complimentary backoff probability model, respectively. Section 3.6, presents a comparison amongst the backoff strategy model. Section 3.7 shows our proposed model for error control protocol, its analysis and performance. Section 3.8 presents the chapter summary, conclusions and the significance of this work.

3.1 System Model

In this thesis we consider a centralized model where we have a Base station (BS) and Subscriber stations (SSs) within its coverage area. Figure 3.1 shows the system model that we consider. The main features of the system models are:

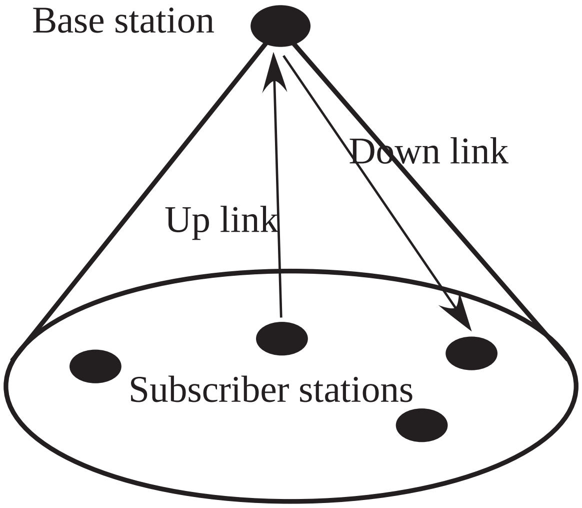


Figure 3.1: System model

1 There is a direct communication between the BS and all SSs.

2 All SSs can communicate directly to the BS and that eliminates the hidden and exposed terminal problems.

3 The system can have single or multiple channels. Channels could be a time slot in TDMA systems, a frequency channel in OFDMA systems, or orthogonal codes in CDMA systems. The channel is subject to errors due to fading and interference.

4 Assume a homogenous traffic mode where each SS carries the same traffic load on average.

5 Collisions occur in the request phase when two or more SSs issue request at the same time on the same channel. Collision occur in the uplink phase. Downlink phase is error free.

The time is divided into frames and each frame has an uplink and downlink phase as shown in Fig. 3.2. Part of the uplink logical channels are dedicated for requests and the other part is for data. The uplink phase is used for communication from the SS to BS whereas downlink phase used for communication from BS to SS.

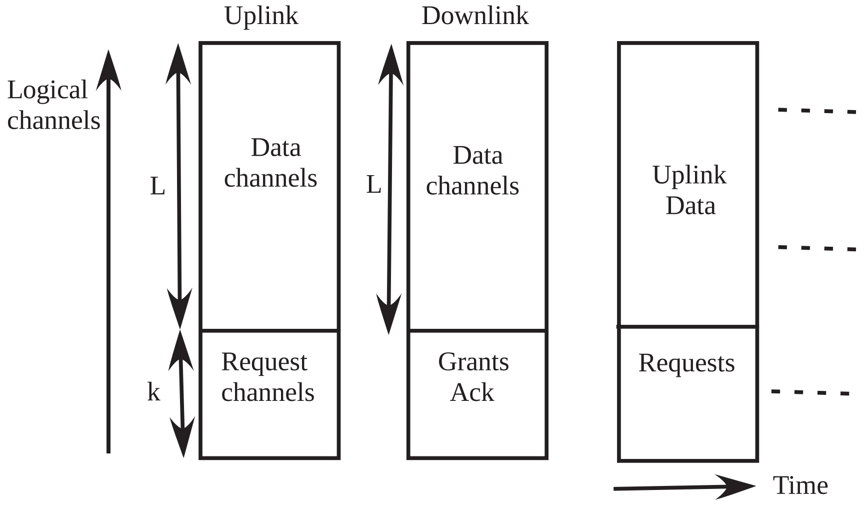


Figure 3.2: Uplink and downlink chart TDD

6 The communication process follows the 4-way handshaking as illustrated in Fig. 3.3

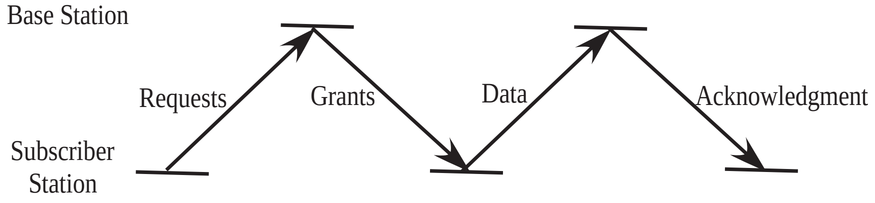


Figure 3.3: Requests and data transmission chart in the uplink

The SS that has data to send issues a request to the BS at the start of the frame. Once the BS receives that request it issues a grant and the SS sends its data. Once the data receives successfully an acknowledgments is sent.

7 Each SS can support different traffic and in Chapter 5 we deal with Quality of Service where traffic is classified into two classes.

In distributed WLANs systems the basic access mechanisms are Aloha and CSMA. These two access mechanisms are not synchronized since when SSs have data to send they issue a request at any time. In our system model these mechanisms can not be used since it is a centralized model as the BS synchronized access for the SSs. However, our system is based on Slotted Aloha (S-Aloha) where SSs can issue request at the beginning of the MAC frame.

In this chapter we proposed four different backoff strategy models. In the first model, the users that did not get an access (collided users) retransmit a request with certain probability. In the second model, the retransmission probability changes to another value when the performance is starting to degrade (two-valued backoff probability). The third model, the collided users issue a request with a probability equals to the idle users request probability. In the fourth model the retransmission probability is proportional to the offered load. In these models we uses Markov chain modeling for the user. In our models we also assume that we have a fixed number of RCH channels in the MAC frame. We also developed error control model for the transmission state. In this model, a Markov chain modeling is used. Our models can be used for other Wireless Local Area Network (WLAN).

3.2 Constant Backoff Probability Model

In the first model, we assume that we have a number of users N that try to request access on the random access phase in the allocated channels. The number of random channels is k. The random channels are channels reserved for random access where users issue request to access to the MAC frame. The MT that has data to send selects one of the allocated channels in the random phase. Collision may take place if two or more MTs request an access on the same random channel. In the request arrivals to the MAC frame random access phase, the user would be in one of three states; $Transmit$ state, if a single request received or $Collide$ state, if two or more MTs issue a request on the same channel or *idle* state if there is no request has been received. The state of any user is independent of its state in the past MAC frame thus, Markov property is valid. In practice the BS will assign this constant backoff probability to the SSs at the start of the operation. In order to analyze the system some assumptions are made:

1. The probability that a user issues a request is a.
2. The probability a user chooses a particular reservation channel (random channel reserved for user's requests) is $1/k$.
3. A collided user retransmits with probability c.
4. The traffic is calculated in one radio cell. No outside traffic is considered.
5. The time step is taken equal to the sum of transmission delay (time required to send a packet) and round trip delay (time required for packet propagation and reception of acknowledgment).
6. Binomial traffic model is used in the section and in the subsequent sections. More traffic models which can be applied as well can be found in [84].

Fig. 3.4 shows the Markov chain state diagram for the user.

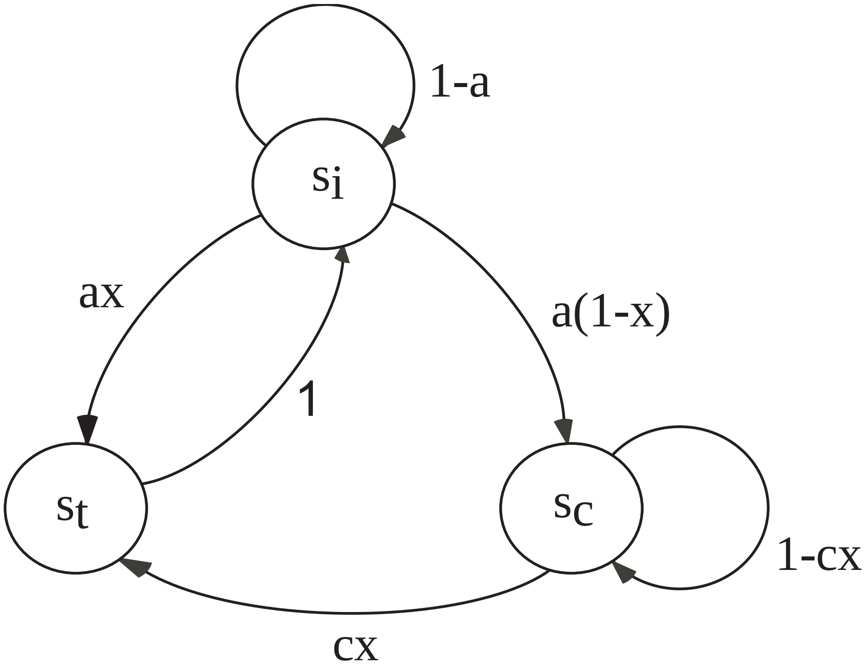


Figure 3.4: Markov state diagram for the user

In Fig. 3.4, x is the probability that a user successfully accesses one of the free channels and is given by:

$$x = \left(1 - \frac{1}{k}\right)^{N_{ave}-1} \tag{3.1}$$

where N_{ave} is the average number of active users:

$$N_{ave} = N(as_i + cs_c) \tag{3.2}$$

3.2.1 System Analysis

A discrete-time Markov chain is characterized by the transition matrix $\mathbf{P}$ and the state vector $\mathbf{s}$ [84]. The state vector $\mathbf{s}$ for the user is organized as:

$$\mathbf{s} = [s_i \quad s_t \quad s_c]^t \tag{3.3}$$

where s_i is the probability that the user is in the *idle* state, s_t is the probability that the user is in the *transmit* state and s_c is the probability that the user is in the *collide* state. The corresponding state transition matrix of the user which is extracted from the state transition diagram shown in Fig. 3.4 is given by:

$$\mathbf{P} = \begin{bmatrix} 1-a & 1 & 0 \\ ax & 0 & cx \\ a(1-x) & 0 & 1-cx \end{bmatrix} \tag{3.4}$$

At equilibrium, the distribution vector elements are obtained by solving the following two equations [84]:

$$\mathbf{Ps} = \mathbf{s} \tag{3.5}$$

$$\sum s_j = 1 \tag{3.6}$$

where $j \in \{i, t, c\}$.

From Eqs. (3.4), (3.5) and (3.6) we can find the state vector elements at equilibrium

$$s = \frac{1}{D_n}[1 \quad ax(1+cy) \quad ay]^t \tag{3.7}$$

where D_n is

$$D_n = 1 + ax(1+cy) + ay \tag{3.8}$$

$$y = 1 - x \tag{3.9}$$

y is the probability that a user selects a busy channel.

3.2.2 Constant Backoff Probability Model Performance

From the system analysis discussion we focus on several performance criteria to evaluate the performance of the proposed model. The parameters that have impact the traffic are: k and a. At this point we would like to clarify some terms. Traditionally, a PDU is called a packet at the network layer. The PDU at the MAC layer is called a frame. However, in this thesis time is divided into frames and each frame has two phases, uplink and down link. To prevent confusion we will continue to use the term packet at the MAC layer.

Throughput

The requests throughput is obtained from the following equation:

$$Th = min(Ns_t, k) \tag{3.10}$$

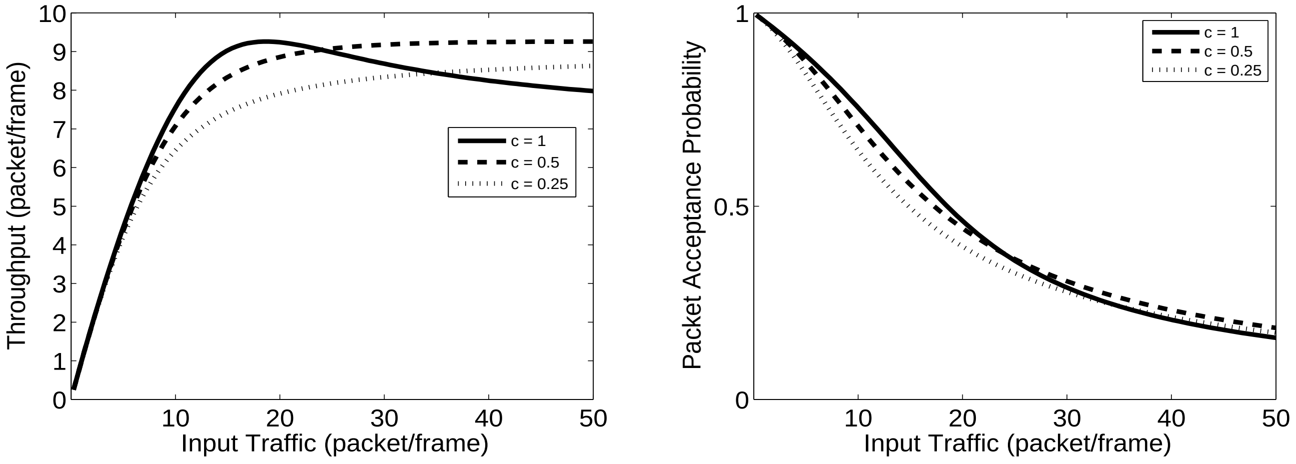
The performance of the proposed model is evaluated for a number of users $N = 50$, and number of channels $k = 25$, access probability (retransmission probability) for the collided users varies from $c = \{0.25, 0.5, 1\}$. Fig. 3.5(a) shows the throughput for different values of c. We notice that as c gets higher the requests throughput improves until input traffic reaches higher value then the throughput degrades.

Acceptance Probability

The requests acceptance probability is defined as the ratio between the throughput and the offered load [84]:

$$p_a = \frac{Th}{Na} \tag{3.11}$$

Fig. 3.5(b) shows the acceptance probability for different values of c and it is noticeable that it improves with the increase of c until the input traffic is higher the acceptance probability is degraded.



(a) Throughput

(b) Acceptance probability

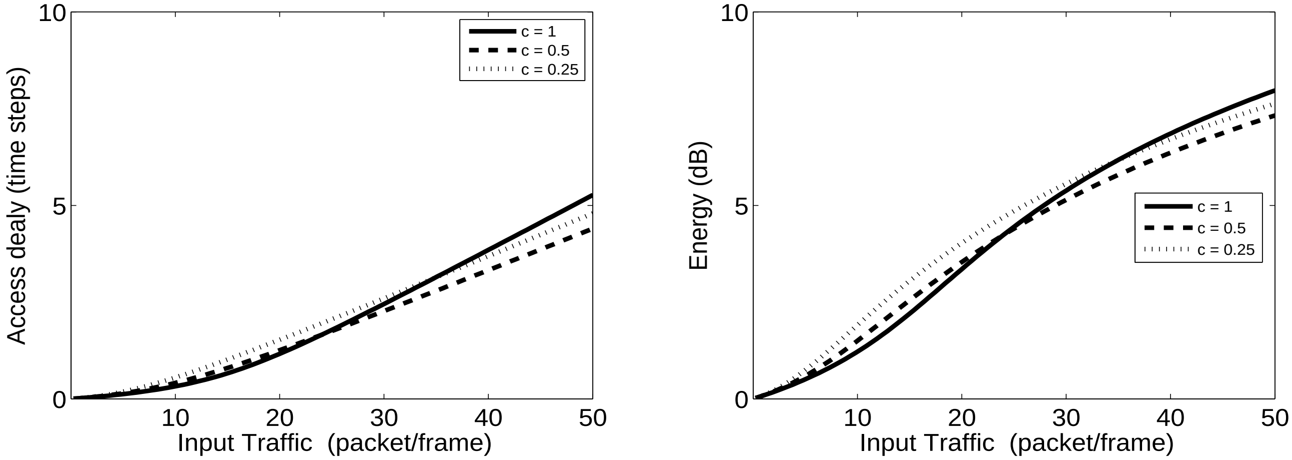
Figure 3.5: Throughput and acceptance probability versus input traffic for fixed backoff probability model.

Access Delay

The delay (D) is the average number of access attempts made by the MTs before they are successfully granted access. It is defined as;

$$\begin{aligned} D &= \sum_{i=0}^{\infty} i(1-p_a)^i p_a \\ &= \frac{1-p_a}{p_a} \end{aligned} \tag{3.12}$$

Fig. 3.6(a) shows the average access delay that the MTs wait until they are granted an access. The delay is getting shorter as c increases until the input traffic gets higher then the delay starts to degrade.



(a) Access Delay

(b) Energy

Figure 3.6: Access delay and energy versus input traffic for fixed backoff probability model.

Energy

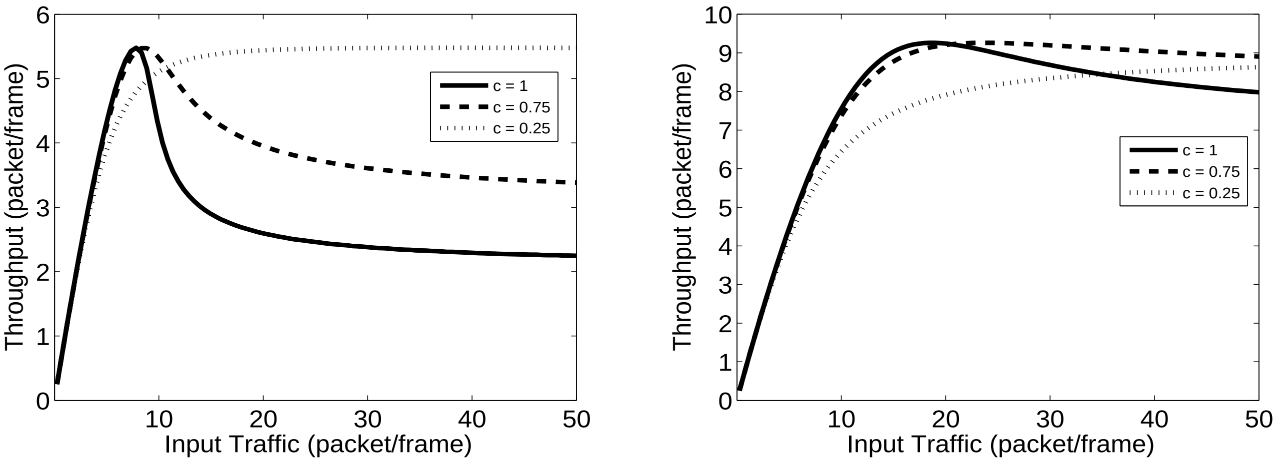
The average energy E_a required to transmit a request successfully can be calculated as follows [85];

$$\begin{aligned} E_a &= E_0 \times \sum_{i=0}^{\infty} (i+1)(1-p_a)^i p_a \\ &= \frac{E_0}{p_a} \\ E_a[dB] &= -10\log(p_a) \end{aligned} \tag{3.13}$$

where E_0 is the energy required to transmit a request once. The energy is normalized to one in the model and in the other models we develop in the next chapters. Fig. 3.6(b) shows the energy required by the MTs to access successfully. The amount of energy is decreased as the value of c increases until the input traffic gets higher then the energy required to transmit a successful request is getting larger.

In order to check the impact of the number of allocated channels, the number of channels is varied

Fig. 3.7(a) shows the throughput for different values of c and for $k = 15$ channels. Fig. 3.7(b) shows the throughput for $k = 25$. By comparing the two figures, we notice that the throughput is higher when we have enough channels as the collision reduced.



(a) $k = 15$

(b) $k = 25$

Figure 3.7: Throughput versus input traffic for different values of c and k

From the previous figures, we notice that there is a cross-over point while we vary the value of c. During the low offered load, the unsuccessful user could issue a retransmission request with probability 1 and better performance is achieved compared to a lower retransmission attempt. The probability could be adapted to a lower value once the performance is deteriorated (i.e. when the input traffic is getting higher). The cross-over point happens when the input traffic exceeds the number of allocated channels. The cross-over point moves as the number of channels changes. In the next section, we will show the results of our new Two-Valued backoff probability model.

3.3 Two-valued Backoff Probability Model

In this model, have the same assumption as in Section 3.2 except for the retransmission probability of the collided users is switched between two different values $c1$ and $c2$. The switching probability happens at the cross-over point where the input traffic exceeds the number of allocated channels. The BS monitors the arriving request and based on this information the number of users N and the frame arrival probability a are determined. Based on these two values, the backoff probability $c1$ or $c2$ are chosen and broadcasted to all SSs according to equation 3.14. The retransmission probability is defined as follows:

$$c = \begin{cases} c1, & \text{if } Na < k; \\ c2, & \text{otherwise} \end{cases} \tag{3.14}$$

3.3.1 Results of the Two-valued Backoff Probability Model

In this subsection, we show how the two-valued probability backoff model could improve the backoff. The performance is measured by the throughput . In Fig. 3.8 before the cross-over point the collided users retransmit with probability 1 to get the highest throughput. After the cross-over point the probability of retransmission probability is reduced to 0.5 and the throughput is maintained in a higher value. The model also could use more than two retransmission probabilities. In the figure we investigated several retransmission probability and the better performance we get is when the users issue a request with a probability 1 during the low offered load and retransmit with probability 0.5 as the offered load gets higher.

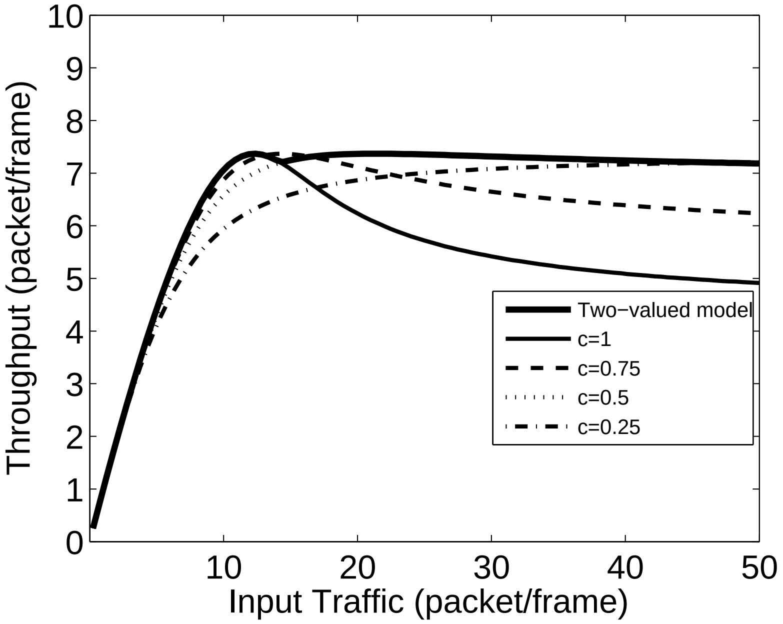


Figure 3.8: Throughput versus input traffic for two-valued backoff model and fixed retransmission values

3.4 Proportional Probability Backoff Model

In this model, we assume that the collided users could retransmit a request with a probability equal to the uncollided users requesting probability from low value until maximum value $\{0, \cdots, 1\}$. The BS monitors the arriving request and based on this information the number of users N and the frame arrival probability a are determined. Based on these two values, the backoff probability c is chosen and broadcasted to all SSs based on equation 3.15.

$$c = a \tag{3.15}$$

A discrete-time Markov chain is characterized by the transition matrix P and a state vector s. The state vector s for a user is organized as:

$$\mathbf{s} = [s_i \quad s_t \quad s_c]^t \tag{3.16}$$

where the transition probability as shown in Fig. 3.4 except the retransmission probability c is replaced with a. s_i is the probability that the user is in the *idle* state, s_t is the probability that the user is in the *transmit* state and s_c is the probability that the user is in the *collide* state. The corresponding state transition matrix P of the user which is extracted from the state transition diagram shown in Fig. 3.4 is

$$\mathbf{P} = \begin{bmatrix} 1-a & 1 & 0 \\ ax & 0 & ax \\ a(1-x) & 0 & 1-ax \end{bmatrix} \tag{3.17}$$

At equilibrium the distribution vector elements are obtained by solving the following two equations [84];

$$Ps = s \tag{3.18}$$

$$\sum s_j = 1 \tag{3.19}$$

where $j \in \{i, t, c\}$. From Eqs.(3.17), (3.18) and (3.19) we can find the state vector elements at equilibrium

$$s = \frac{1}{D_{n1}} \left[1 \quad ax(1+ay) \quad ay\right]^t \tag{3.20}$$

where D_{n1} is

$$D_{n1} = 1 + ax(1+ay) + ay \tag{3.21}$$

The average number of active users N_{ave} in the system now can be calculated by;

$$N_{ave} = Na(s_i + s_c) \tag{3.22}$$

3.4.1 Results of Proportional Probability Backoff Model

The performance results for this model is measured by the requests throughput. The number of users is fixed to $N = 50$ and the number of channels is varied $k = 20, 25$. Fig. 3.9 shows the throughput. From the figure, the higher the number of channels the better throughput is obtained. The higher throughput occurs at the middle where the requesting probability for both groups of users (collided and uncollided) is 0.5. When the offered load is low, the throughput is low since the requesting probability is low. However, when we have high load the throughput is getting lower since the resources are limited and hence the collision is high.

3.5 Complementary Backoff Probability Model

In this model the retransmission probability of the collided users is a compliment of the input traffic. The BS monitors the arriving request and based on this information the number of users N and the frame arrival probability a are determined. Based on

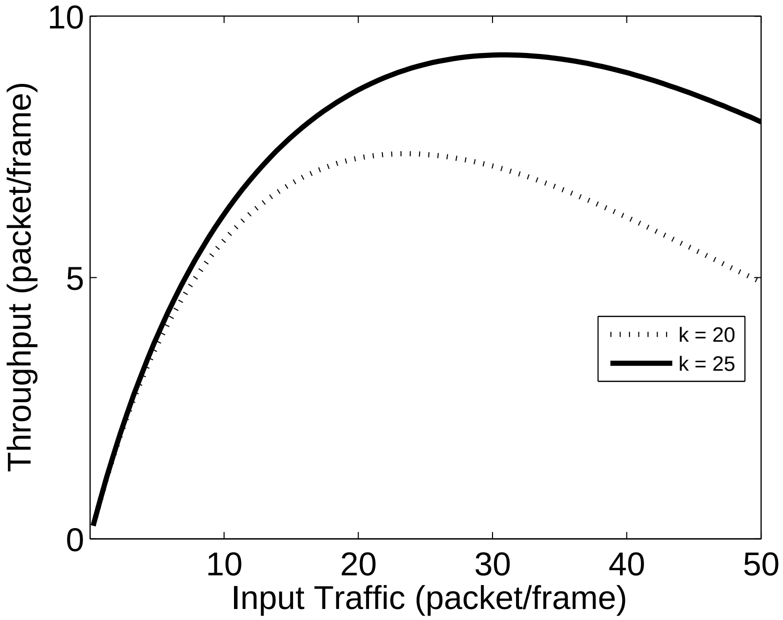


Figure 3.9: Throughput versus input traffic for the proportional Backoff probability Model

these two values, the backoff probability c is chosen and broadcasted to all SSs based on equation 3.23.

The retransmission probability is calculated as follows:

$$c = 1 - a \tag{3.23}$$

Fig. 3.10 shows the throughput of the complementary backoff probability model. The number of users is 50 and the number of channels $k = 20, 25$. From the figure the throughput increases until the saturation. After the saturation the throughput stays at the saturation since the retransmission probability is adaptively adjusted to the input traffic and the collided users requesting probability is lower at high load.

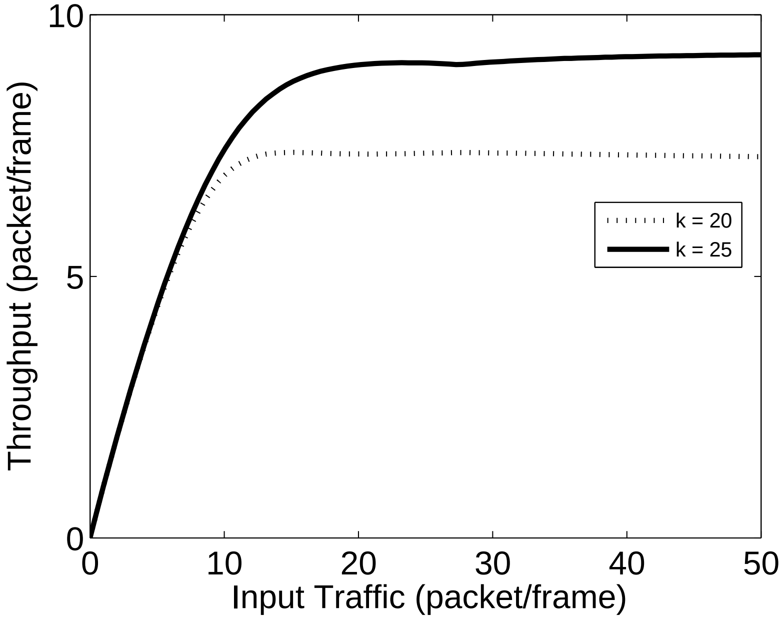


Figure 3.10: Throughput versus input traffic for the complementary backoff probability model

3.6 Comparison of the Backoff Strategies Models

This section compares the obtained results of the four backoff models. The comparison is done for $N = 50$ and $k = 20$. Fig. 3.11 shows the requests throughput comparison. From the figure, the complementary backoff probability model is giving better throughput compared to the other models since the retransmission probability of the collided user is decreased adaptively according to the offered load. We also notice that when the value of $c = a$, the best throughput is achieved around the middle since the requesting probability at that point is 0.5 and at the beginning we almost have no throughput since the requesting probability is very low. However, once the requesting probability exceeds 0.5 for the two groups of users, the throughput is getting worse since the collision is higher.

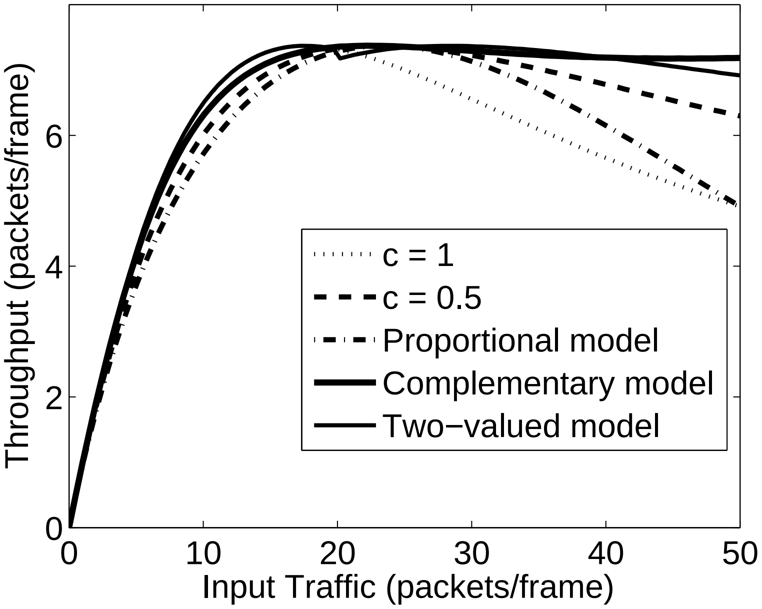


Figure 3.11: Backoff models comparison

3.7 Error Control Protocol Model

In this section we extended our model by applying error control in transmission states. We apply Stop-and-Wait ARQ (SW ARQ) error control protocol for the transmission state. we assume that N users try to request access on the random access phase. The number of random access channels is assumed to be k. An MT that has data to send selects one of the random channels. Collision occurs if two or more MTs choose the same channel. A user could be in one of three states; *transmit* state, if a single request received or *collide* state, if two or more MTs issues a request on the same channel or *idle* state if there is no request has been received. In order to analyze the system behavior, some assumptions are made in addition to the assumptions in Section 3.2;

1. The average length of a packet is b bits.
2. The probability that the transmitted packet contained error is e.
3. The forward channel has random noise and the probability that a bit will be received in error is ϵ, (BER).
4. The feedback channel is error free.
5. The sender will keep sending a packet n times.
6. Forward Error Correction (FEC) is not used in the model and in the subsequent models.
7. Hard coding is not used in this model and in the subsequent models.

The error control protocol states are shown in Fig. 3.12 represented by s_{t0} until s_{tn} have the following properties:

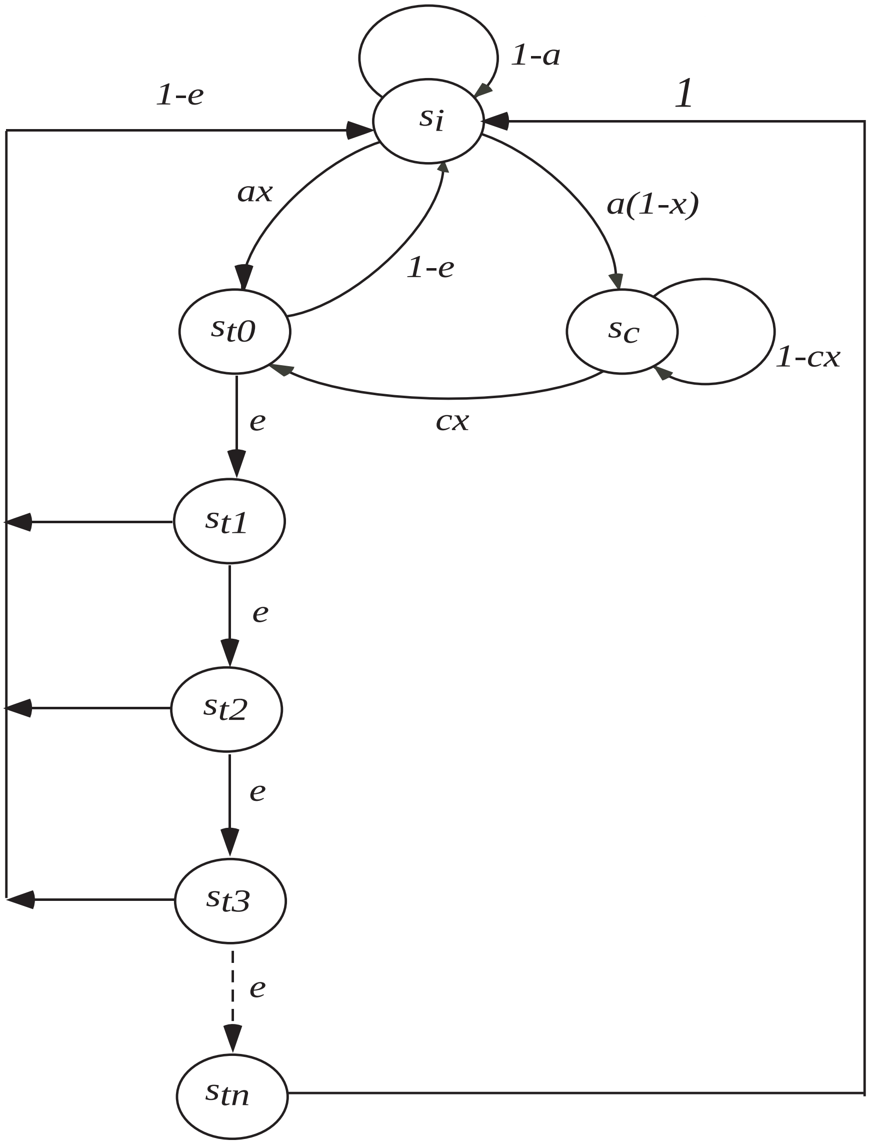


Figure 3.12: Markov state diagram for a user

1. State s_{ti} indicates that the MT is retransmitting the packet for the i^{th} time whereas, state s_{t0} indicates error-free transmission.
2. The number of retransmission states is $n + 1$.
3. The time step is taken equal to the sum of transmission delay (time required to send a packet) and round trip delay (time required for packet propagation and reception of acknowledgment) .

The error is calculated by;

$$e = 1 - (1 - \epsilon)^b \tag{3.24}$$

where b is the number of bits in a packet. Assume x is the probability that a user successfully accesses one of the free channels. x is given by;

$$x = \left(1 - \frac{1}{k}\right)^{N_{ave}-1} \tag{3.25}$$

where N_{ave} is the average number of active users;

$$N_{ave} = N(as_i + cs_c) \tag{3.26}$$

3.7.1 Model Analysis

A discrete-time Markov chain is characterized by the transition matrix $\mathbf{P}$ and the state vector $\mathbf{s}$ [84]. The state vector $\mathbf{s}$ for the user is organized as follows;

$$\mathbf{s} = [s_i \;\; s_{t0} \;\; s_{t1} \;\; s_{t2} \;\; s_{t3} \;\; \cdots \;\; s_{tn} \;\; s_c]^t \tag{3.27}$$

where s_i is the probability that the user is in the *idle* state, s_t is the probability that the user is in the *transmit* state and s_c is the probability that the user is in the *collide* state. The MT will keep sending the packet if there is no acknowledgment is received (i.e the packet sent with an error probability e) n times. When a packet is correctly received the MT goes to *idle* state with probability $1-e$. The corresponding state transition matrix of the user which is extracted from the state transition diagram shown in Fig. 3.12 is given by;

$$\mathbf{P} = \begin{bmatrix} 1-a & 1-e & 1-e & 1-e & 1-e & \cdots & 1 & 0 \\ ax & 0 & 0 & 0 & 0 & \cdots & 0 & cx \\ 0 & e & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & e & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & e & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & e & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 \\ a(1-x) & 0 & 0 & 0 & 0 & \cdots & 0 & 1-cx \end{bmatrix} \tag{3.28}$$

At equilibrium, the distribution vector elements are obtained by solving the following two equations [84];

$$\mathbf{Ps} = \mathbf{s} \tag{3.29}$$

$$\sum s_j = 1 \tag{3.30}$$

where $j \in \{i, t0, t1, t2, \cdots, tn, c\}$

From Eqs. (3.28), (3.29) and (3.30) we can find the state vector elements at equilibrium

$$s = \frac{1}{D_{n2}}[1 \quad B \quad eB \quad e^2B \quad e^3B \quad \cdots \quad e^{n-1}B \quad a(1-x)]^t \tag{3.31}$$

where B

$$B = ax\left[1 + c(1-x)\right] \tag{3.32}$$

and D_{n2} is

$$D_{n2} = 1 + B + eB + e^2B + e^3B + \cdots e^{n-1}B + a(1-x) \tag{3.33}$$

3.7.2 Performance of Error Control Protocol Model

We study the performance of this model measured by the average number of retransmission and the efficiency. We applied one backoff strategy model (constant backoff probability model) as an example. The average number of retransmissions for a packet is given by:

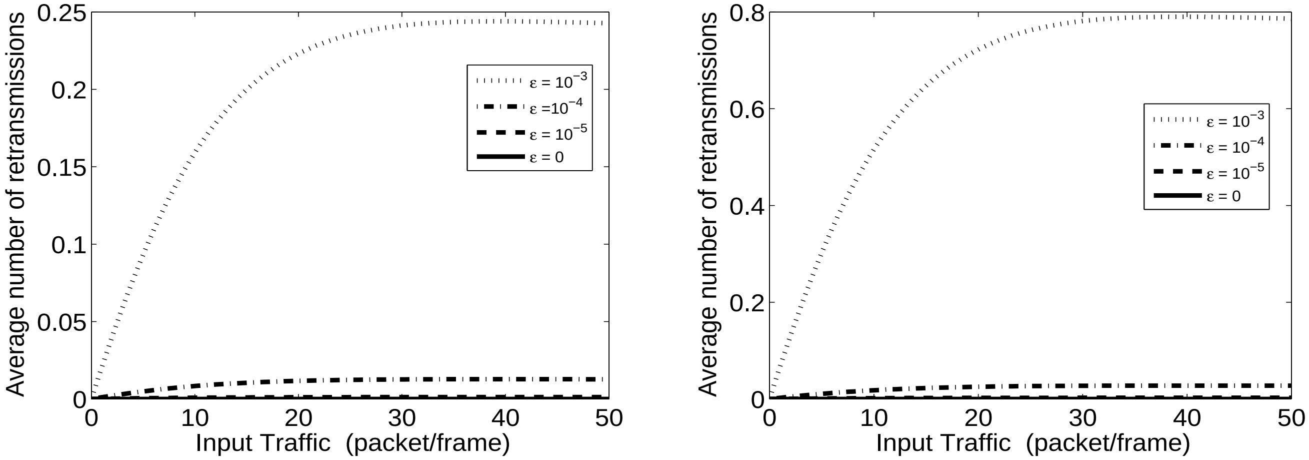
$$\begin{aligned} N_t &= s_1 + 2s_2 + 3s_3 + \cdots \\ &= eB + 2e^2B + 3e^3B + \cdots + ne^nB \\ &= \sum_{i=1}^{n} ie^iB \quad transmission/packet \end{aligned} \tag{3.34}$$

The efficiency is defined as the total number of transmission which indicates the first retransmission plus the average number of retransmission and it is given by:

$$\eta = \frac{1}{1 + N_t} \tag{3.35}$$

In our analysis we assumed $N = 50$ users, the retransmission probability $c = 0.75$, the number of channels $k = 20$. We studied the performance of the model for $\epsilon \in \{0, 10^{-5}, 10^{-4}, 10^{-3}\}$, and the length of packets b is varied $\in \{500, 1000, 10000\}$ bits.

Figs. 3.13 and 3.14 show the comparison for the average retransmission probability when we vary the bit error rate and the packet length. Fig. 3.13(a) shows this comparison when the number of bits is 500. When the bit error rate is high 10^{-3} the average number of retransmission is high. The average number of retransmission decreases as the bit error rate decreases until it reaches zero where the bit error rate is zero. When the bit error rate is zero that means the channels is error free. Fig. 3.13(b), shows the comparison when the number of bits is 1000. The average number of retransmission is higher compared to the case when we only have 500 bits. Fig. 3.14, shows the comparison when the number of bits is 10000. The average number of retransmission is getting higher. However, when the bit error rate is zero, the average number of retransmission is zero since the channel is error free.



(a) Number of bits $b = 500$

(b) Number of bits $b = 1000$

Figure 3.13: Average number of retransmission versus input traffic

Figs. 3.15 and 3.16, show the comparison for efficiency when the bit error rate and the number of bits are varied. Fig. 3.15(a), shows the efficiency comparison for 500 bits, with different bit error rates. The figure shows that as the bit error rate decreases the efficiency increases until we reach the maximum value 1 where the channel is error free $\epsilon = 0$. Fig. 3.15(b), shows the same comparison but with different number of bits. The efficiency is decreases as the number of bits increases. Fig. 3.16, shows the efficiency comparison when the number of bits is 10000 with different error rates. From the figure, the efficiency decreases compared to that when we have less number of bits to send. From the figures as the channel is error free $\epsilon = 0$ we reach the maximum channel efficiency $\eta = 1$ and the average number of retransmissions $N_t = 0$

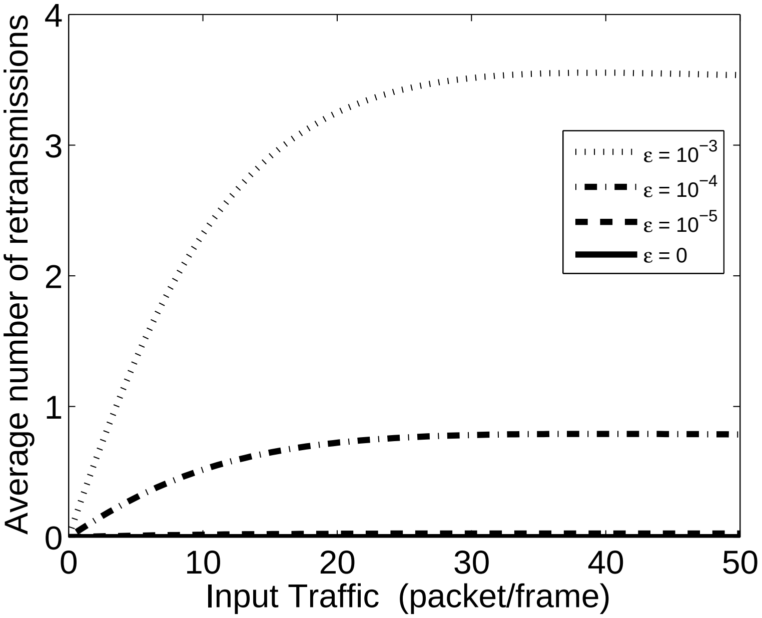
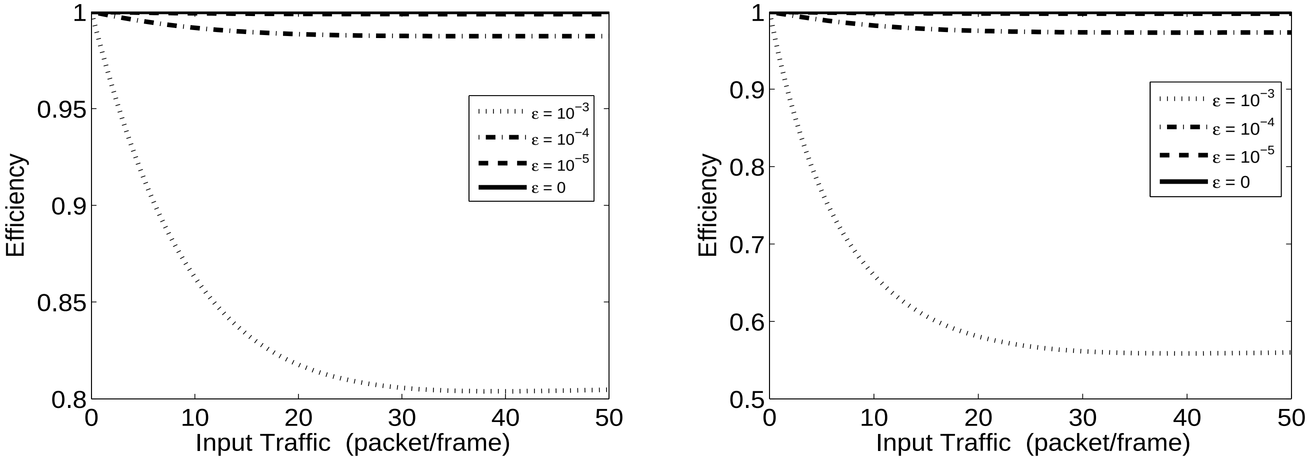


Figure 3.14: Average number of retransmission versus input traffic for 10000 bits



(a) Number of bits 500

(b) Number of bits 1000

Figure 3.15: Efficiency versus input traffic

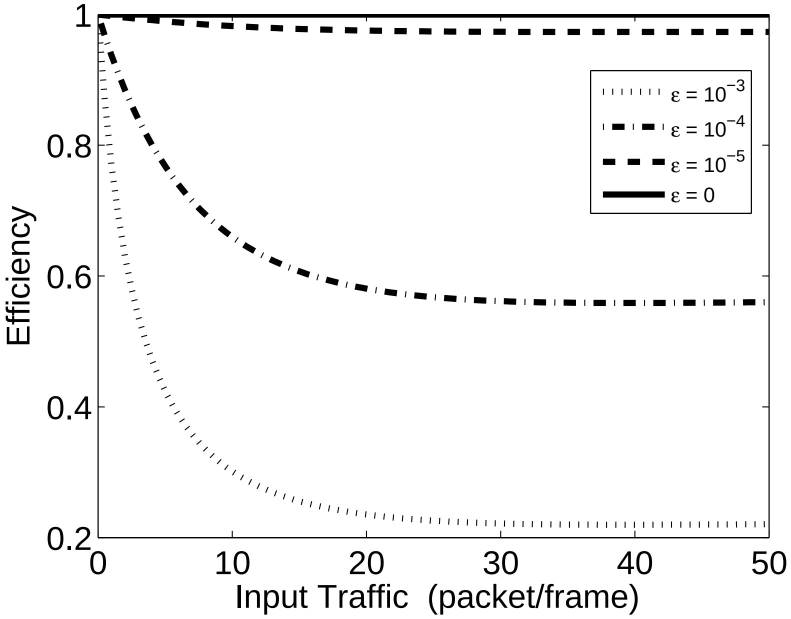


Figure 3.16: Efficiency versus input traffic for 10000 bits

3.8 Chapter Summary

In this paper, we proposed four backoff strategies models in random access phase. In these proposed models the number of random access channels is fixed. The impact of the access probability of the collided users is studied. The performance metrics for the models are shown. In the results, the proposed models show a good performance compared to other models where the collided users adopts a binary exponential backoff instead of simple backoff. In all our models, the minimum throughput either stay in a saturated level or decayed to a lower value. However, the lowest value is still better than the throughput obtained in aloha or slotted aloha protocol in higher load. In the last section we proposed error control model for the transmission state. Instead of assuming an error free channel, our model considers that the channel might be in error. We studied the impact for different bit error rate and for different number of bits. The average number retransmissions is lower when we have lower bit error rate and low number of bits. The efficiency reaches one when the bit error rate is zero and decreases as the bit error rate increases. This work has been published in [13] and [14].

Chapter 4

Modeling Uplink Channel Utilization

This chapter presents the second contribution in our dissertation which is the uplink channel utilization. In this chapter the uplink channel utilization for data transmission in one class is studied for centralized WLAN. We evaluated the uplink channel utilization for several WLANs standards with single channel and multi channel access networks. We compare the performance for these standards in terms of uplink channel utilization for data and also the net acceptance probability. We also study the data channel performance. Moreover, we develop a unified model for the wireless channel when the request and data channels are in error.

This chapter is organized as follows; Section 4.1 presents our model description and analysis, Section 4.2 presents our data channel performance model, Section 4.3 presents our request mechanism and data transmission model, Section 4.4 shows our results and comments and Section 4.5 shows our chapter summary and discussion.

4.1 Model Description

In this section we show the channel utilization for the network model. We consider a centralized WLAN such as WiMAX. In the centralized wireless network the Base

Station coordinate the access to the medium. Subscriber Stations (SS) that have data to send, sends request on the random request channels. The BS allocates the resources for the SSs. Once the users send their requests on the request channels, the successful user will be assigned certain bandwidth on the uplink. Fig. 4.1 shows using Time Division Duplexing (TDD) where time is broken down into frames and each frame has downlink and uplink phases. We have k requesting channels and L data channels. The channels could be time slots in case of the wireless networks that use the TDMA (Hiperlan 2) as their medium access. It can be frequencies for the networks that have frequency domain their medium access (WiMAX) or codes in CDMA network (3G). Users request access on the request channels k. The access point receives the requests and issues grants to the users. Once the users receive their allocated grants, they start sending their data. The balance point between the requesting channels k and the data channels L is a challenge. Increasing k will reduce the collision but affects the allocated data channels and as a result degrade the throughput. On the other hand, reducing k collision will increase and as a result access delay is high.

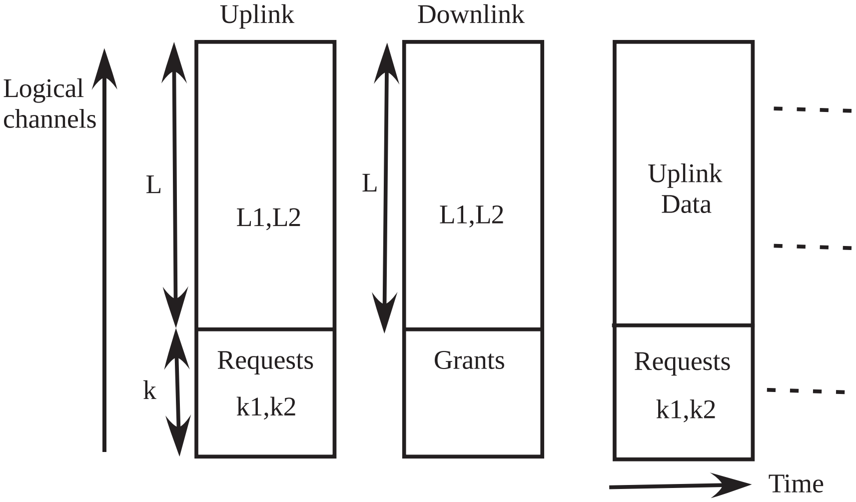


Figure 4.1: Uplink and downlink chart TDD

The uplink procedure is shown in Fig. 4.2. The process has six stages as numbered in Fig. 4.2. In the uplink phase in order for the users PDUs to be delivered they have to go through these stages; Stage 1: Users PDUs are sent by the application layers are placed in uplink queues based on their QoS criteria. Stage 2: the application layer scheduler picks up a PDU for transmission. Stage 3: MAC layer issues a request to reserve bandwidth for the scheduled PDU. Stage 4: the successfully transmitted requests from different subscriber stations are placed in the request/grant queues according to QoS criteria for both users and applications. Stage 5: the grant/application scheduler picks up which application to be sent to. Stage 6: the subscriber stations receive their grants and send their actual PDUs.

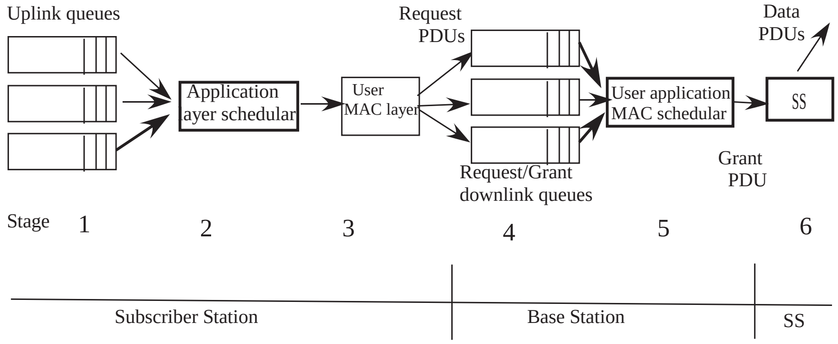


Figure 4.2: Uplink process

The downlink phase is shown in Fig 4.3. Stage 1: the successfully received requests from different subscriber stations are placed in the request/grant queues according to QoS criteria for both users and applications. Stage 2: the grant/application scheduler picks up which application to be sent to. Stage 3: the subscriber stations receive their grants and send their actual PDUs. Once that step completed the subscriber stations send Acknowledgments

We considered different channels (AWGN, Rayleigh fading channel and Rician channel) with different modulations scheme (BPSK and 16QAM). BPSK used as a

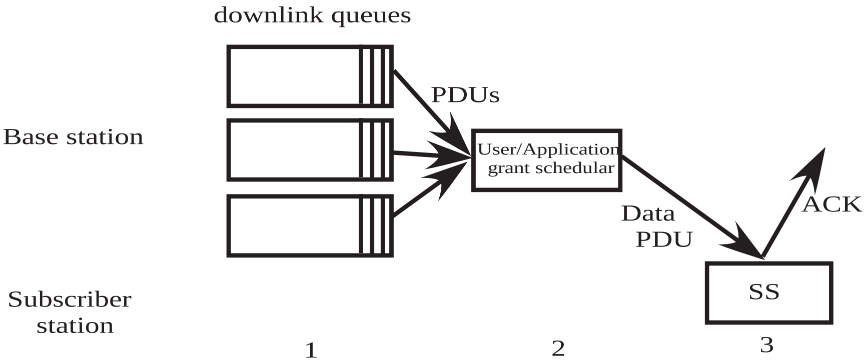


Figure 4.3: Down link process

fundamental mode in most or the wireless standard since it does not requires high SNR and usually the control data is send on this mode. The typical minimum SNR required for acceptable performance is $24dB$ [86]. To maintain $BER = 10^{-3}$ in Rayleigh fading channel we need $24dB$ and it requires $SNR = 8dB$ in AWGN and $20dB$ in Rician channel. Fig. 4.4 shows the SNR versus BER for different channels and different modulation scheme. The figure shows the required SNR for these channels and modulation to obtain the targeted BER.

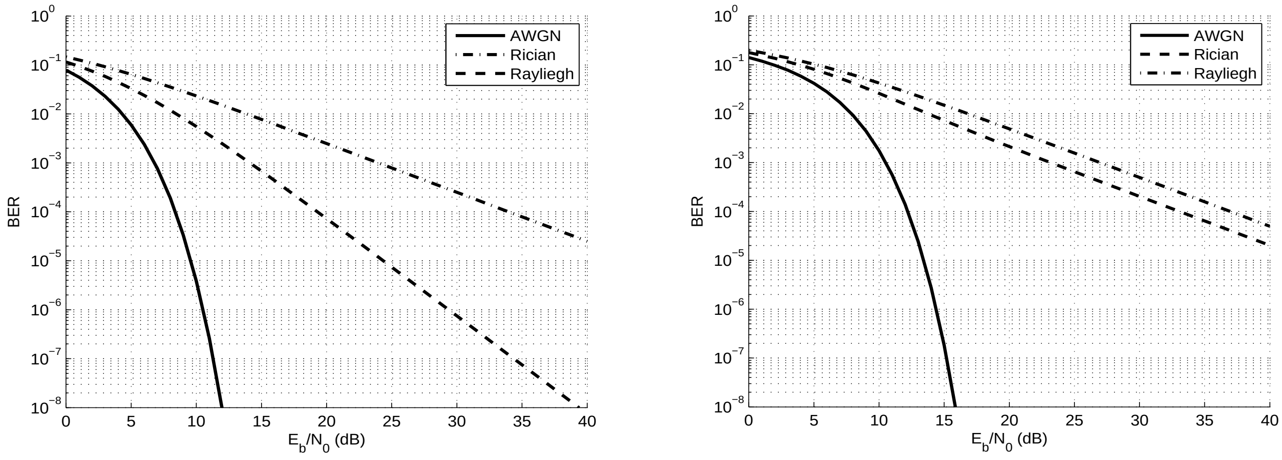
Uplink channel utilization: Equation 4.1 calculates the data uplink channel utilization for the data channels

$$\eta_U = \frac{\min\{L, Ns_t\}}{L} \tag{4.1}$$

Net acceptance probability: This equation is to find the net acceptance probability for the data channels

$$P_{a(net)} \begin{cases} p_a, & NTh < L; \\ p_a \frac{L}{Ns_t}, & NTh > L. \end{cases} \tag{4.2}$$

where L is the number of data channels, N is the number of users, and s_t is success probability extracted from the state vector.



(a) SNR versus BER for BPSK (b) SNR versus BER for 16QAM

Figure 4.4: SNR versus BER for different modulation and channels

4.2 Data channel Model and Performance

In the previous sections we presented the requests performance and channel utilization. In this section the data channels performance is presented. This is the performance of the data channels. All assumptions in the pervious section are valid, but in this model we study the data channels performance when we vary the number of data channels.

The data channels throughput can be calculated by;

$$Th_{data} = \min\{L, Nst\} \tag{4.3}$$

The data channels acceptance probability can be calculated by:

$$Pa_{data} = \frac{Th_{data}}{Na} \tag{4.4}$$

The data channels average delay can be calculated by;

$$D_{data} = \frac{1 - Pa_{data}}{Pa_{data}} \tag{4.5}$$

The data channels average energy can be calculated by;

$$E[dB] = -10 \log Pa_{data} \tag{4.6}$$

4.3 Request Mechanism and Data Transmission Model

We study the request mechanism and data transmission. Fig 4.5 shows the four steps that the SSs follow in order for its data been delivered to the receiver. The SSs issue request on the random access request channels. Once the BS receives these requests it issue grants to the successful SSs and inform them at what time in the MAC frame those users have to send their data. Then SSs send their data. Once this data is delivered an acknowledgment is issued.

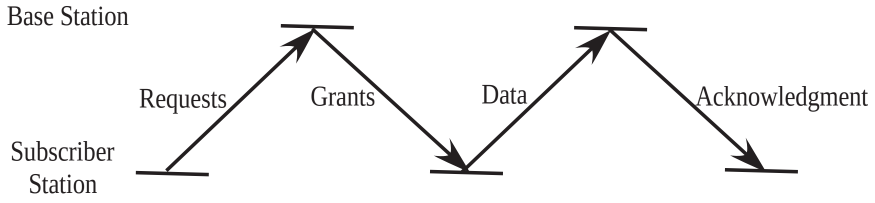


Figure 4.5: Requests and data transmission chart

4.3.1 Model assumptions

We assume that N SSs try to request access on the random requesting channels. The number of request channels is assumed to be k. In order to analyze the system behavior, some assumptions are made;

1. The probability that a SS issues a request is a.

2. The probability a SS chooses a particular reservation channel is $1/k$.
3. A collided user retransmits with probability c.
4. The traffic is calculated in one radio cell. No outside traffic is considered.
5. The average length of a request packet is $b1$ bits.
6. The average length of a data packet is $b2$ bits.
7. The probability that the transmitted request packet contained error is $e1$.
8. The probability that the transmitted data packet contained error is $e2$.
9. The feedback channel is error free.
10. The sender will keep sending a packet n times.

The error control and MAC protocol states for requests and data are shown in Fig. 4.6 represented by s_{t0} until s_{tn} have the following properties:

1. State s_{ti} indicates that the SS is retransmitting the frame for the i^{th} time whereas, state s_{t0} indicates error-free transmission.
2. The forward channel has random noise and the probability that a bit will be received in error is ϵ, (BER).
3. The number of transmission states is $n + 1$.
4. The time step is taken equal to the sum of transmission delay (time required to send a frame) and round trip delay (time required for frame propagation and reception of acknowledgment).

A Subscriber Station (SS) that has data to send issues a request on one of the k random requesting channels. Contention may occur if two or more SSs choose the same requesting channel. A SS could be in one of three states; *transmit* state, if a single request received or *collide* state, if two or more SSs issues a request on the same channel or *idle* state if there is no frame has been received.

Fig. 4.6 shows integrated model Markov chain state diagram for request and data with error control. The collided SS adapts a constant probability backoff algorithm in which the collided SSs retransmit with a probability c [13]. The request error is calculated by;

$$e1 = 1 - (1 - \epsilon 1)^{b1} \tag{4.7}$$

where $b1$ is the number of bits in a request message. The data error is calculated by;

$$e2 = 1 - (1 - \epsilon 2)^{b2} \tag{4.8}$$

where $b2$ is the number of bits in a data message.

The probability that a user successfully accesses one of the free channels is given by;

$$x = \left(1 - \frac{1}{k}\right)^{N_{ave}-1} \tag{4.9}$$

where N_{ave} is the average number of active users;

$$\begin{aligned} N_{ave} &= N(as_i + cs_c) && (4.10) \\ y &= 1 - x && (4.11) \end{aligned}$$

y is the probability that a user selects a busy channel.

A discrete-time Markov chain is characterized by the transition matrix $\mathbf{P}$ which can be obtained from the state diagram and the state vector $\mathbf{s}$ [84]. The state vector $\mathbf{s}$ for the user is organized as follows;

$$\mathbf{s} = [s_i \quad s_c \quad s_{t0} \quad s_{t1} \quad s_{t2} \quad s_{t3} \quad \cdots \quad s_{tn}]^t \tag{4.12}$$

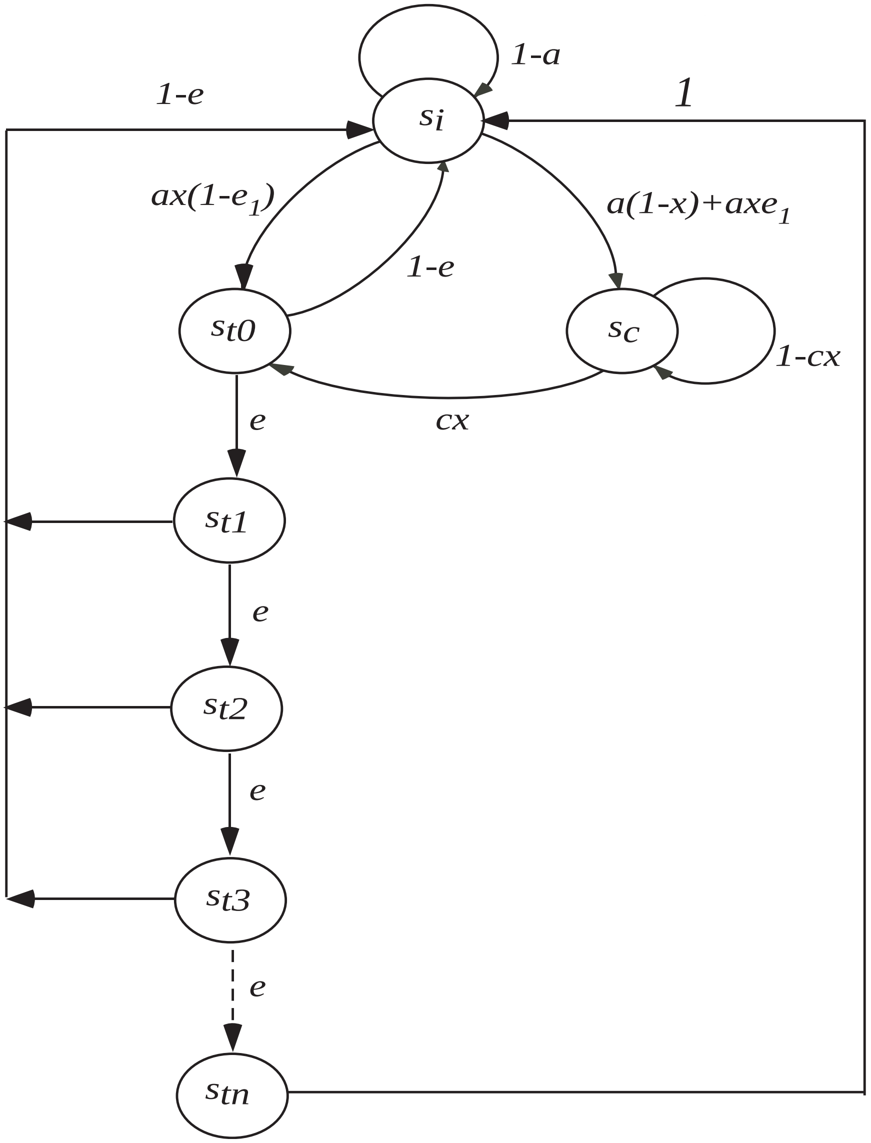


Figure 4.6: Markov state diagram request and data

where s_i is the probability that the user is in the *idle* state, s_t is the probability that the user is in the *transmit* state and s_c is the probability that the user is in the *collide* state. The SS will keep sending the packet if there is no acknowledgment is received (i.e the packet sent with an error probability e) n times. When a packet is correctly received the SS goes to *idle* state with probability $1-e$. At equilibrium, the distribution vector elements are obtained by solving the following two equations [84];

$$\begin{aligned} \mathbf{Ps} &= \mathbf{s} && (4.13) \\ \sum s_j &= 1 && (4.14) \end{aligned}$$

where $j \in \{i, t0, t1, t2, \cdots, tn, c\}$. From Eqs. (4.13) and (4.14) we can find the state vector elements at equilibrium as follows;

$$\begin{aligned} s_i &= \frac{1}{G} \\ s_c &= \frac{a(1-x) + axe_1}{G} \\ s_{tj} &= \frac{W}{G} \sum_{j=0}^{n-1} e^j && (4.15) \end{aligned}$$

where

$$W = ax(1-e_1) + acx(1-x) + acx^2 e_1 \tag{4.16}$$

and

$$G = 1 + [a(1-x) + axe_1] + W + eW + e^2 W + \cdots e^n W \tag{4.17}$$

4.3.2 Model Performance

We study the performance of this model in this subsection. We applied one backoff strategy model (Constant backoff probability model) where the collided user retransmit with probability as an example. The requests throughput is obtained from the following equation:

$$Th = \min(Ns_t, k) \tag{4.18}$$

The requests acceptance probability is defined as the ratio between the throughput and the offered load [84]:

$$p_a = \frac{Th}{Na} \tag{4.19}$$

The requests access delay (τ) is the average number of access attempts made by the SSs before they are successfully granted a channel. It is defined as;

$$\begin{aligned}\tau &= \sum_{i=0}^{\infty} i(1-p_a)^i p_a \\ &= \frac{1-p_a}{p_a} \qquad (4.20)\end{aligned}$$

The requests average energy E_a required to transmit a request successfully can be calculated as follows [85];

$$\begin{aligned}E_a &= E_0 \sum_{i=0}^{\infty} (i+1)(1-p_a)^i p_a \\ &= \frac{E_0}{p_a} \\ E_a[dB] &= -10\log(p_a) \qquad (4.21)\end{aligned}$$

where E_0 is the energy required to transmit a request once.

The Data channel throughput can be calculated by;

$$Th_{data} = \min\{L, Nst\} \qquad (4.22)$$

Data channel acceptance probability can be calculated by:

$$Pa_{data} = \frac{Th_{data}}{Na} \qquad (4.23)$$

The data channel average delay can be calculated by;

$$\tau_{data} = \frac{1-Pa_{data}}{Pa_{data}} \qquad (4.24)$$

The data channel average energy can be calculated by;

$$E_{data}[dB] = -10\log(Pa_{data}) \qquad (4.25)$$

4.4 Results

In the performance, we used, $N = 50$, number of bits = 500, $BER = 10^{-3}$, constant backoff probability is assumed with retransmission probability $c = 0.75$ and $k = 25$. Fig 4.7 and Fig 4.8 show the obtained results for the single class model. Fig. 4.7, shows the throughput of the single class. The throughput increases with the incoming traffic and starts to decrease in the heavy traffic which is natural since the resources are limited and the collided users are retransmitting.

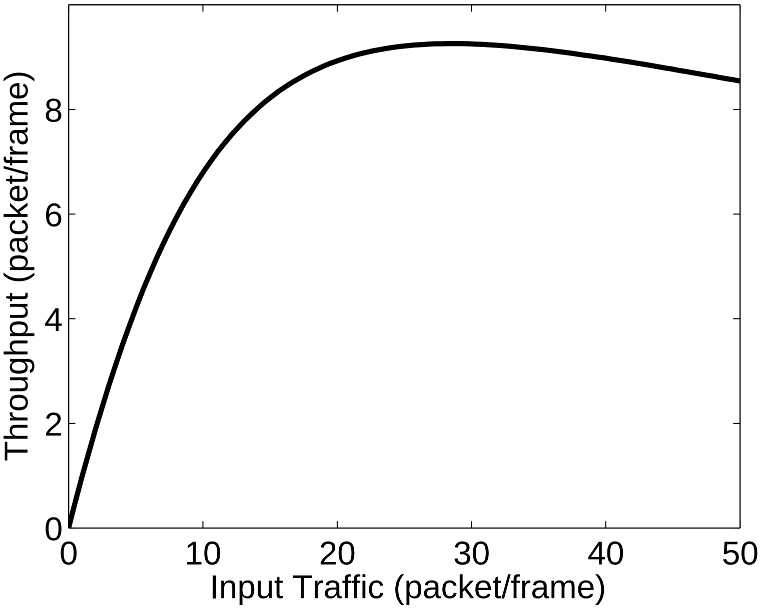
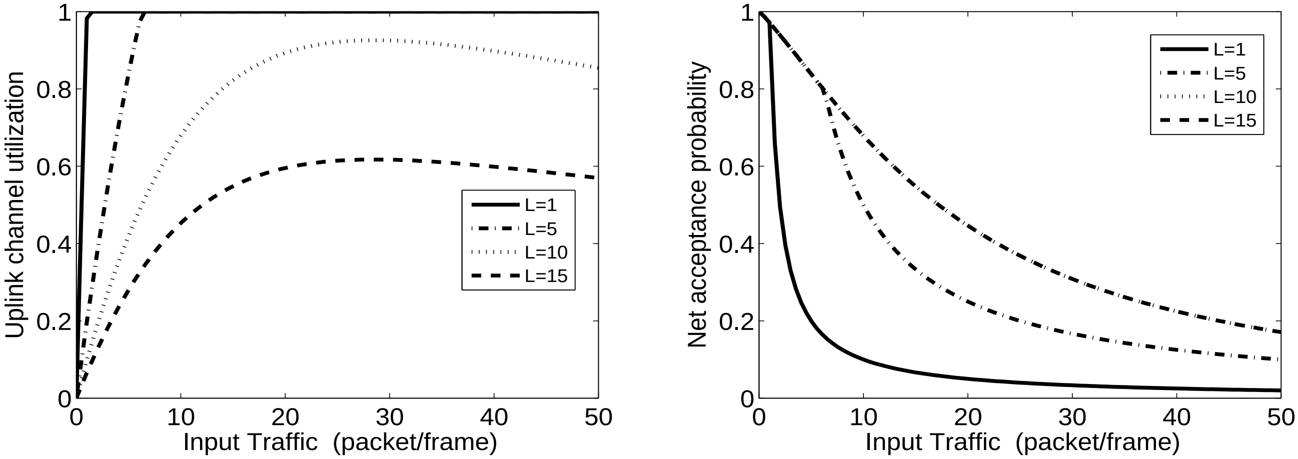


Figure 4.7: Requests throughput versus input traffic

Fig. 4.8a shows the uplink channel utilization when we vary $L \in \{1, 5, 10, 15\}$ When $L = 1$ which is a special case for IEEE802.11 we notice that the channel is fully utilized. When we increase L the uplink channel utilization is going down. That case is for multiple channel WLANs. Fig. 4.8b, shows the net acceptance probability for the single class model. When $L = 1$, 802.11a case, the net acceptance probability is lower compared to the other wireless multichannel standards. Since IEEE802.11a has only one channel its net acceptance probability is lower compared to other WLANs as the collision is higher and it has only one channel that the users send their traffic. As the number on access data channels is higher the net acceptance probability is closer (exactly) as the requests acceptance probability. Therefore, as we have more data channels (multiple access WLANs) almost all granted requests get their data transmitted.



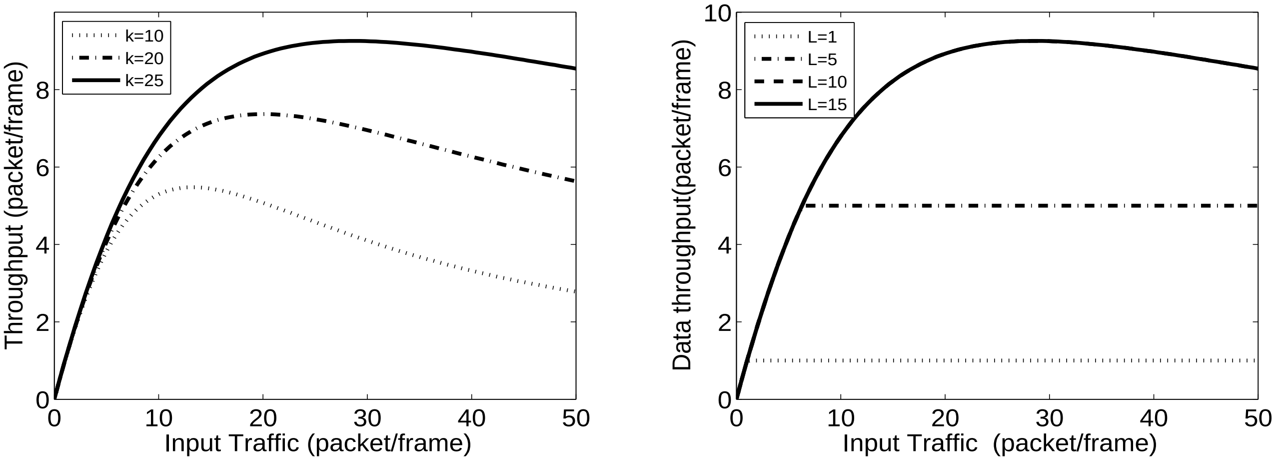
(a) Class one uplink utilization

(b) Net acceptance probability

Figure 4.8: Performance for single class model

Fig. 4.9 shows the requests and data throughput. In Fig. 4.9a, requests throughput ($L = 10$, $k = \in \{10, 20, 25\}$) is shown and it is not effected by varying the number of data channels L. It is only affected by the number of requesting channels k. As the number of requesting channels increases the requests throughput increases. However, in the heavy the offered load the requesting throughput decreases as a result of collision since the collided users retransmit. In Fig. 4.9b the data throughput is presented. In the figure we can see that as we vary the number of data channels L

the throughput increases until it reaches the value of the requests throughput. That means all the granted users requests' get their data transmitted. The worst data throughput is when we have only one data channel and that is a special case for IEEE802.11a.

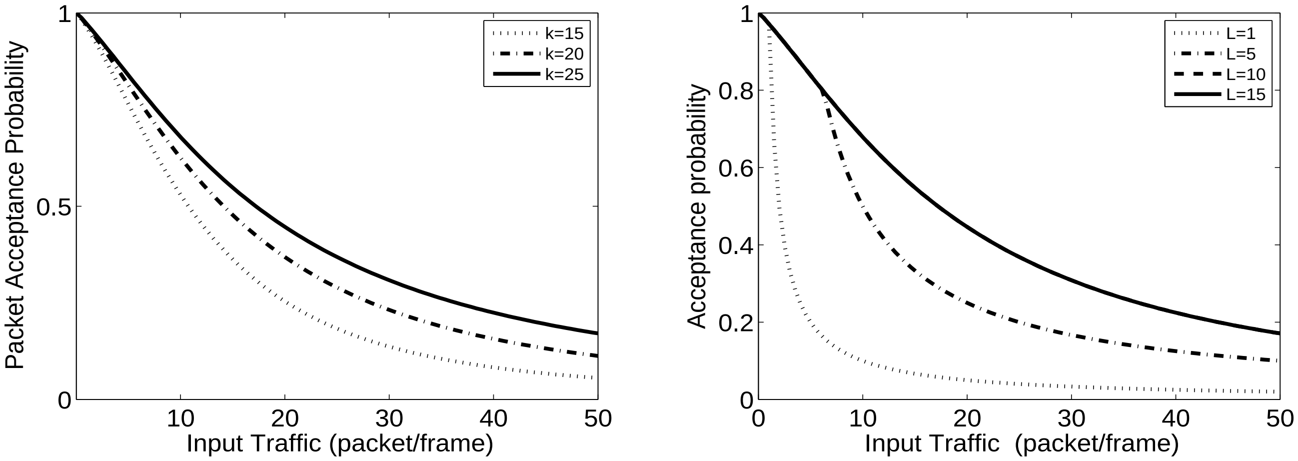


(a) Requests throughput

(b) Data throughput

Figure 4.9: Requests and data throughput

Fig. 4.10 shows the acceptance probability. The requests and data acceptance probability as at maximum value when we have a very small load and small number of users are requesting. However, as the load increase the acceptance probability decreases and this is normal since many users are competing for access and collision increases. The IEEE802.11a has the lowest acceptance probability since it only has one access channel and the collision is higher compared to other wireless standards. The requests and data acceptance probability are the same when we have many data channels and all successful requests get data channels to send their data. The acceptance requesting probability varies with number of requesting channels k and not affected by the number of data channels L.



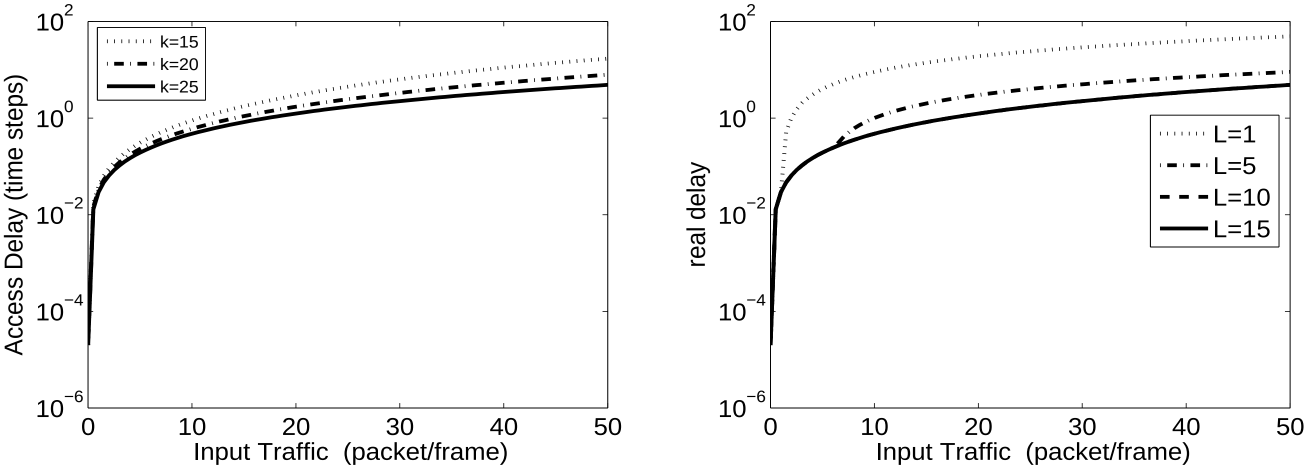
(a) Requests acceptance probability

(b) Data acceptance probability

Figure 4.10: Requests and data acceptance probability

Fig. 4.11 shows our results for the average access delay. The one channel standard encounters the longest delay. The delay decreases as the number of data channels increases until the average requests access delay is similar to the average data delay. The requesting delay decreases as the number of requesting channels increases. However, increasing the requesting channels affects the MAC frame duration and as a result the data transmission delay affected. The average energy comparison is shown in Fig. 4.12. The average request energy is the same as the data average energy when the number of data channels is high. However, the average data energy is higher when we have less number of data channels as shown in Fig. 4.12b.

The results for the last model when the error in the request channels is considered are presented in Fig 4.13 to Fig 4.16 In the performance results we assume we have $N = 50$, $b1 = 50$ bits, $b2 = 500$ bits, $L = 10$, $k = 25$ and $BER = \in \{10^{-2}, 10^{-3}, 0\}$. Fig. 4.13a shows the requests throughput. When the BER is zero the throughput is higher and it degrades as the BER is getting higher. Fig 4.13b shows the requests



(a) Requests delay (b) Data delay

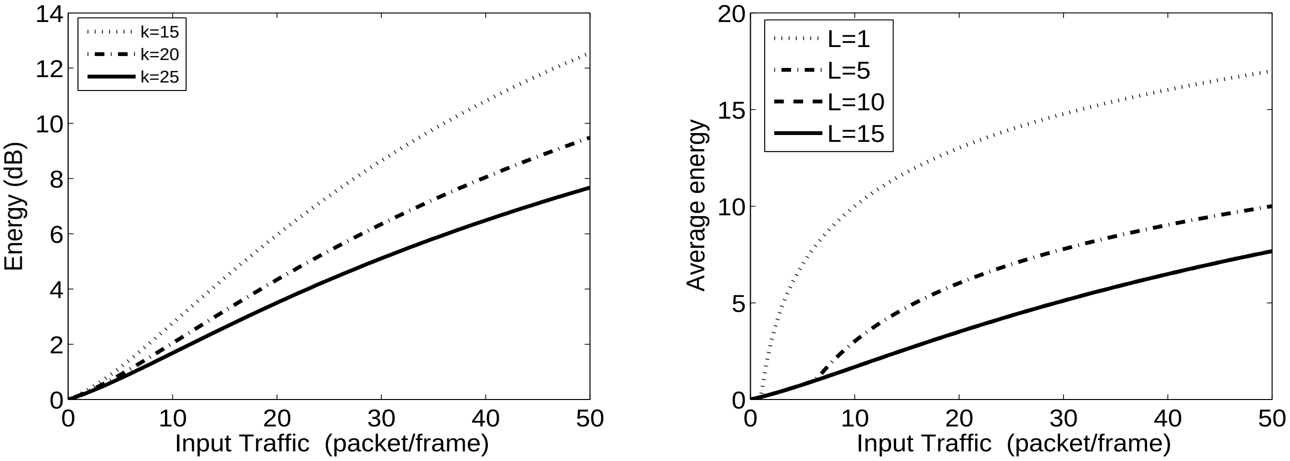
Figure 4.11: Requests and data delay

acceptance probability. The highest acceptance probability is obtained when the channel is error free but as the BER is getting higher the acceptance probability is getting lower.

Fig. 4.14a presents the requests average delay. The worst delay encountered when the BER is high is the SNR is low. When the channel is in better condition the delay is shorter. Fig. 4.14b shows the average requests energy. The highest energy users have to consume is when the BER is high and it is getting lower as the BER improves.

The data channels throughput as shown in Fig. 4.15a is at it is higher value in the better channel condition and is degrades as the channel condition deteriorated. The data channels and request channels are similar when we allocate more data channels. Fig 4.15b shows the data channels acceptance probability. We can obtain higher acceptance probability when the channel condition is better.

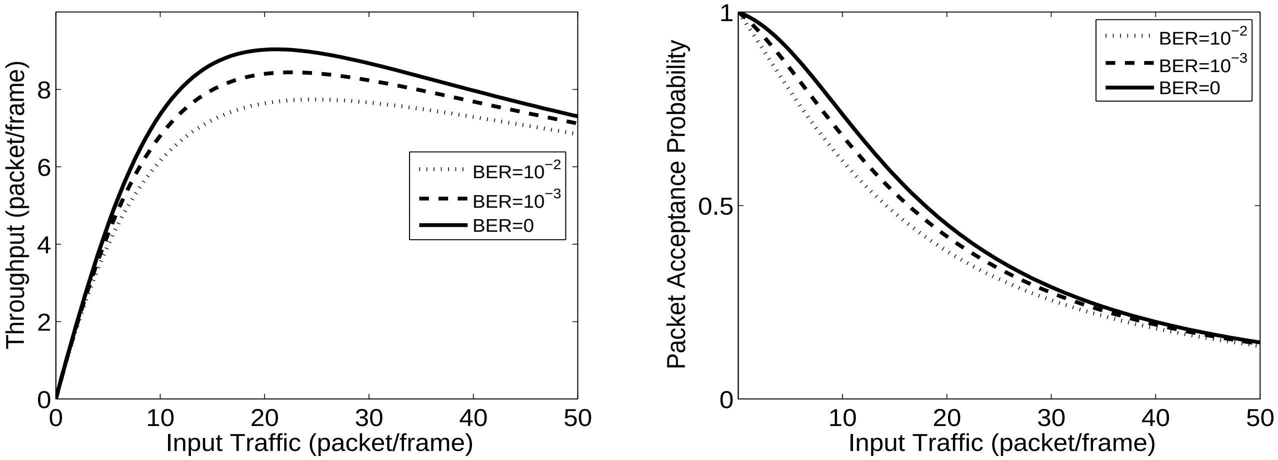
Fig. 4.16a shows the data channels average energy. When the BER is low the



(a) Requests energy

(b) Data energy

Figure 4.12: Requests and data energy

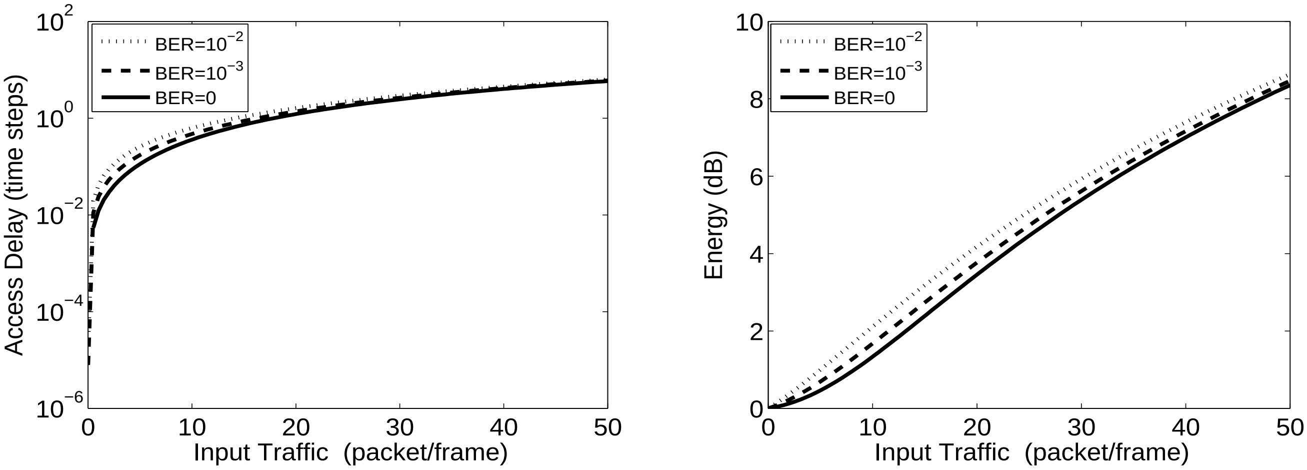


(a) Requests throughput

(b) Requests acceptance probability

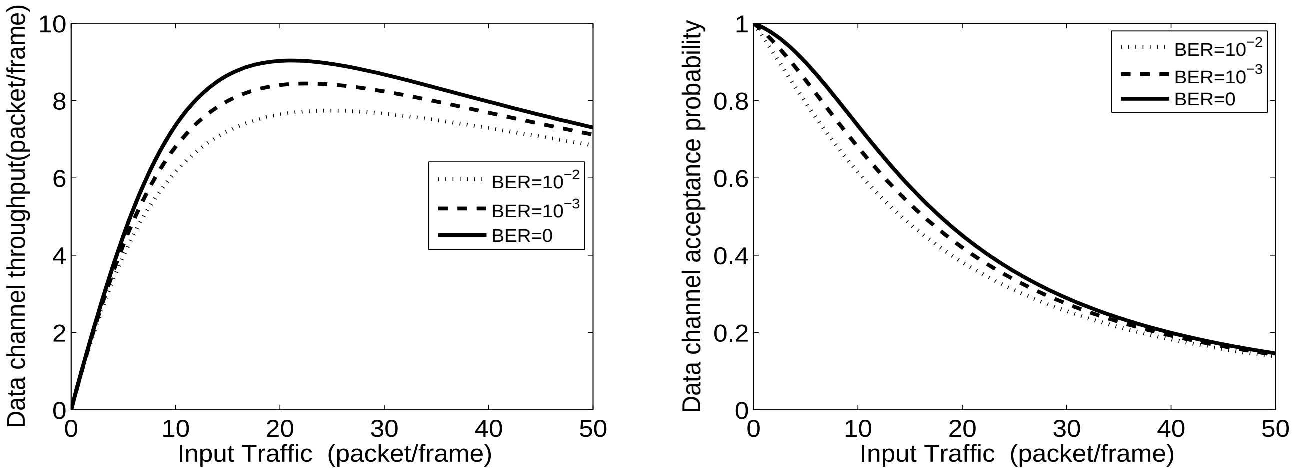
Figure 4.13: Requests throughput and acceptance probability versus input traffic

channel performs better. However, when the BER is high the consumed energy is



(a) Requests average delay (b) Requests average energy

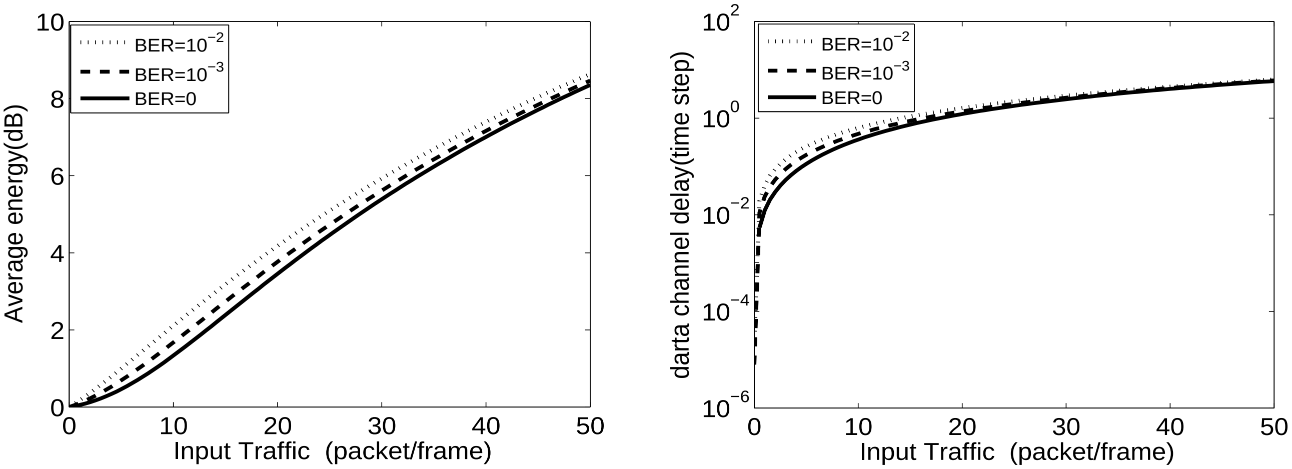
Figure 4.14: Requests average delay and energy versus input traffic



(a) Data channels throughput (b) data channel acceptance probability

Figure 4.15: Data channels throughput and acceptance probability versus input traffic

higher. In a similar trend, Fig. 4.16b shows the data channels average delay. We can notice that the average delay is higher when the BER is high and the average delay is less as the channel condition improves.



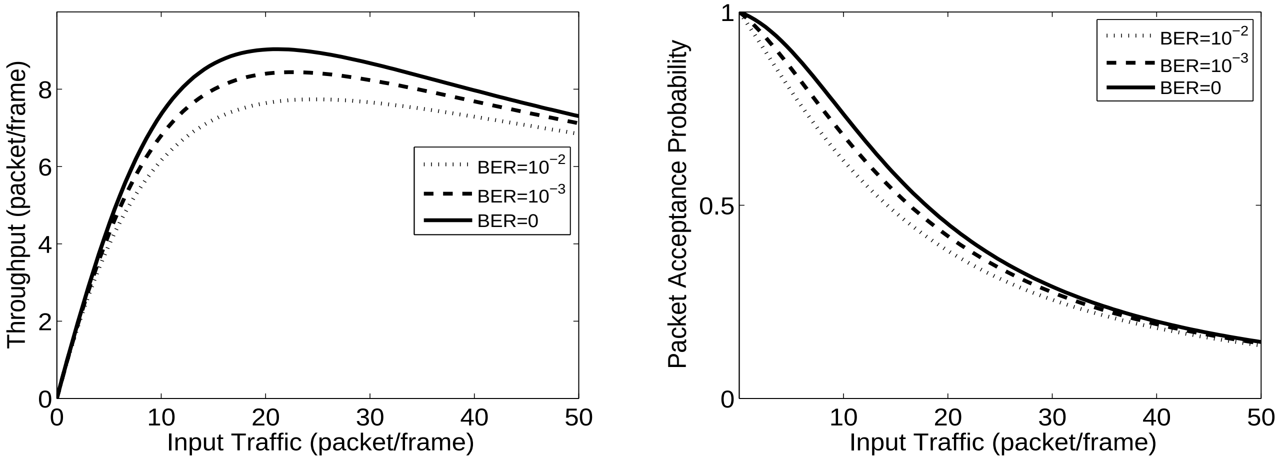
(a) Data channels average energy

(b) Data channels average delay

Figure 4.16: Data channels average energy and delay versus input traffic

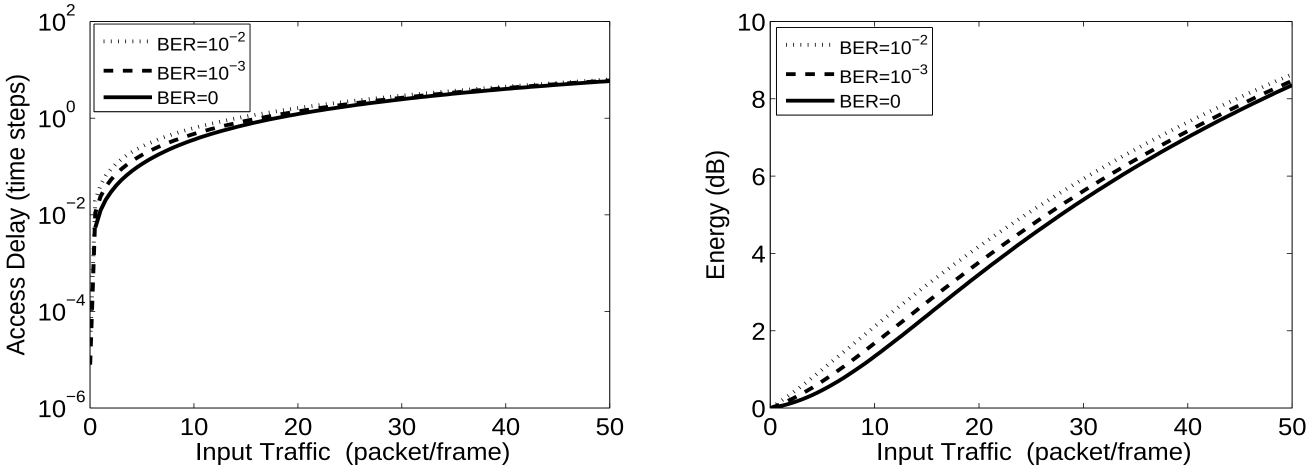
When the number of channels reduced to $L = 5$ we obtain the results shown in Fig 4.17 to Fig 4.20. As the number of data channels is limited the requests performance stayed unaffected since it is independent of the number of data channels. However, the data channels performance is affected. Fig. 4.19a shows the requests throughput is it similar to the requests throughput that we obtained in Fig. 4.15a when we have $L = 10$. The requests acceptance probability is also the same since the requests performance are affected by varying the number or requesting channels not by varying the number of data channels

Fig 4.18a shows the requests delay and 4.18b shows the requests average energy when we assume that we have $L = 5$. The performance of the request performance similar to the one we obtained earlier when when have $L = 10$



(a) Data channels throughput (b) Data channels acceptance probability

Figure 4.17: Data channels throughput and acceptance probability versus input traffic

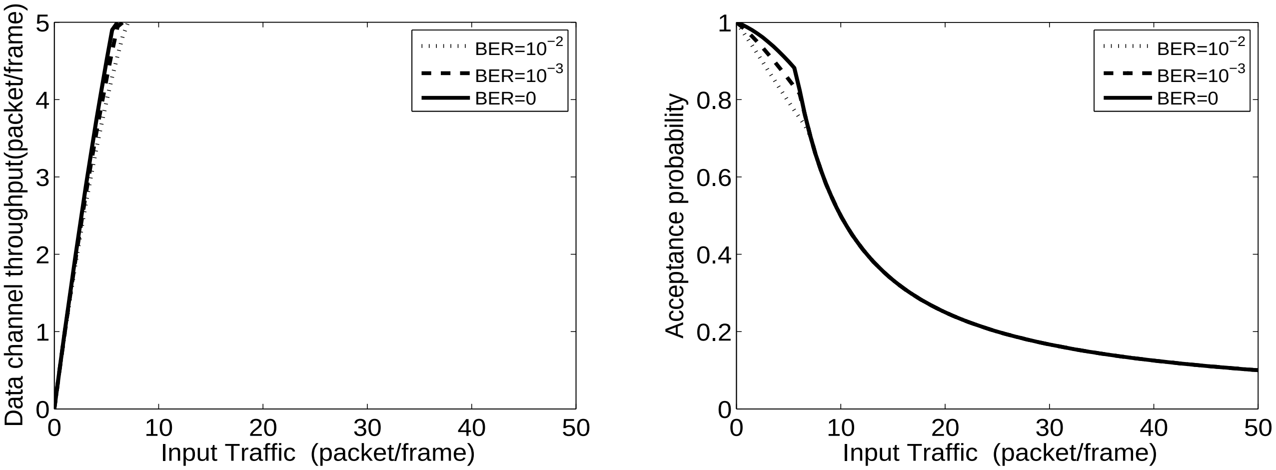


(a) Requests access delay (b) Requests average energy

Figure 4.18: Requests delay and average energy versus input traffic

The data channels performance when we allocate $L = 5$ is shown in Fig. 4.19 and

Fig. 4.20. The data channels throughput is limited to the number of data channels. The throughput when the BER is low is better compared to the throughput when the BER is higher. In a similar trend the data acceptance probability is better when we have lower BER.

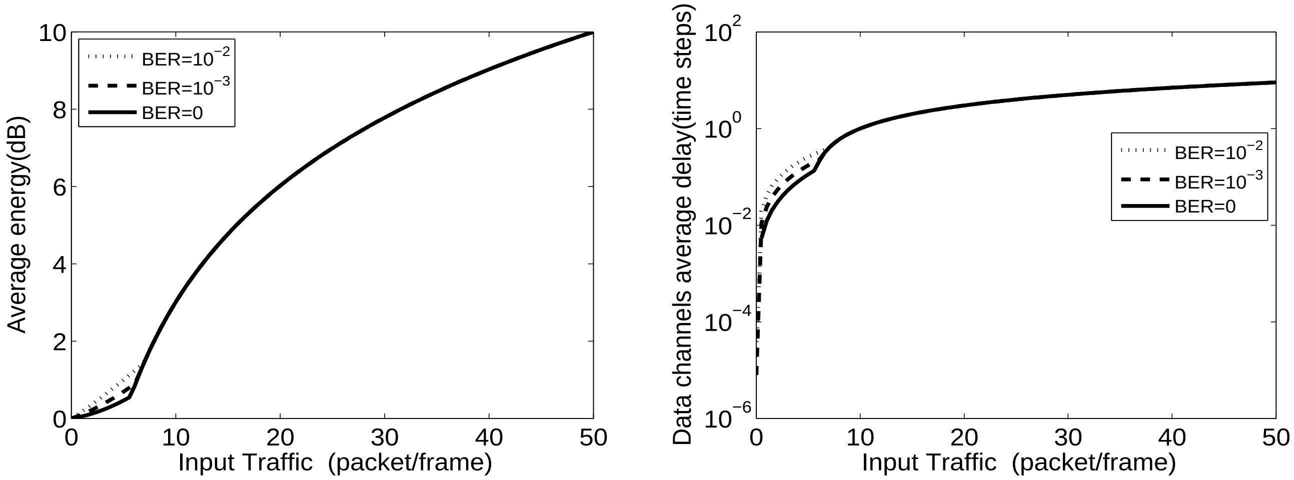


(a) Data channels throughput

(b) Data channels acceptance probability

Figure 4.19: Data channels throughput and acceptance probability versus input traffic

The consumed average data channel is lower when we have lower BER, and it is higher as the BER is high. The average data channel delay is shown in Fin 4.20b. The delay is longer when we have higher BER and it is lower when BER is low.



(a) Data channels average energy

(b) Data channels average delay

Figure 4.20: Data channels average energy and delay versus input traffic

4.5 Chapter Summary

In this chapter we developed a model for the uplink channel utilization. We also studied the net acceptance probability for this model. In this model the uplink is fully utilized when we have only one access data channel as in IEEE802.11a. However, the utilization is lower when we have multiple access channel WLAN standard such as WiMAX and Hiperlan 2. Furthermore, the net acceptance of one class model is lower when the transmitted data is low and the net acceptance probability is higher as the data transmission is higher. We also concluded that as the number of access data channels getting higher the net acceptance probability is getting close to the requests acceptance probability. Therefore, all granted requests will get their data transmitted. the uplink channel utilization reaches full channel utilization when we have only one channel which is a special case for IEEE802.11a and the utilization starts to go down as we have more channels. This model can be applied into different wireless standards. This work is published in [15]. We also developed a model for request mechanism and data transmission channels in wireless networks. We studied the impact of varying several parameters such as the requesting channels and the data channels. The requests performance in dependant only on the number of requesting channels whereas the data performance is depended only on the data channels. the requesting channels is independent of the data channels. As the number of requesting channels increases the performance of the requests improved and vise versa. Also, the data performance improved as the number of data channels increases. However, we can not allocate many number of requests channels since that is affects the data channels. So, the balance point between the number of requesting channels and data channels is a challenge. We noticed that the single channel wireless standard performs badly compared to multichannel standards. This work is published in [16]. Finally, when we consider the channel error both in the request and in the data transmission. The performance of the model is affected by the channel condition. When the BER is higher the throughput for the requests and the data is lower. The data transmission performance is affected more since the SS has to retransmit its data packets again. However, the requests performance is also affected as the users has to re-issue a request again.

Chapter 5

Modeling Quality of Service in Wireless Networks

This chapter presents the third contribution of this dissertation which is the quality of service support in infrastructure wireless LANs. We propose a Quality of service model with error control protocol. In this chapter we demonstrate that certain class of traffic gets better quality of service than other class. We use Markov chain modeling. We classify our traffic into two classes and evaluate the performance of our model. We also investigate the effects of several parameters on the performance of the model. We also applied our proposed backoff strategies and we applied our proposed error control protocol on our proposed quality of service model.

This chapter is organized as follow: Section 5.1, presents the proposed quality of service model and, analysis and performance. In this section we will present our developed backoff strategies on the quality of service model. In section 5.2 we present our error control protocol that is enhanced our quality of service model. In Section 5.3, we present our results and Section 5.4 presents our chapter summary.

5.1 Constant Backoff Probability Model with QoS Support

In this section we propose quality of service model for our proposed backoff strategy models. In this model, we assume that we have N users try to request access on the random channels. The number of random channels is k. The MAC frame is divided into control and data logical channels and random request channels as shown in Fig. 5.1. Users request access to MAC frame through the k random access channels and send their data through the data channels. The random access channels k is split into two groups k_1 and k_2, where $k_2 < k_1$ as shown in Fig. 5.2. Traffic is classified into two classes, high priority class and low priority class. From the figure, high priority class traffic compete for access on k_1 random access channels and low priority traffic compete for access on k_2 random access channels as shown in Fig. 5.2. An MT that has data to send selects one of k_1 random access channels if it is from high priority class and selects one of the k_2 random access channels if it is from low priority class.

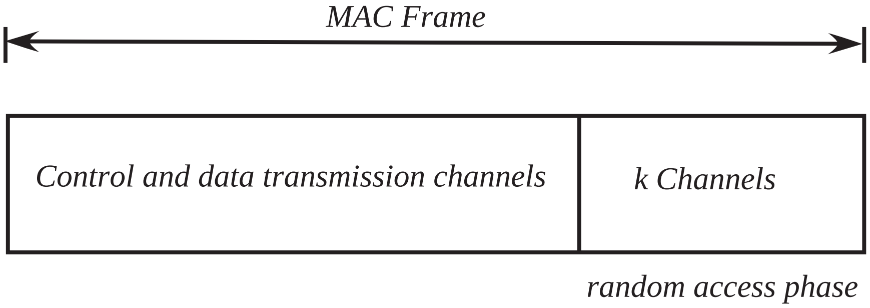


Figure 5.1: Logical channels in a MAC frame

An arriving packet belongs to high priority class with probability l and belongs to low priority class with probability $1 - l$. Collision may occur if two or more MTs choose the same channel. In order to analyze the system behavior some assumptions are made;

1. The probability that a user issues a request is a

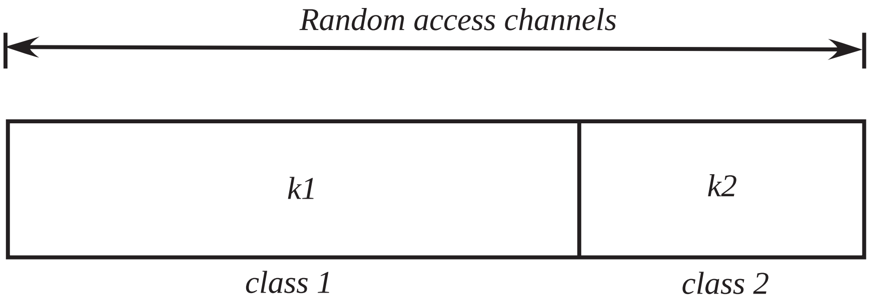


Figure 5.2: Logical channels with two classes of users

2. The probability that a packet from high priority class chooses a particular channel is $1/k_1$ and $1/k_2$ for low priority class.

3. The collided user from high priority class retransmit with probability c_1 and from low priority class is c_2.

4. We assume a non-preemptive traffic where the high class traffic will not interrupt low class traffic while it is in service.

An MT could be in one of the three states; *transmit* state, if a single request is received or *collide* state, if two or more MTs issue requests on the same channel or *idle* state if there is no request has been received. Fig. 5.3 shows the Markov chain state diagram for the user. There are two classes of traffic.

From Fig. 5.3, x_1 is the probability that a user from class one accesses successfully one of the k_1 random channels. x_1 is given by:

$$x_1 = \left(1 - \frac{1}{k_1}\right)^{N_{1a}-1} \tag{5.1}$$

where N_{1a} is the average number of active users from high priority class (class one) and it calculated by:

$$N_{1a} = N(l \times a \times s_i + c_1 \times s_{c1}) \tag{5.2}$$

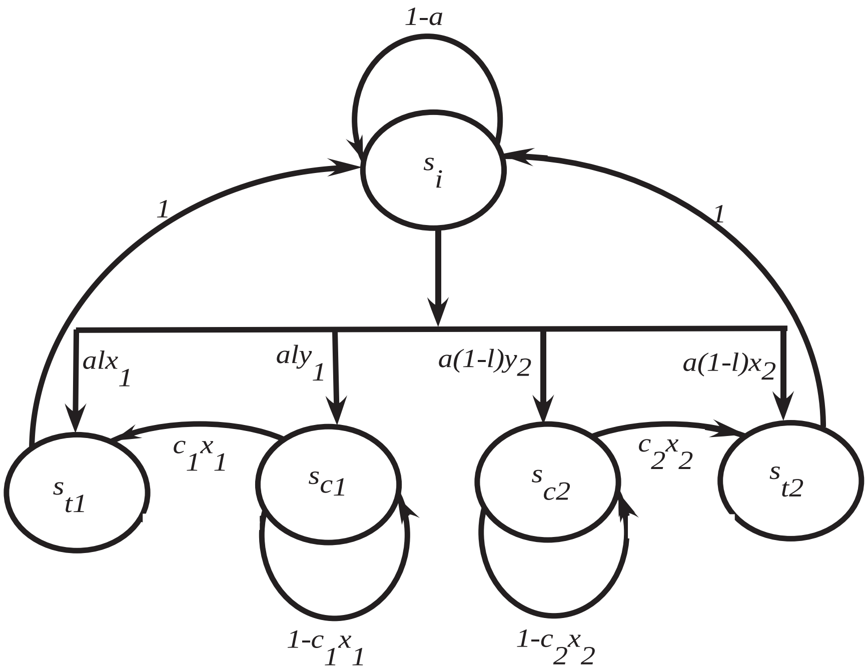


Figure 5.3: Markov state diagram for a user

The probability that the user from class one (high priority) select a busy channels is given by:

$$y_1 = 1 - x_1 \tag{5.3}$$

x_2 is the probability that a user from low priority class (class two) successfully accesses one of the k_2 random channels. x_2 with binomial distribution is given by:

$$x_2 = \left(1 - \frac{1}{k_2}\right)^{N_{2a}-1} \tag{5.4}$$

N_{2a} is the average number of active users from class two(low priority), and calculated by:

$$N_{2a} = N((1-l) \times a \times s_i + c_2 \times s_{c2}) \tag{5.5}$$

The probability that a user from class two selected one of the busy channels is given by:

$$y_2 = 1 - x_2 \tag{5.6}$$

The allocated channels for the two classes are allocated by:

$$k_1 = \left\lfloor \frac{l \times m}{l \times m + (1-l)} k_{max} \right\rfloor \tag{5.7}$$

$m > 0$, and the allocated channels for the second class are calculated by:

$$k_2 = k_{max} - k_1 \tag{5.8}$$

where m is the weight factor to determine the number of channels allocated to both classes and k_{max} is the maximum number of random access channels.

5.1.1 System Analysis

A discrete-time Markov chain is characterized by the transition matrix **P** and the state vector **s** [84]. The state vector for a user **s** is organized as:

$$\mathbf{s} = [s_i \quad s_{t1} \quad s_{c1} \quad s_{t2} \quad s_{c2}]^t \tag{5.9}$$

where s_i is the probability that a user is in the *idle* state, s_{c1} is the probability that the user from class one is in the *collide* state and s_{t1} is the probability that the user from class one is in the *transmit* state. On the other hand, s_{c2} is the probability that the user from class two is in the *collide* state and s_{t2} is the probability that the user from class two is in the *transmit* state. The corresponding state transition matrix of the users which is extracted from the state transition diagram shown in Fig. 5.3 is given by:

$$P = \begin{bmatrix} 1-a & 1 & 0 & 1 & 0 \\ aly_1 & 0 & 1-c_1x_1 & 0 & 0 \\ alx_1 & 0 & c_1x_1 & 0 & 0 \\ a(1-l)y_2 & 0 & 0 & 0 & 1-c_2x_2 \\ a(1-l)x_2 & 0 & 0 & 0 & c_2x_2 \end{bmatrix} \tag{5.10}$$

At equilibrium, the distribution vector elements are obtained by solving the following two equations [84]:

$$\mathbf{P}\mathbf{s} = \mathbf{s} \tag{5.11}$$

$$\sum s_j = 1 \tag{5.12}$$

$j \in \{i, t1, c1, t2, c2\}$ From Eqs. (5.10), (5.11) and (5.12) we can find the state vector elements at equilibrium.

$$s = \frac{1}{D_n}[1 \quad alx_1(1+y_1c_1) \quad aly_1 \quad a(1-l)x_2(1+y_2c_2) \quad a(1-l)y_2]^t \tag{5.13}$$

where D_n is

$$D_n = 1 + aly_1 + alx_1(1+y_1c_1) + a(1-l)y_2 + a(1-l)x_2(1+y_2c_2) \tag{5.14}$$

5.1.2 Applying Backoff Strategies for QoS

In this subsection, two backoff strategy models are applied. Instead of fixing the retransmission probability c to a certain value, the collided users can retransmit with other probabilities. We name these backoff models as proportional backoff probability and complementary backoff probability models. The following items discuss these two models.

1. Proportional backoff probability with QoS support. In this model, all the assumption in Section 5.1 are valid except that the collided users retransmission probability is changed. The BS monitors the arriving request and based on this information the number of users N and the frame arrival probability a are determined. Based on these two values, the backoff probability c is chosen and broadcasted to all SSs .In this model, the retransmission probability is:

$$c(i) = a \qquad \text{i=1,2} \tag{5.15}$$

2. Complementary backoff probability with QoS. In this model, all the assumption in Section 5.1 are valid except that the collided users retransmission probability is changed. The BS monitors the arriving request and based on this information the number of users N and the frame arrival probability a are determined. Based on these two values, the backoff probability c is chosen and broadcasted to all SSs. In this model, the retransmission probability is:

$$c(i) = 1 - a \qquad \text{i=1,2} \tag{5.16}$$

5.1.3 Model Performance

Based on the system analysis, we study the performance of this model measured by the throughput, acceptance probability, access delay and energy.

The requests throughput for both classes can be calculated as follows:

$$Th_1 = \min\left(Ns_{t_1}, k_1\right) \tag{5.17}$$

$$Th_2 = \min\left(Ns_{t_2}, k_2\right) \tag{5.18}$$

The requests acceptance probability is defined as the ratio between the throughput and the offered load [84]:

$$p_{a_1} = \frac{Th_1}{l \times N \times a} \tag{5.19}$$

$$p_{a_2} = \frac{Th_2}{(1-l) \times N \times a} \tag{5.20}$$

The requests access delay ($D_{1,2}$) is the average number of access attempts made by an MT before it is successfully granted an access. It is defined as:

$$D1 = \frac{1 - p_{a1}}{p_{a1}} \tag{5.21}$$

$$D_2 = \frac{1 - p_{a2}}{p_{a2}} \tag{5.22}$$

The average energy $E_{a1,a2}$ required to transmit a request successfully can be calculated as follows [85]:

$$E_{a1} = \frac{E_0}{p_{a1}} \tag{5.23}$$

where E_0 is the energy required to transmit a request once. Normalizing relative to E_0, average energy in dB is given by:

$$\begin{aligned} E_{a1}[dB] &= -10\log(p_{a1}) && (5.24)\\ E_{a2} &= \frac{E_0}{p_{a2}} \\ E_{a2}[dB] &= -10\log(p_{a2}) && (5.25) \end{aligned}$$

5.2 Error Control Protocol Model with QoS Support

In this section, we develop an error control model for the QoS support model developed in Section 5.1. All access schemes in Section 5.1 are valid except for the transmission states. In the transmission states the user keep sending the packets in error n times from either class as shown in Fig. 5.4.

Fig. 5.4 shows the Markov chain state diagram for the user. There are two classes of traffic. In order to analyze the system behavior some assumptions are made in addition to the assumption made in Section 5.1;

1. The probability that the transmitted packet contained error is e.
2. The forward channel (from SS to BS) has random noise and the probability that a bit will be received in error is ϵ, (BER).
3. The feedback channel (from BS to SS) is error free.

   The error control states as shown in Fig. 5.4 represented by s_{t1} until s_{tn} have the following properties:

(a) State s_{ti} indicates that the MT is retransmitting the packet for the i^{th} time.

(b) The number of retransmission states is n.

(c) The time step is taken equal to the sum of transmission delay (time required to send a packet) and round trip delay (time required for packet propagation and reception of acknowledgment) .

The error is calculated by;

$$e = 1 - (1 - \epsilon)^b \tag{5.26}$$

where b is the number of bits.

Assume x_1 and x_2 defined as in Eqs. 5.1 and 5.4, respectively. The average number of active users from each class N_{1a} and N_{2a} are calculated by Eqs. 5.2 and 5.5, respectively.

5.2.1 Model Analysis

A discrete-time Markov chain is characterized by the transition matrix $\mathbf{P}$ and the state vector $\mathbf{s}$ [84]. The state vector $\mathbf{s}$ for the user is organized as:

$$\mathbf{s} = [s_i \quad s_{t1} \quad s_{t2} \quad s_{t3} \quad \cdots s_{tn} \quad s_{c1} \quad s'_{t1} \quad s'_{t2} \quad s'_{t3} \quad \cdots \quad s'_{tn} \quad s_{c2}]^t \tag{5.27}$$

where s_i is the probability that the user is in the *idle* state, s_c is the probability that the user is in the *collide* state and s_{ti} is the probability that the user is in the *transmit* state from high priority class users and s'_{ti} is the probability that the user from low priority class is in the *transmit* state. The MT will keep sending the packet contained if there is no acknowledgment is received (i.e the packet sent with an error probability e). When a packet is correctly received the MT goes to *idle* state with probability $1-e$. The corresponding state transition matrix for the user which is extracted from the state transition diagram shown in Fig. 5.4 is given by:

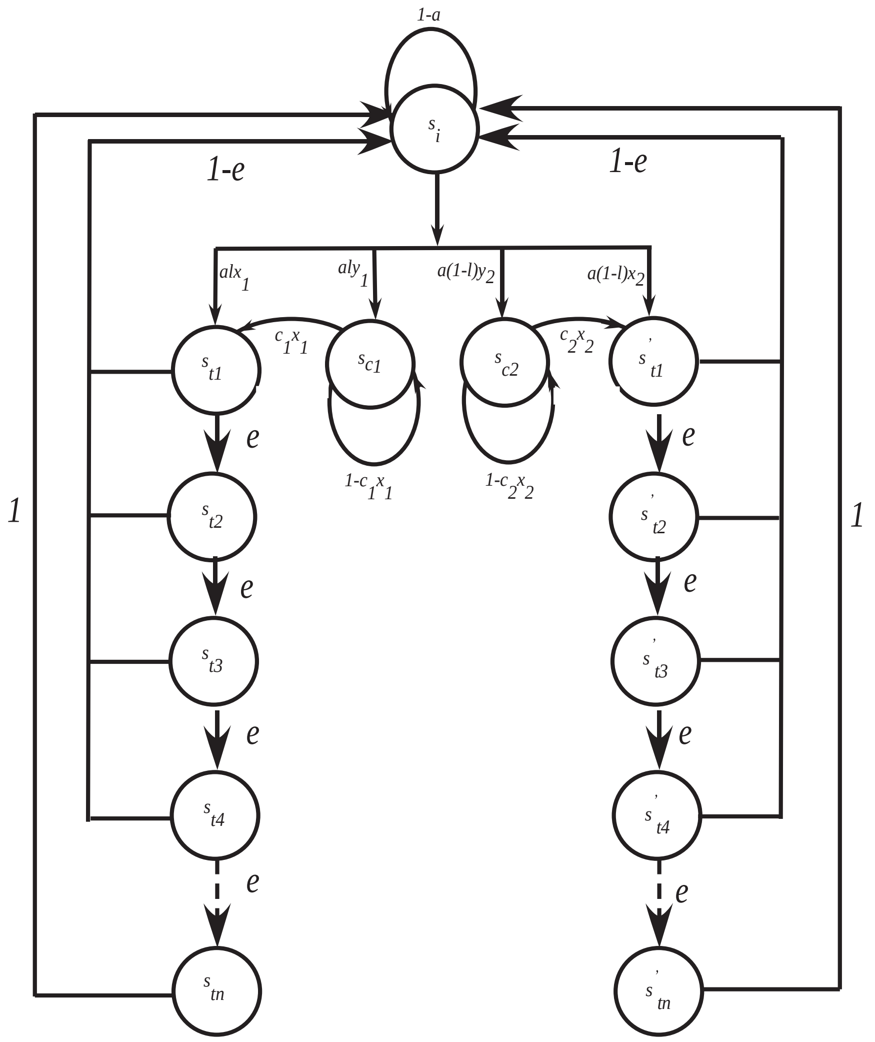


Figure 5.4: Markov state diagram for users of two-class

$$\mathbf{P} = \begin{bmatrix} 1-a & 1-e & \cdots & 1 & 0 & 1-e & 1-e & \cdots & 1 & 0 \\ alx_1 & 0 & \cdots & 0 & c_1x_1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & e & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 & 0 \\ \vdots & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & \vdots & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 & 0 \\ aly_1 & 0 & \cdots & 0 & 1-c_1x_1 & 0 & 0 & \cdots & 0 & 0 \\ a(1-l)x_2 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 & c_2x_2 \\ 0 & 0 & \cdots & \vdots & 0 & e & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & e & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 & \vdots & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & \vdots & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & \vdots & 0 \\ a(1-l)y_2 & 0 & \cdots & 0 & 0 & 0 & 0 & \cdots & 0 & 1-c_2x_2 \end{bmatrix} \tag{5.28}$$

from the state diagram we can find the steady state distribution vector elements:

$$\begin{aligned} s_{t1} &= alx_1s_i + c_1x_1s_{c1} \\ s_{t2} &= es_{t1} \\ s_{t3} &= es_{t2} \\ s_{tn} &= es_{t(n-1)} \\ s_{c1} &= aly_1s_i \\ s'_{t1} &= a(1-l)x_2s_i + c_2x_2s_{c2} \\ s'_{t2} &= es'_{t1} \\ s'_{t3} &= es'_{t2} \\ s'_{tn} &= es'_{t(n-1)} \\ s_{c2} &= a(1-l)y_2s_i \end{aligned} \tag{5.29}$$

At equilibrium, the distribution vector elements are obtained by solving the following two equations [84]:

$$\begin{aligned} \mathbf{Ps} &= \mathbf{s} && (5.30) \\ \sum s_j &= 1 && (5.31) \end{aligned}$$

$j \in \{i, t1, t2, \cdots, tn, c1, t1', t2', \cdots, tn', c2\}$ by solving Eqs. (5.28), (5.30) and (5.31) we can find the state vector elements at equilibrium

$$s = \frac{1}{D_{n1}}[1 \ \ B_1 \ \ eB_1 \ \ e^2B_1 \ \ \cdots e^{n-1}B_1 \ \ aly_1B_2 \ \ eB_2 \ \ e^2B_2 \ \ \cdots e^{n-1}B_2 \ \ a(1-l)y_2]^t \tag{5.32}$$

where

$$D_{n1} = [1+B_1+eB_1+e^2B_1+\cdots+e^{n-1}B_1+aly_1+B_2+eB_2+e^2B_2+\cdots+e^{n-1}B_2+a(1-l)y_2] \tag{5.33}$$

$$\begin{aligned} B_1 &= alx_1 + c_1x_1aly_1 \\ B_2 &= a(1-l)x_2 + c_2x_2a(1-l)y_2 && (5.34) \end{aligned}$$

5.2.2 Performance of Error Control Protocol Model

The performance of the error control protocol is measured by the average number of retransmission of a packet and the efficiency. The average number of retransmission for each class is given by [84]:

$$\begin{aligned} N_{t1} &= s_{t1} + 2s_{t2} + 3s_{t3} + \cdots ns_{tn} \\ &= eB_1 + 2e^2B_1 + 3e^3B_1 \cdots ne^nB_1 \\ &= \sum_{i=1}^{n} ie^iB_1 \ \ \text{retransmissions/packet} && (5.35) \\ N_{t2} &= s'_{t1} + 2s'_{t2} + 3s'_{t3} + \cdots ns'_{tn} \end{aligned}$$

$$\begin{aligned} &= eB_2 + 2e^2B_2 + 3e^3B_2 \cdots ne^nB_2 \\ &= \sum_{i=1}^{n} ie^iB_2 \;\; \text{retransmissions/packet} \end{aligned} \tag{5.36}$$

The efficiency for each class calculated by [84]:

$$\eta_1 = \frac{1}{1+N_{t1}} \tag{5.37}$$

$$\eta_2 = \frac{1}{1+N_{t2}} \tag{5.38}$$

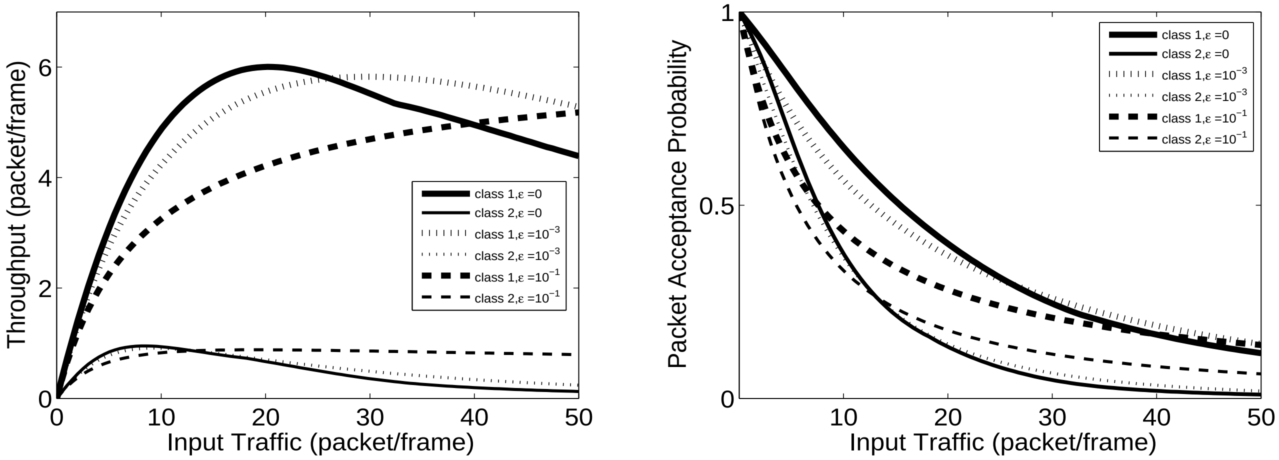
For the error free channel $e = 0$ and the average number of retransmissions is 0. That means the packet is sent only once for a successful transmission.

5.3 Results

This section presents our results for the proposed models. The parameters used in the analysis are as follows: $N = 50$, $k_{max} = 20$, $c1 = c2 = 0.75$, $l = 0.75$, $m = 2$, $\epsilon \in \{0, 10^{-3}, 10^{-1}\}$ and the number of bits $b \in \{1000, 1500\}$.

Fig. 5.5 to Fig. 5.7 show the results for 1000 bits whereas Fig. 5.8 to Fig. 5.10 show the results for 1500 bits.

Fig. 5.5 shows the throughput and the acceptance probability for 1000 bits, with different BER. The throughput of the high priority class is higher than that of the low priority class. As the BER increases the throughput rise up since the number of retransmissions increases. Therefore, the packets will be send at the end. However, when the BER is low the throughput is decaying at the very high load. The acceptance probability for the high priority class traffic is better than that of low class traffic. However, the acceptance probability when the BER is high is lower than that when the BER is low in the low offered load. Moreover, the acceptance probability for high BER is improved in the high load because or the number of retransmissions is high.



(a) Number of bits 1000

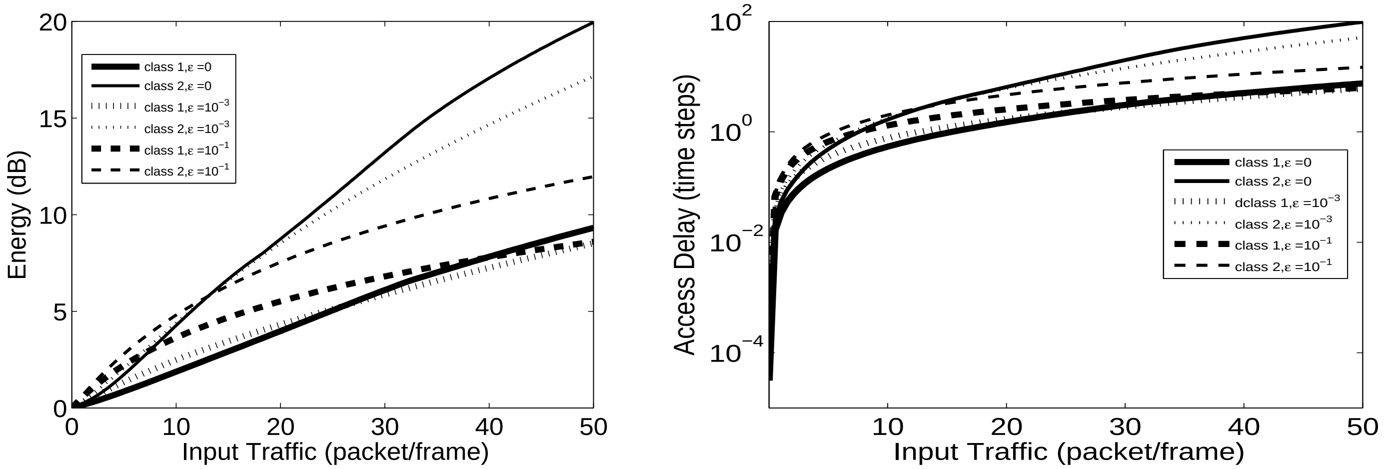
(b) Number of bits 1000

Figure 5.5: Throughput and acceptance probability versus input traffic.

Fig. 5.6 shows the energy and the access delay for 1000 bits, with different BER. The energy consumed by the low priority class users for successful transmission is higher compared to that for high priority class traffic since the allocated channels are higher. For higher BER the energy is improving at higher load because of the acceptance probability improvement. In the access delay, the longest access delay is marked for low priority traffic due to low number of allocated channels. Regarding the impact of BER, as the offered load is getting higher, the delay for high BER is getting better than that of low BER due to the acceptance probability improvement.

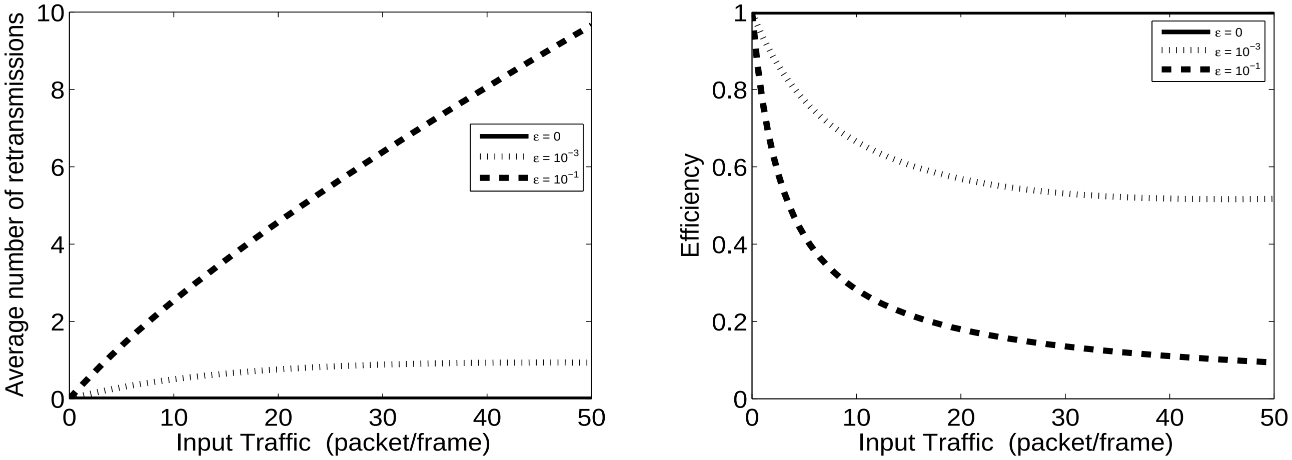
Fig. 5.7 shows the overall retransmissions and the efficiency. The average number of retransmissions increases as the BER increases since there are more packets are received in errors. The efficiency decreases as the BER increases since the number of retransmission is higher when the BER is higher.

Fig. 5.8 shows the throughput and the acceptance probability for 1500 bits, with different BER. When there are more packets, the throughput when the channel in



(a) Number of bits $n = 1000$ (b) Number of bits $n = 1000$

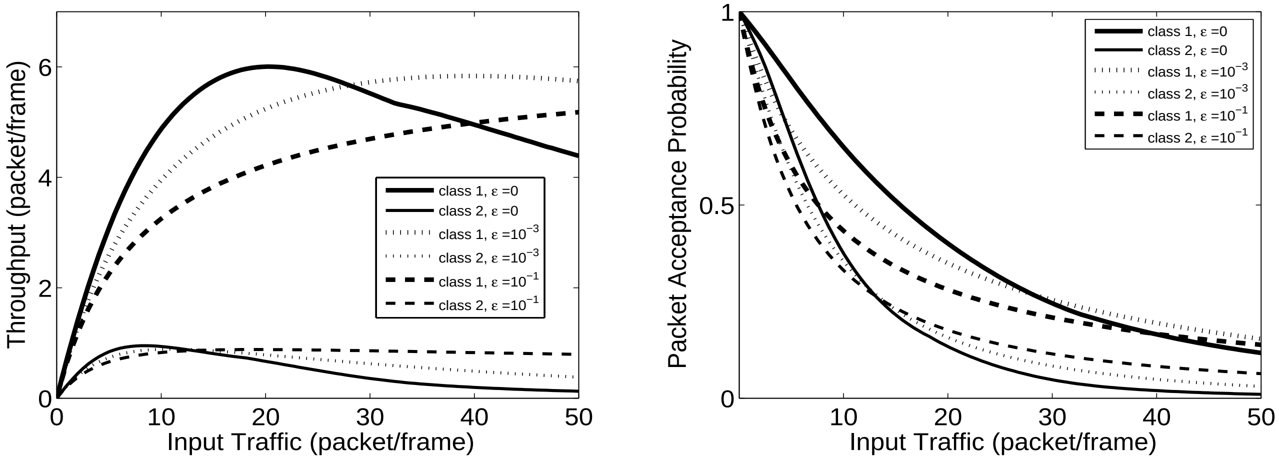
Figure 5.6: Energy and access delay versus input traffic.



(a) Number of bits $n = 1000$ (b) Number of bits $n = 1000$

Figure 5.7: Average number of retransmissions and the efficiency versus input traffic.

error is increasing since the retransmissions are higher and more packets will be send. The acceptance probability is also better when we have more packets as shown in Fig. 5.8.



(a) Number of bits $n = 1500$

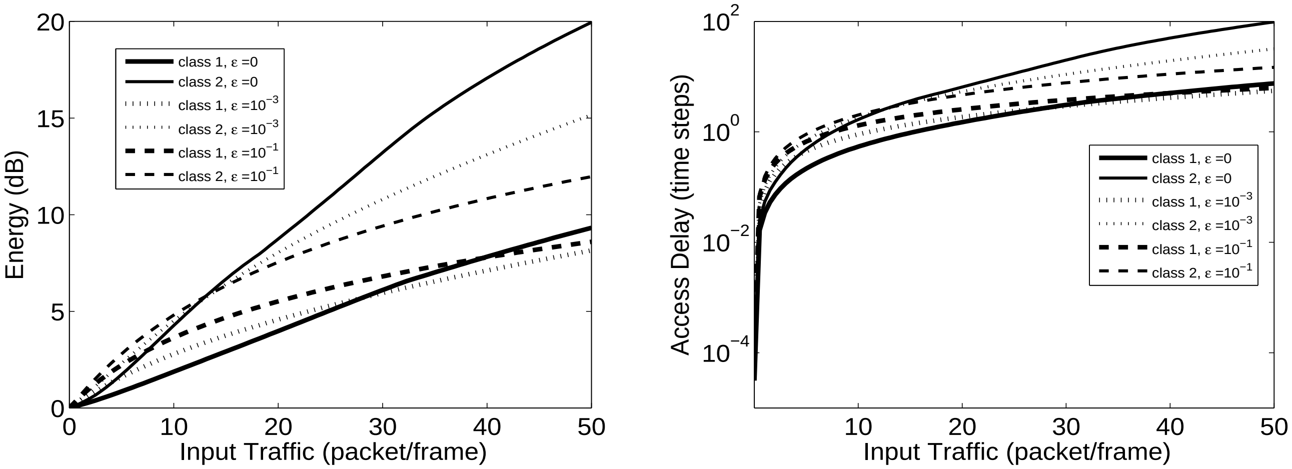
(b) Number of bits $n = 1500$

Figure 5.8: Throughput and acceptance probability versus input traffic.

Fig. 5.9 shows the energy and the access delay for 1500 bits, with different BER. The energy consumed to grant access when the channel is error free is the same as when we have 1000 bits. However, the energy is a bit lower since the retransmissions is more and the throughput is better as a results we have a bit of lower energy consumption and also a shorter delay.

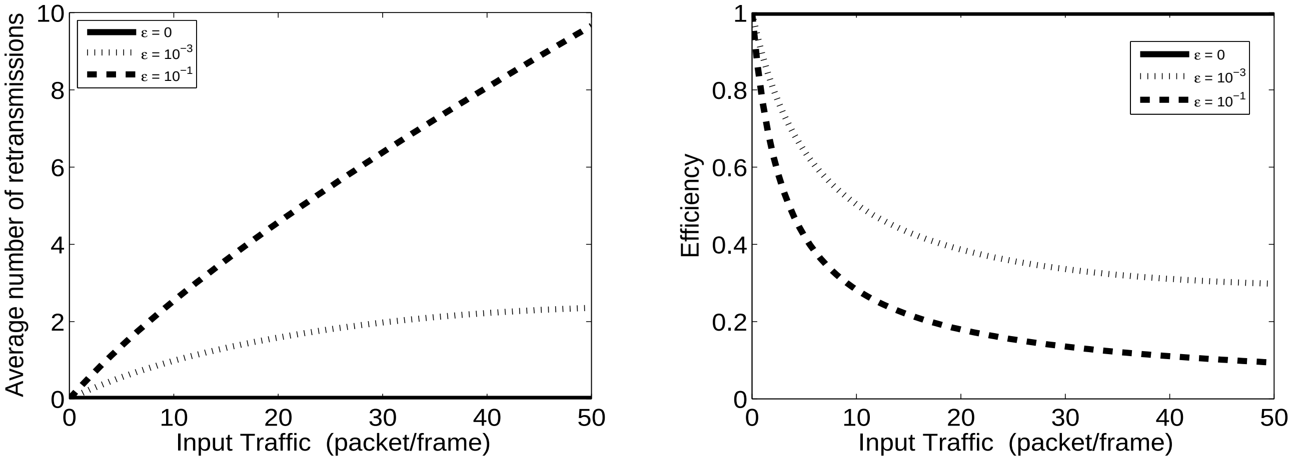
Fig. 5.10 shows the overall average number retransmissions and the efficiency for 1500 bits. When the number of packets is higher, the retransmission probability is higher when the channel is in error. The efficiency is also lower when we have more packets since the average number of retransmission is higher.

The impact of the packet priority probability for the three backoff schemes is shown in table 5.1. In the comparison, the acceptance probability at the full load



(a) Number of bits $n = 1500$ (b) Number of bits $n = 1500$

Figure 5.9: Energy and access delay versus input traffic.



(a) Number of bits $n = 1500$ (b) Number of bits $n = 1500$

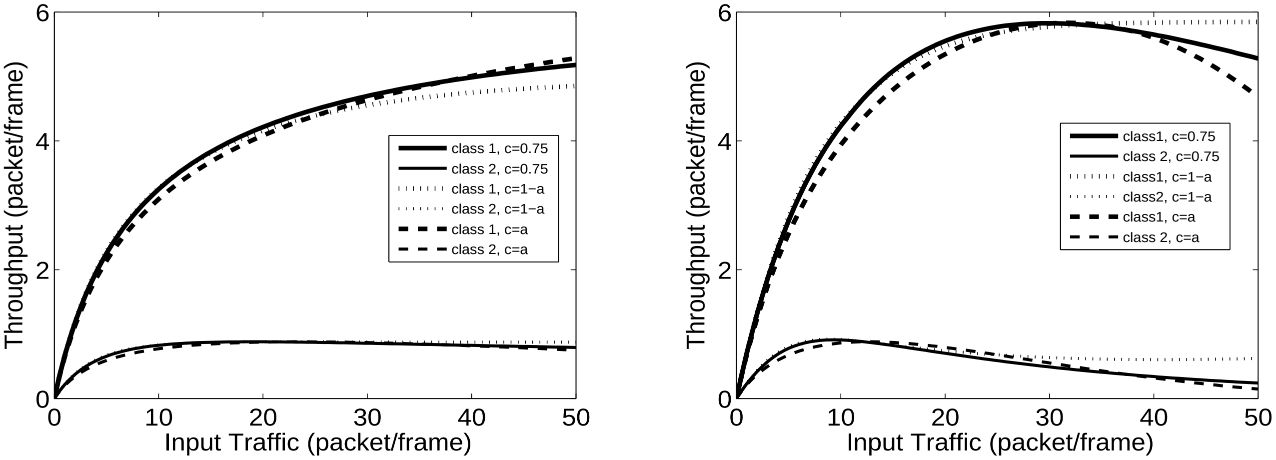
Figure 5.10: Average number of retransmissions and the efficiency versus input traffic.

Table 5.1: The impact of the packet priority probability l on the three backoff strategies

	l	0.1	0.3	0.5	0.7	0.9
$c = 0.75$	p_{a1}	0.1708	0.2000	0.1710	0.1432	0.1163
	p_{a2}	0.1070	0.0700	0.0468	0.0334	0.0620
$c = 1 - a$	p_{a1}	0.1733	0.1930	0.1750	0.1573	0.1388
	p_{a2}	0.1306	0.1020	0.0822	0.0681	0.0968
$c = a$	p_{a1}	0.1589	0.1930	0.1595	0.1274	0.0973
	p_{a2}	0.0902	0.0563	0.0343	0.0226	0.0455

is compared. From the constant retransmission probability model, the acceptance probability increases when l is small since there are enough resources. However, when $l = 0.7$ the acceptance probability decreases as most of the packets belongs to high priority class and the collision become higher. On the other hand, for the low priority class, as l increases the acceptance probability increases since most of the packet belongs to the high priority class and that makes the collision lower in the low priority class. In the proportional backoff probability model, the acceptance probability following the same flow as of the constant backoff probability model. The same flow is also applied in the complementary backoff probability model. However, the highest acceptance probability amongst the three backoff schemes is the acceptance probability in the complementary backoff probability model. The reason is that in the higher load the retransmission probability is low. The lowest acceptance probability is for the proportional backoff probability since the retransmission probability is high and the collision is getting higher.

Fig. 5.11 shows more comparison amongst the three backoff strategies for different $BER \in \{10^{-1}, 10^{-3}\}$. When BER is high, all the three strategies perform similar to each other since there are many retransmissions. However, as the BER is smaller, the complementary backoff probability perform better since the retransmission probability at higher load is lower. The proportional backoff probability model has the worst performance at high load since the collision is high.



(a) $BER = 10^{-1}$ (b) $BER = 10^{-3}$

Figure 5.11: Throughput versus input traffic for the Backoff Strategies with different BER

In order to achieve $BER = 10^{-3}$ we need an average signal to noise ratio SNR of $7dB$ if we have AWGN for BPSK and we need over $20dB$ if it is Raleigh faded. If we use different modulation schemes such MQAM for the same targeted BER, then we require higher SNR. However, higher physical modes can be used. For instance, in case of $4QAM$ we require an SNR of $10dB$, around $15dB$ for $16QAM$ and $18dB$ for $64QAM$ in case of $AWGN$ channel. On the other hand these values are way higher if a Rayliegh faded channel is assumed [86].

5.4 Chapter Summary

In this chapter we proposed a QoS model support in wireless LANs. we applied our proposed backoff strategy models in random access phase in WLAN. In these proposed models the number of random access channels is fixed. The impact of the access probability of the collided users is studied. The performance metrics for the models are shown. In the results, the proposed models show a good performance compared to other models where the collided users adopts a binary exponential backoff instead of simple backoff. We showed the QoS guaranteed for high priority traffic.

In all our models, the minimum throughput either stay in a saturated level or decayed to a lower value give better performance than other models such as aloha or slotted aloha. In the last section we proposed error control model for the transmission state. Instead of assuming an error free channel, our model considers that the data might be in error. We studied the impact for different bit error rates and for different packet sizes. The average number retransmissions is lower when we have lower bit error rate and low number of packets. The efficiency reaches one when the bit error rate is zero and decreases as the bit error rate increases. This work has been published in [18] and [19].

Chapter 6

Modeling Uplink Channel Utilization with QoS Support

This chapter presents the forth contribution in our dissertation which is the uplink channel utilization with the QoS support. In this chapter we developed an intergraded model for request mechanism and data transmission in the uplink phase in the presence of channel noise. This model supports quality of service. The wireless channel is prone to many impairments. Thus, certain techniques have to be developed to deliver data to the receiver. We calculated the performance metrics for single and multichannel wireless networks, like the requests throughput, data channel throughput and the requests acceptance probability and data acceptance probability. The proposed model is general model since it can be applied to different wireless networks such as IEEE802.11x, IEEE802.16, CDMA operated networks and Hiperlan\2. We also developed a model when the request and data channels are in error.

This chapter is organized as follows; Section 6.1 presents our proposed work and model description, Section 6.2 presents the requests mechanism and data transmission model, Section 6.3 shows our results and comments and Section 6.4 shows our chapter summary and discussion.

6.1 Model Description

In this section we show an example of a network model. This network model applies to the infrastructure wireless networks. Figure 6.1 shows using Time Division Duplexing (TDD) where time is broken down into frames and each frame has uplink and downlink phases and random access phase. These phases use logical channels. The logical channels could be time slots in case of networks that use the TDMA (Hiperlan 2) as their medium access. They can be frequencies for networks that have frequency domain their medium access (WiMAX) or codes in CDMA network (3G). The SS requests access using one of the k request logical channels which are split into $k1, k2$ depends on the class of traffic. The BS receives the requests and issues grants to the SSs. Once the SSs receive their allocated grants, they start sending their data on one or more of the L data logical channels which are split into $L1, L2$. The balance point between the resources dedicated to the requesting channels k and the data channels L is a challenge. Increasing k will reduce the request collision probability but affects the allocated data channels and results in degradation in the performance. On the other hand, reducing k will increase the collision and as a result access delay is high.

To differentiate between traffic classes and support Quality of Service (QoS), the total number of random channels (requesting) is split into two groups $k1$ and $k2$, where $k2 < k1$ as shown in Fig. 6.1. Traffic is classified into two classes, high priority class and low priority class. From Fig. 6.1, high priority class traffic users compete for access on $k1$ channels and low priority class traffic users compete for access on $k2$ channels. Also data channels are divided into $L1$ for high priority traffic and $L2$ for low priority traffic.

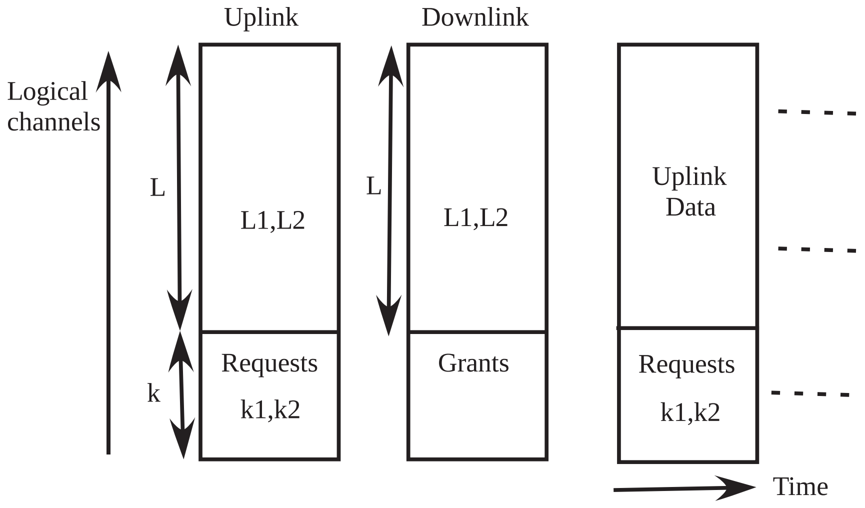


Figure 6.1: Uplink and downlink quality of service chart TDD

6.1.1 Model Performance

Channel utilization: This equation is to calculate the data channel utilization for each class

$$\eta_{U1} = \frac{\min\{L_1, Ns_{t1}\}}{L_1} \tag{6.1}$$

$$\eta_{U2} = \frac{\min\{L_2, Ns_{t2}\}}{L_2} \tag{6.2}$$

where $L_{1,2}$ are the allocated data channels for both classes.

Net acceptance probability: The net acceptance probabilities for data channels for both classes can be calculated by;

$$P_{a(net)1} \begin{cases} p_{a1}, & NTh1 < L_1; \\ p_{a1}\frac{L1}{Ns_{t1}}, & NTh1 > L_1. \end{cases} \tag{6.3}$$

and for class two traffic;

$$P_{a(net)2} \begin{cases} p_{a2}, & NTh2 < L_2; \\ p_{a2}\frac{L2}{Ns_{t2}}, & NTh2 > L_2. \end{cases} \tag{6.4}$$

6.2 Data Channel Performance

In this section we evaluate the data channels performance.

The Data channels throughput can be calculated by;

$$Th(i)_{data} = \min\{L(i), Nst(i)\} \quad i \in \{1,2\} \tag{6.5}$$

The data channels acceptance probability can be calculated by:

$$Pa(i)_{data} = \frac{Th(i)_{data}}{Na} \quad i \in \{1,2\} \tag{6.6}$$

The data channels average delay can be calculated by;

$$D(i)_{data} = \frac{1 - Pa(i)_{data}}{Pa(i)_{data}} \quad i \in \{1,2\} \tag{6.7}$$

The data channels average energy can be calculated by;

$$E(i)[dB] = -10 \log Pa(i)_{data} \quad i \in \{1,2\} \tag{6.8}$$

6.3 Quality of Service Support Model with Channel Error in Request and Data Channels

In this model the channel error is considered in the request channel and the data channel. We assume that the error is different in these channels. The users retransmit the request in two cases either when they suffer collision or when the channel is in error.

6.3.1 Model Assumptions

We assume that we have N SSs try to issue requests on request channels. The number of request channels are k, split into $k1$ channels for high priority traffic and $k2$ channels for low priority traffic $k2 < k1$. We have L data channels, $L1$ data channels for high priority traffic and $L2$ data channels for low priority traffic, $L2 < L1$. To analyze the model, some assumption are made:

1. The probability that a user issues a request is a
2. The probability that a user from high priority class chooses a particular channel is $1/k1$ and $1/k2$ for low priority class.
3. The collided user from high priority class retransmit with probability c_1 and from low priority class is c_2.
4. The packet priority probability l for high class traffic and $1 - l$ for low class traffic.

Fig. 6.2 shows the Markov chain state diagram for the model.

From Fig. 6.2, x_1 is the probability that a user from class one accesses successfully one of the $k1$ random channels. $x1$ is given by:

$$x_1 = \left(1 - \frac{1}{k_1}\right)^{N_{1a}-1} \tag{6.9}$$

where N_{1a} is the average number of active users from high priority class (class one) and it calculated by:

$$N_{1a} = N(l \times a \times s_i + c_1 \times s_{c1}) \tag{6.10}$$

The probability that the user from class one (high priority) selected on of the collided channels is given by:

$$y_1 = 1 - x_1 \tag{6.11}$$

x_2 is the probability that a user from low priority class (class two) successfully accesses one of the k_2 random channels. x_2 is given by:

$$x_2 = \left(1 - \frac{1}{k_2}\right)^{N_{2a}-1} \tag{6.12}$$

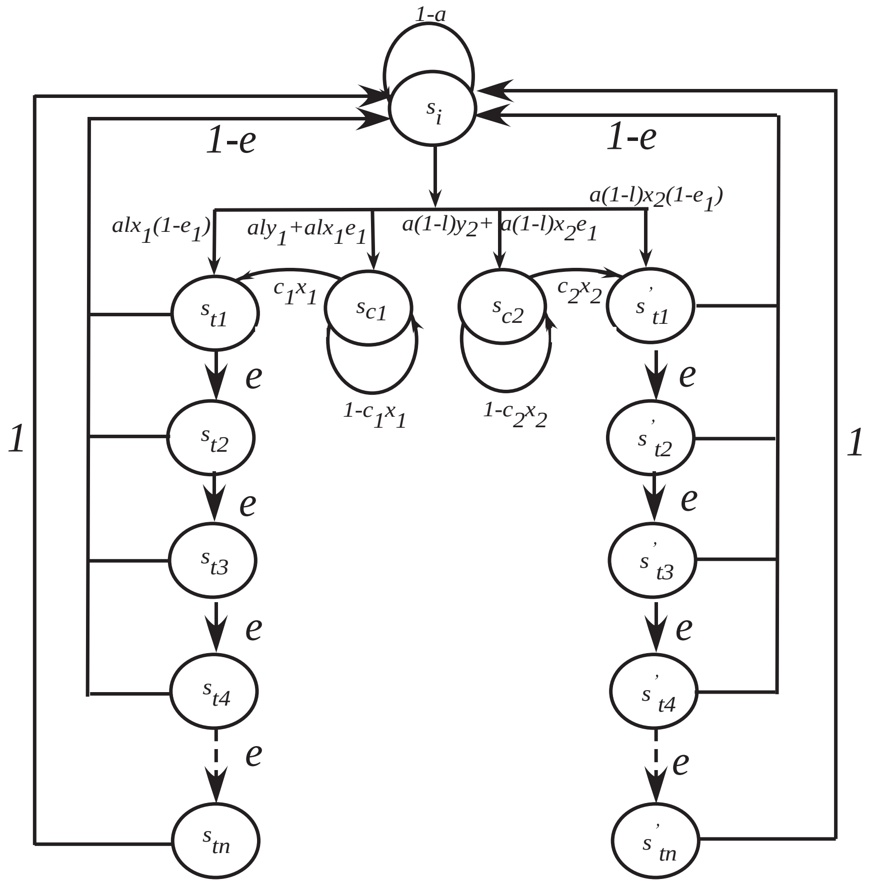


Figure 6.2: Markov state diagram for quality of support model with error in request and data

N_{2a} is the average number of active users from class two(low priority), and calculated by:

$$N_{2a} = N((1 - l) \times a \times s_i + c_2 \times s_{c2}) \tag{6.13}$$

The probability that a user from class two selected one of the busy channels is given by:

$$y_2 = 1 - x_2 \tag{6.14}$$

The allocated channels for the two classes are allocated by:

$$k1 = \left\lfloor \frac{l \times m}{l \times m + (1 - l)} k_{max} \right\rfloor \tag{6.15}$$

and the allocated channels for the second class are calculated by:

$$k2 = k_{max} - k1 \tag{6.16}$$

where m is the weight factor to determine the number of channels allocated to both classes and k_{max} is the maximum number of request channels.

1. The probability that the transmitted packet contained error is e.
2. The forward channel has random noise and the probability that a bit will be received in error is ϵ, (BER).
3. The feedback channel is error free.

   The error control states as shown in Fig. 6.2 represented by s_{t1} until s_{tn} have the following properties:

   (a) State s_{ti} indicates that the MT is retransmitting the packet for the i^{th} time.
   (b) The number of retransmission states is n.
   (c) The time step is taken equal to the sum of transmission delay (time required to send a packet) and round trip delay (time required for packet propagation and reception of acknowledgment) .

   The requests channel error is calculated by;

$$e1 = 1 - (1 - \epsilon 1)^{n1} \tag{6.17}$$

where $\epsilon 1$ is the bit error rate in the request channels. and the data channel error is calculated by;

$$e = 1 - (1 - \epsilon 2)^{n2} \tag{6.18}$$

where $\epsilon 2$ is the bit error rate in the data channels. where $n1$ is the number of bits in the request message and $n2$ is the number of bits in the data message.

6.3.2 Model Analysis

A discrete time Markov chain is characterized by the transition matrix P which can be obtained from the Markov state diagram shown in Fig.6.2 and the state vector s. The state vector is organized as follows;

$$\mathbf{s} = [s_i \quad s_{t1} \quad s_{t2} \quad s_{t3} \quad \cdots s_{tn} \quad s_{c1} \quad s'_{t1} \quad s'_{t2} \quad s'_{t3} \quad \cdots \quad s'_{tn} \quad s_{c2}]^t \tag{6.19}$$

where s_i is the probability that the user is in the *idle* state, s_c is the probability that the user is in the *collide* state and s_{ti} is the probability that the user is in the *transmit* state from high priority class users and s'_{ti} is the probability that the user from low priority class is in the *transmit* state. The SS will keep sending the packet contained if there is no acknowledgment is received (i.e the packet sent with an error probability e). When a packet is correctly received the SS goes to *idle* state with probability $1 - e$. The request may be collided or may contains error so it goes to the collide state in these two events. At equilibrium, the distribution vector elements are obtained by solving the following two equations [84]:

$$\mathbf{Ps} = \mathbf{s} \tag{6.20}$$

$$\sum s_j = 1 \tag{6.21}$$

$j \in \{i, t1, t2, \cdots, tn, c1, t1', t2', \cdots, tn', c2\}$

By solving Eqs. 6.20 and 6.21 we can find the state vector elements at equilibrium;

$$
\begin{aligned}
s_{t1} &= \frac{1}{X1}Y1 \\
s_{t2} &= e\frac{1}{X1}Y1 \\
s_{t3} &= e^2\frac{1}{X1}Y1 \\
s_{tn} &= e^{n-1}\frac{1}{X1}Y1 \\
s_{c1} &= \frac{1}{X1}(aly_1 + alx_1e_1) \\
s'_{t1} &= \frac{1}{X2}Y2 \\
s'_{t2} &= e\frac{1}{X2}Y2 \\
s'_{t3} &= e^2\frac{1}{X2}Y2 \\
s'_{tn} &= e^{n-1}\frac{1}{X2}Y2 \\
s_{c2} &= \frac{1}{X2}[a(1-l)y_2 + a(1-l)x_2e_1] \qquad (6.22)
\end{aligned}
$$

where

$$
\begin{aligned}
Y1 &= alx_1(1-e_1) + c_1x_1(aly_1 + alx_1e_1) \\
X1 &= 1 + (aly_1 + alx_1e_1) + Y1 + eY1 + e^2Y1 + \cdots + e^{n-1}Y1 \\
Y2 &= a(1-l)x_2(1-e_1) + c_2x_2[a(1-l)y_2 + a(1-l)x_2e_1] \\
X2 &= 1 + [a(1-l)y_2 + a(1-l)x_2e_1] + Y2 + eY2 + e^2Y2 + \cdots + e^{n-1}Y2
\end{aligned}
$$

6.3.3 Model Performance

In this section we will show the performance of our proposed model when the request and data channel might be in error. The request channel performance is as follows:

The requests throughput for both classes can be calculated as follows:

$$Th_1 = \min(Ns_{t_1}, k_1) \qquad (6.23)$$

$$Th_2 = \min\left(Ns_{t_2}, k_2\right) \tag{6.24}$$

The request acceptance probability is defined as the ratio between the requests throughput and the offered load:

$$p_{a_1} = \frac{Th_1}{l \times N \times a} \tag{6.25}$$

$$p_{a_2} = \frac{Th_2}{(1-l) \times N \times a} \tag{6.26}$$

The requests access delay ($D_{1,2}$) is the average number of access attempts made by a SS before it is successfully granted a request channel. It is defined as:

$$D_1 = \frac{1 - p_{a1}}{p_{a1}} \tag{6.27}$$

$$D_2 = \frac{1 - p_{a2}}{p_{a2}} \tag{6.28}$$

The average energy $E_{a1,a2}$ required to transmit a request successfully can be calculated as follows:

$$E_{a1} = \frac{E_0}{p_{a1}} \tag{6.29}$$

where E_0 is the energy required to transmit a request once. Normalizing relative to E_0, average energy in dB is given by:

$$\begin{aligned} E_{a1}[dB] &= -10\log(p_{a1}) && (6.30) \\ E_{a2} &= \frac{E_0}{p_{a2}} \\ E_{a2}[dB] &= -10\log(p_{a2}) && (6.31) \end{aligned}$$

The data channels performance is as follows:

Data channel throughput The data channel throughput can be calculated by;

$$Th(i)_{data} = \min\{L(i), Nst(i)\} \quad i \in \{1, 2\} \tag{6.32}$$

Data channel acceptance probability Data channel acceptance probability can be calculated by:

$$Pa(i)_{data} = \frac{Th(i)_{data}}{Na} \quad i \in \{1, 2\} \tag{6.33}$$

Data channel average delay; The data channel average delay can be calculated by;

$$D(i)_{data} = \frac{1 - Pa(i)_{data}}{Pa(i)_{data}} \quad i \in \{1, 2\} \tag{6.34}$$

Data average energy The data average energy can be calculated by;

$$E(i)[dB] = -10 \log Pa(i)_{data} \quad i \in \{1, 2\} \tag{6.35}$$

6.4 Results

In the performance evaluation we set the parameters as follows; $N = 50$, $k_{max} = 20$, $L1 = L2 \in \{1, 5, 10\}$, $c1 = c2 = 0.75$, $m = 2$, $l = 0.75$, $BER = 10^{-3}$ and $n = 500 bits$. Fig. 6.3 shows the requests throughput. The figure shows that the quality of service is assured for the high priority traffic.

Fig. 6.4, shows the uplink channel utilization. From the figure, when $L1, L2 = 1$, which is a special case for IEEE802.11a, where we have only one channel, we notice that the channel is fully utilized with class one users when the input traffic is low and kept fully utilized. When $L1 = L2 = \{5, 10\}$ the utilization is decreased. In that case we have multiple channels and we can send more data and the channels are not fully utilized. We also guarantee quality of service in the high priority class traffic as can be seen from Fig. 6.4a and Fig. 6.4b. From the figure we conclude that the high priority traffic has better channel utilization.

Fig. 6.5, shows the net acceptance probability for both classes. When $L1, L2$ are small the acceptance probability is low, however, the acceptance probability is getting

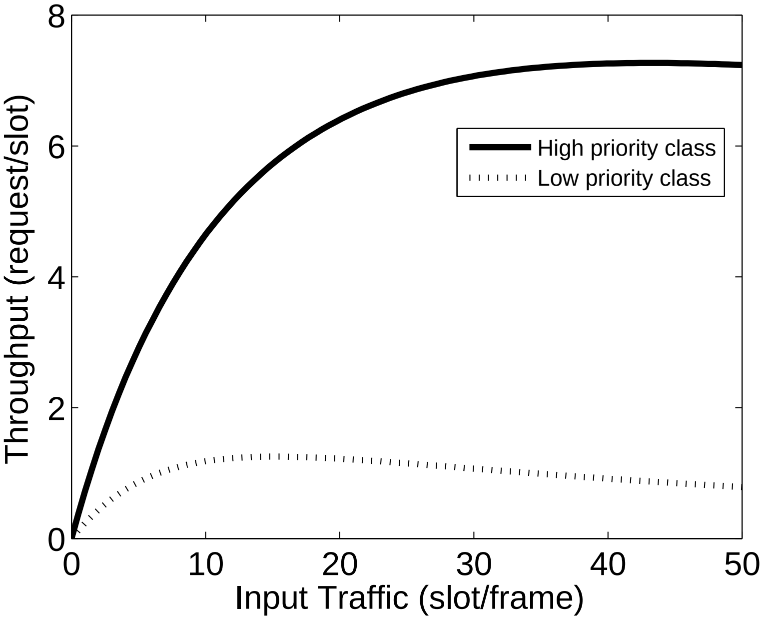
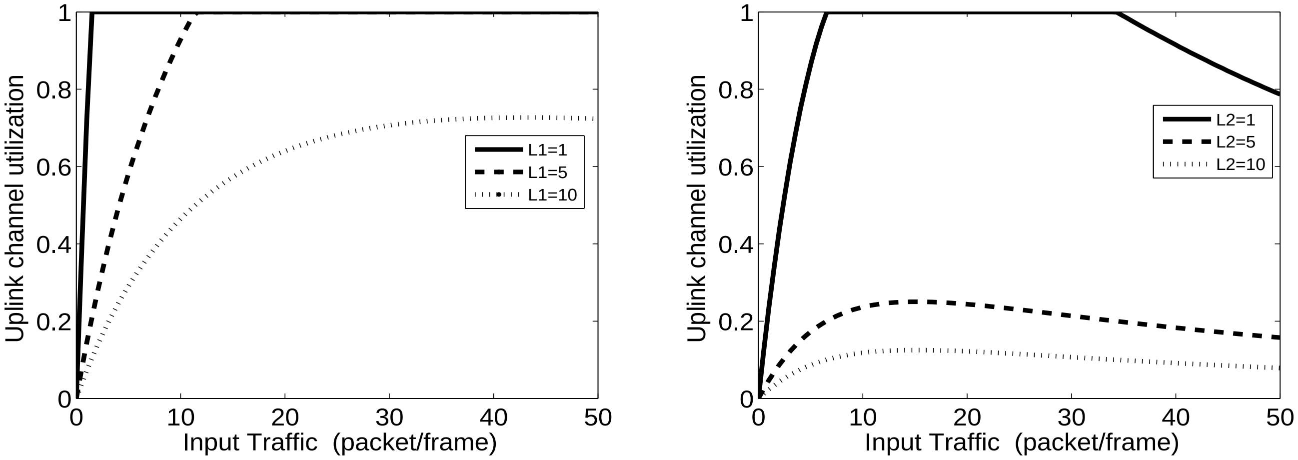


Figure 6.3: Requests throughput for QoS model

higher as the number of data channels increase. Furthermore, the net acceptance probability of the low priority class is better when $L1, L2 = 1$ the reason is that more traffic is coming from higher priority class than low priority class. However, when $L1, L2$ increases the net acceptance probability of higher priority class is better since the allocated resources are fully used. Thus, the net acceptance probability for one channels WLANs (IEEE802.11a) is low compared to the other WLANs with multiple channels. That is due high collision in IEEE802.11a and limited access channels. As the number of data channels increase the net acceptance probability is closer (exactly) to the requests acceptance probability. Therefore, as we have more data channels (multiple access WLANs) almost all granted requests get their data transmitted.

In the performance for request mechanism and data channels we used, $N = 50$, number of bits $= 500$, $BER = 10^{-3}$, constant backoff probability is assumed with



(a) Class one uplink utilization

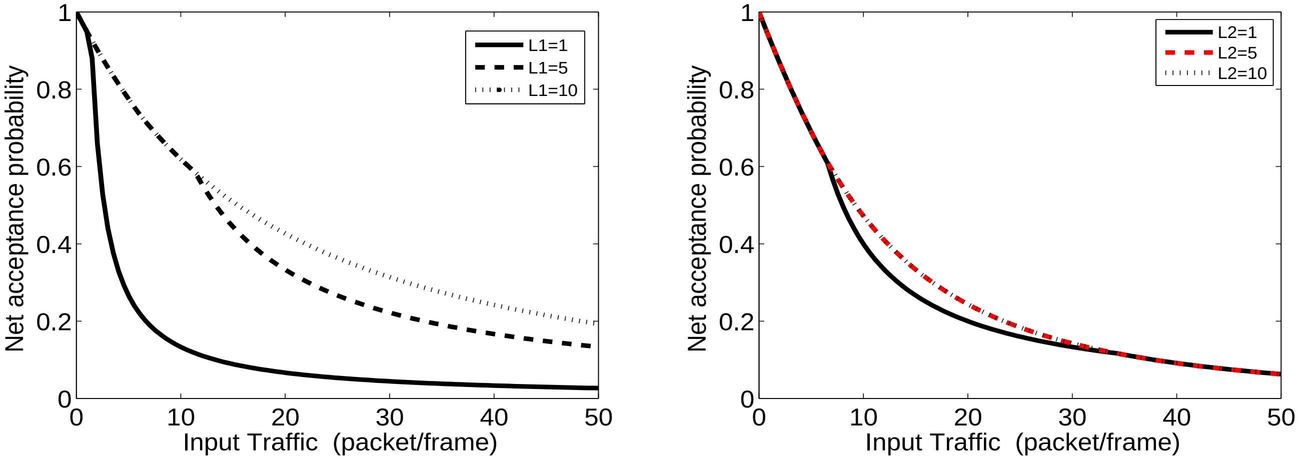
(b) Class two uplink utilization

Figure 6.4: Uplink channel utilization for QoS support model

retransmission probability $c1, c2 = 0.75$, $k_{max} \in \{20, 25\}$, $l = 0.75$, $L1 = 5$, $L2 = 3$. Figs. 6.6 to 6.9 show the obtained results for requests and data channels when we vary the number of request channels. Fig. 6.6a, shows the requests throughput. The high priority class has higher throughput. Also, the throughput is higher when we allocate higher number of request channels. Fig. 6.6b, shows the data throughput with different number of allocated channels. High class model gives better throughput compared to low priority class. However, the data channels throughput does not exceed the maximum number of allocated data channels.

Fig. 6.7a shows the request acceptance probability. The request acceptance probability is higher for the high priority class. The acceptance probability is higher when the request channels is high. The data channels acceptance probability is also better for the high priority class. Also, when we have more requesting channels the performance is better since the collision is lower.

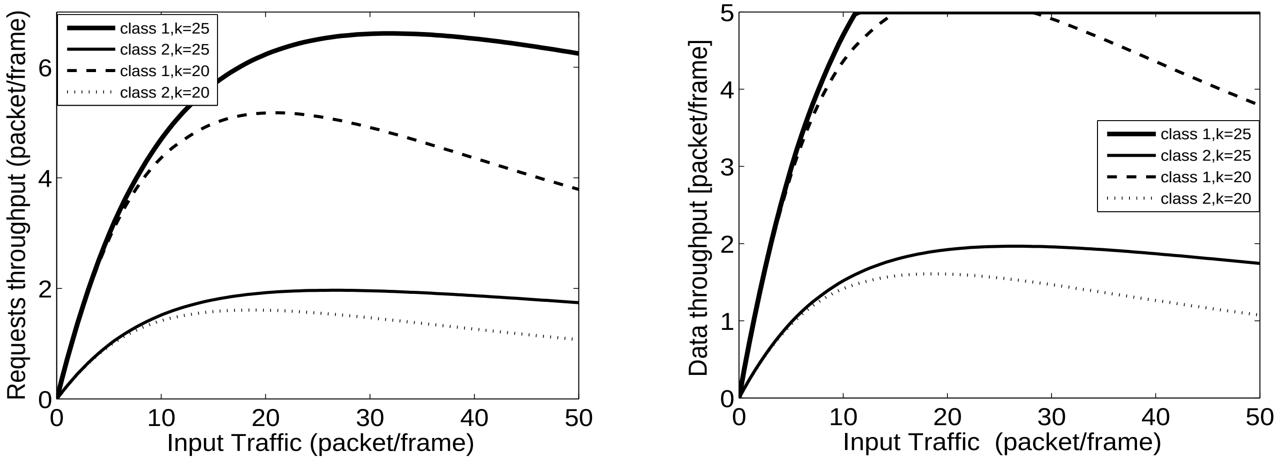
Fig. 6.8a shows the request access delay. The high class traffic encounters shorter



(a) Class one net acceptance probability

(b) Class two net acceptance probability

Figure 6.5: Net acceptance probability for QoS support model

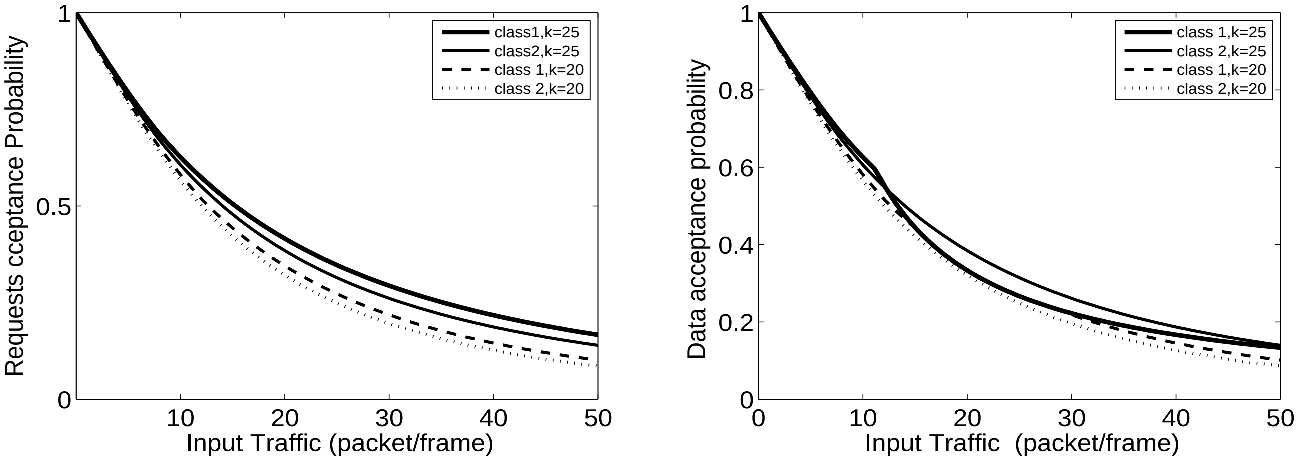


(a) Requests throughput

(b) Data channels throughput

Figure 6.6: Request and data channels throughput versus input traffic

delay compared to low class traffic and that is assures the quality of service for high



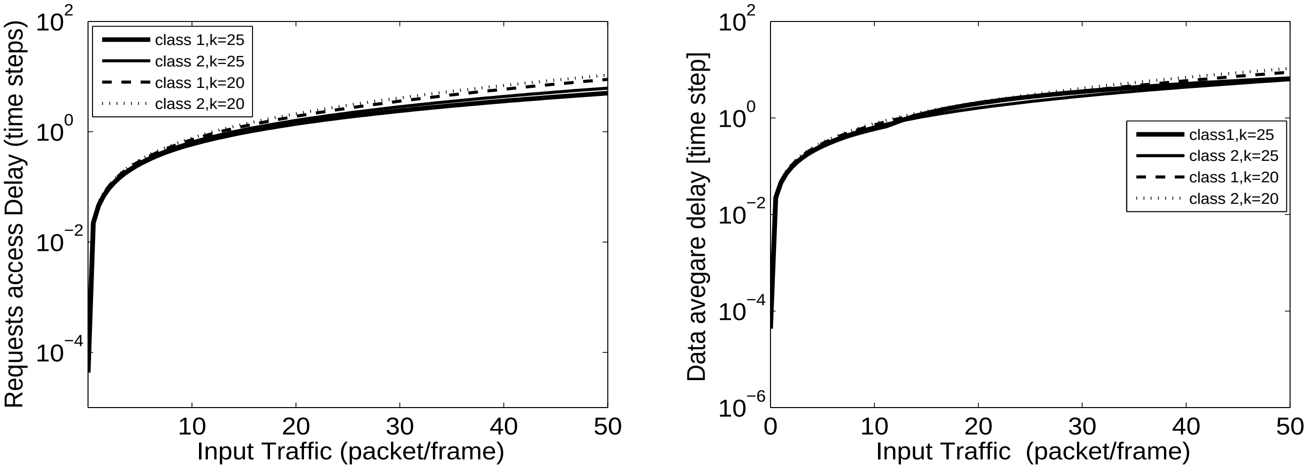
(a) Requests acceptance probability (b) Data channel acceptance probability

Figure 6.7: Request and data channels throughput versus input traffic

class traffic. Fig. 6.8b shows the data channels average delay. Similar to requests, the high class traffic encounters less delay compared to low class traffic. The delay is also less when we have more channels.

Fig. 6.9a shows the average request energy. From the figure we see that as the number of channels increases the request energy decreases. Also, high class traffic spend less energy as the allocated resources of this class is higher compared to low class traffic. Fig. 6.9b shows the data channels average energy. When the number of request channels is higher then the energy is less but that also limited to the number of data channels.

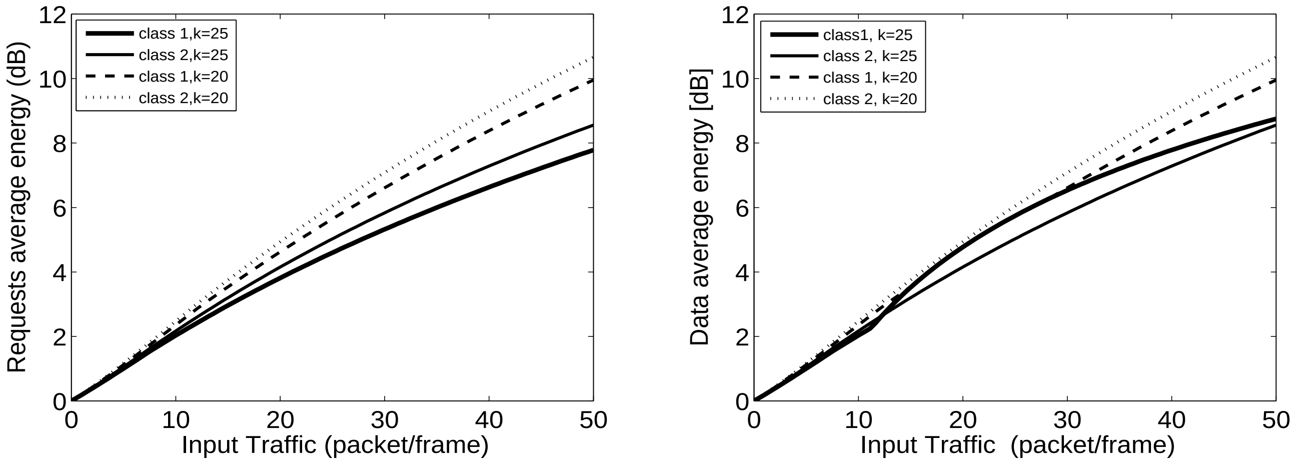
Figs. 6.10 to Fig. 6.13 shows the performance results for the proposed model when we vary the number of data channels. We allocated $K_{max} = 25$ and we vary the number of data channels $L1, L2$. Fig. 6.10a shows the data channels throughput for high class traffic while Fig. 6.10b shows the data channels throughput for low class traffic. From the figure, the high class traffic have higher throughput. Also, Even



(a) Requests delay

(b) Data channel delay

Figure 6.8: Request and data channels average delay versus input traffic

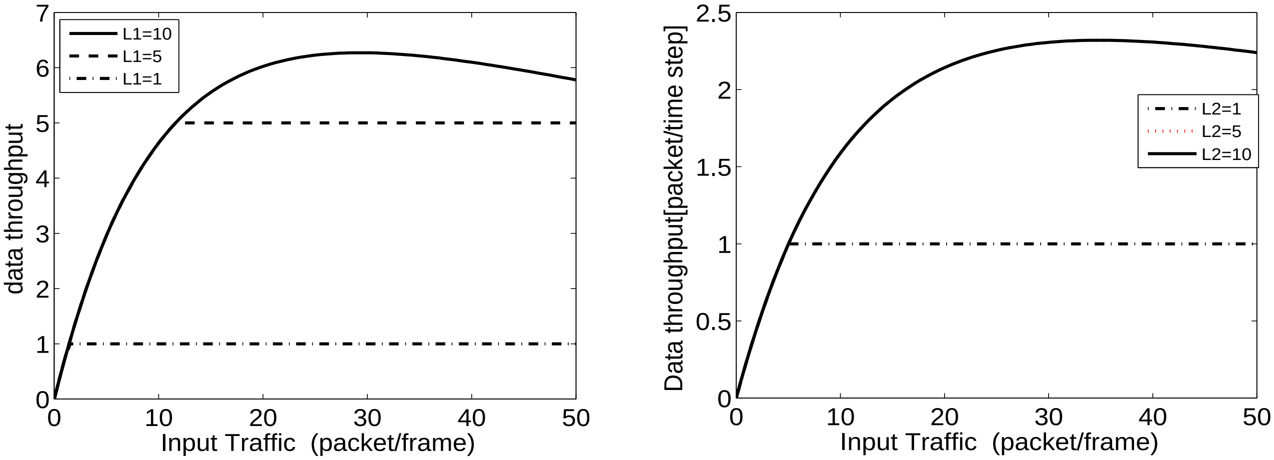


(a) Requests energy

(b) Data channels energy

Figure 6.9: Request and data channel average energy versus input traffic

when we have high number of data channels, the data channels throughput do not exceed the requests channel throughput. The single channel WLANs give the lowest throughput since the collision is high on that channel and that is a special case in IEEE802.11a.



(a) Data throughput class 1

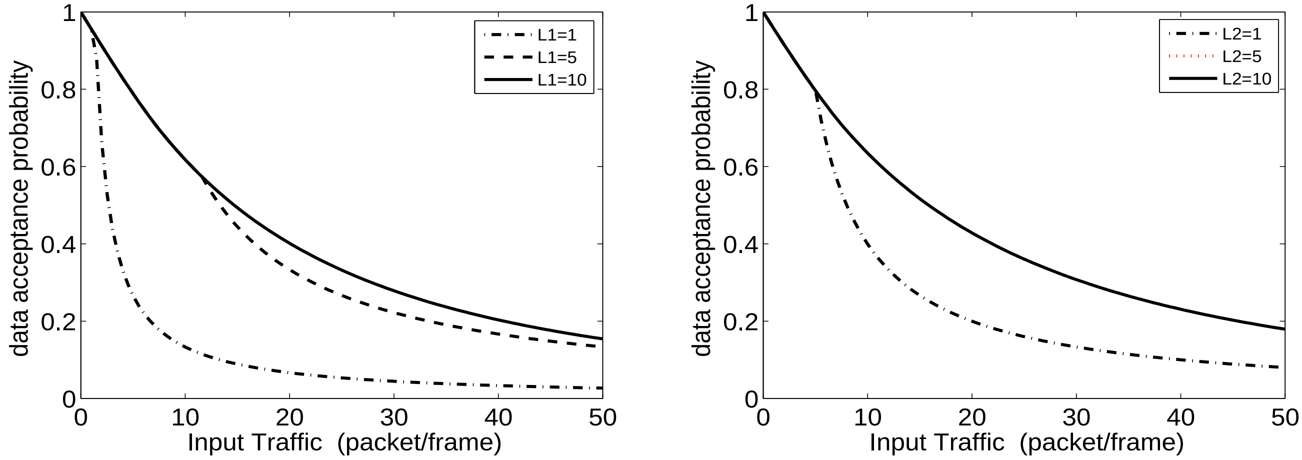
(b) Data throughput class 2

Figure 6.10: Data throughput for both classes versus input traffic

Fig. 6.11 shows the data channel acceptance probability for both classes with different number of data channels. As the number of data channels increases the data channels acceptance probability gets better. The higher acceptance probability does not exceed the request acceptance probability.

Fig. 6.12 shows the data channels average delay. When the number of data channels is higher the users encounters less delay to send their data as there are many resources available. However, as the number is less the average delay is higher. One channel WLAN has the highest delay.

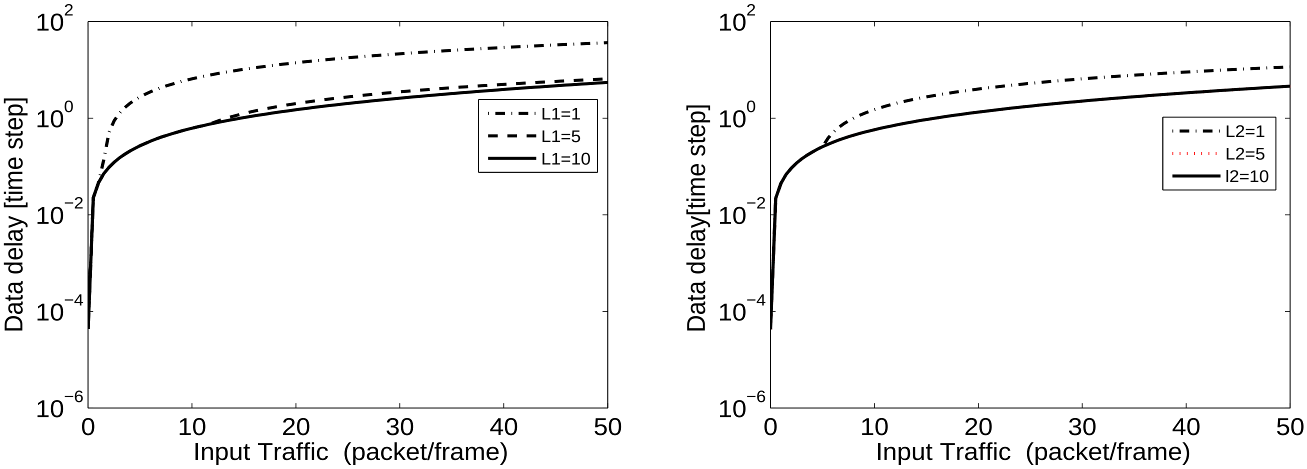
Fig. 6.13 shows the data channels average energy. When the number of data channels is higher the users consume less energy to send their data as there are many resources available. However, as the number is less the average energy is higher.



(a) Data acceptance probability class 1

(b) Data acceptance probability class 2

Figure 6.11: Data acceptance probability for both classes versus input traffic

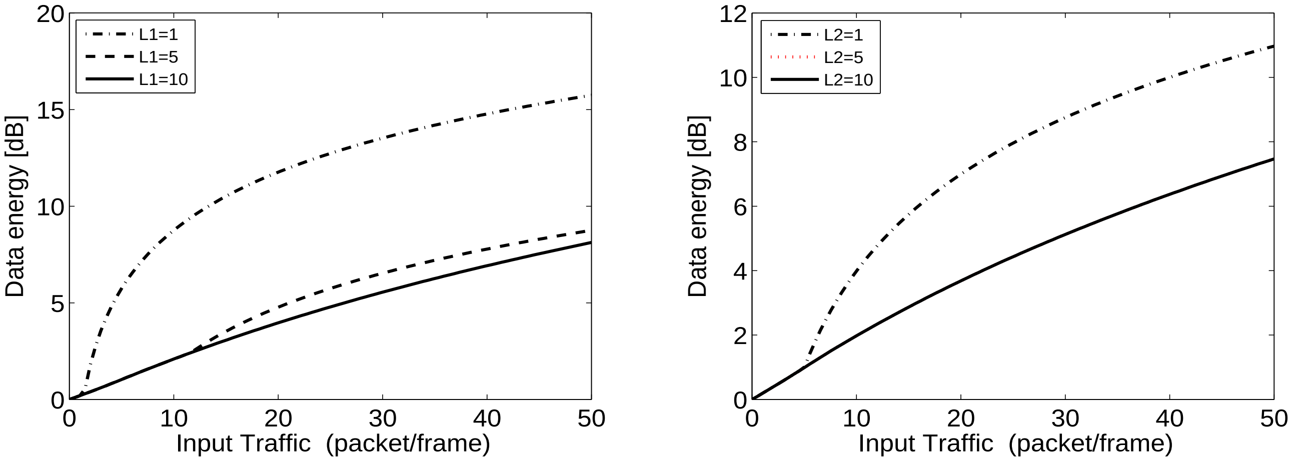


(a) Data average delay for class 1

(b) Data average delay for class 2

Figure 6.12: Data average delay for both classes versus input traffic

The results for the last model we have error in the request and data channels are



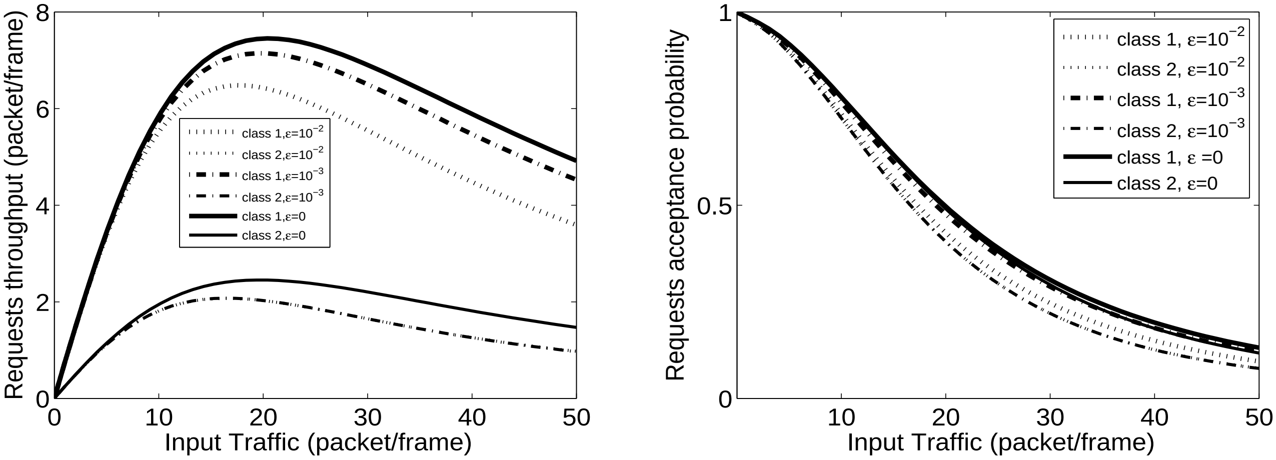
(a) Data average energy for class 1

(b) Data average energy for class 2

Figure 6.13: Data average energy for both classes versus input traffic

presented in Fig. 6.14 to Fig. 6.17 The parameters used in the performance analysis, the number of users $N = 50$, the retransmission probabilities $c1 = c2 = 0.75$, data packets $500 bits$, request packets $50 bits$ the packet priority probability $L = 0.75$, data BER $= 10^{-3}$, request BER$=\in \{10^{-2}, 10^{-4}, 0\}$, request channels $K_{max} = 25$, data channels $L1 = 10$, $L2 = 6$. Fig. 6.14a shows the requests throughput when the error in the request channels is considered. When the BER in the request channels is high the requests throughput is low and as the BER decreases the requests throughput improves. Also, the QoS is achieved as the requests throughput for high class traffic is higher than that in the low priority class traffic. Fig. 6.14b shows the requests acceptance probability for this model. The acceptance probability for the high priority traffic when the channel is error free is the highest compared to the acceptance probabilities when the request channel BER is high. Therefore, the error in the request channels has an impact on the request acceptance probability.

Fig. 6.15a shows the average consumed energy for the requests. When the channel



(a) Requests throughput

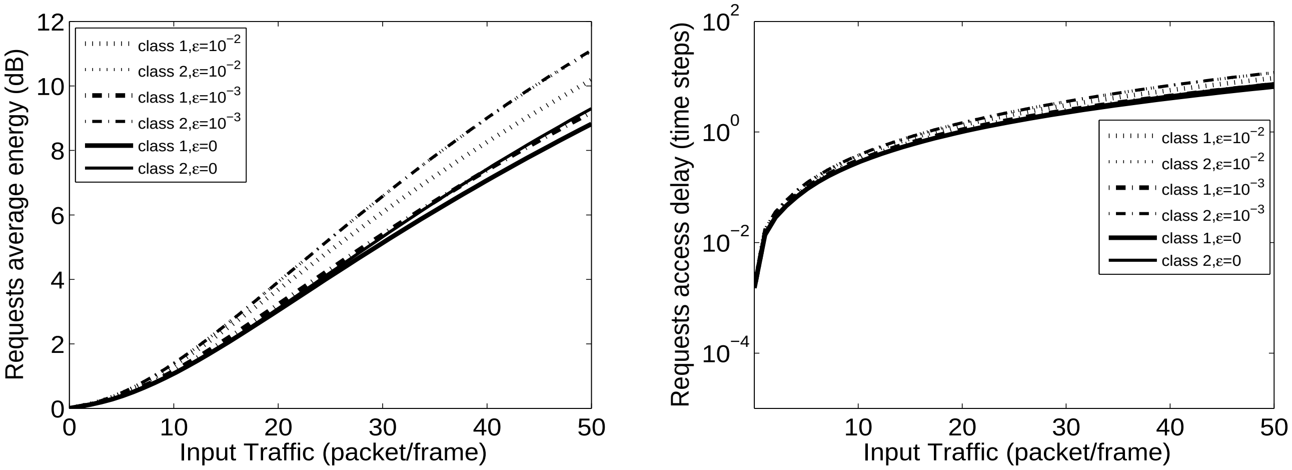
(b) Acceptance probability

Figure 6.14: Requests throughput and acceptance probability for QoS support model

condition is bad (high BER) the consumed energy is higher. The high priority class with low BER consumes the least energy. Fig. 6.15b shows the average requests delay. The average delay is the highest when the BER is high. The request granted after long delay compared to that when the channel condition is better when BER is low.

Fig. 6.16 and Fig 6.17 shows the performance for the data channels. Fig. 6.16a shows the throughput for the data channels. The highest throughput is achieved for the high priority class when the channels is error free. The throughput is degraded as the BER is getting higher. Also, the higher priority class has higher throughput compared to low priority class. Fig. 6.16b presents the data channels acceptance probability. The acceptance probability for high class traffic is higher than that of low class traffic and the higher acceptance probability is obtained when we have low BER. Thus, the channel condition has a big impact on the performance.

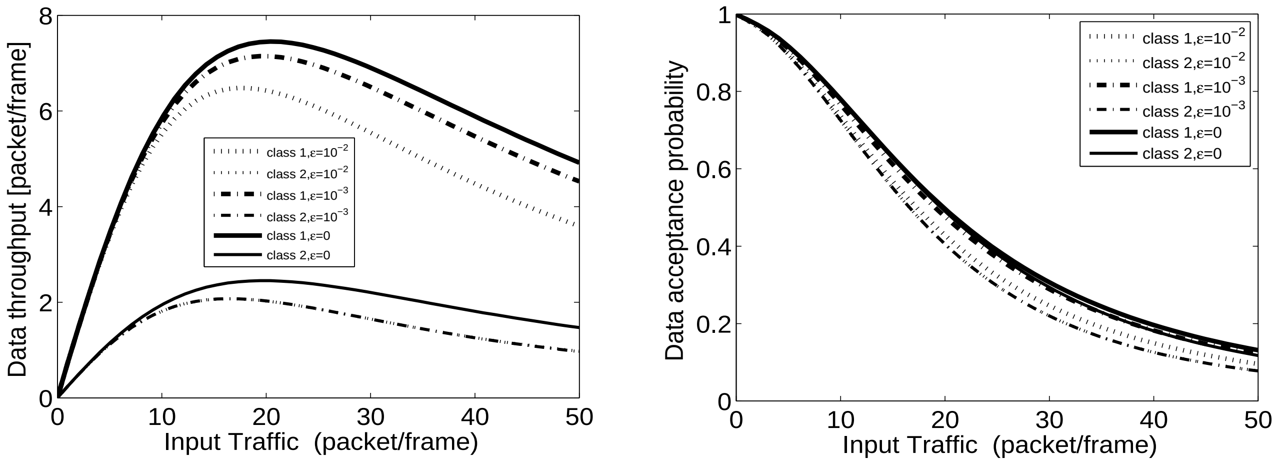
Fig. 6.17a presents the data channels consumed energy. The highest consumed energy is for the low class traffic when the BER is high. The lowest consumed energy



(a) Requests average energy

(b) requests average delay

Figure 6.15: Requests average energy and delay for QoS support model

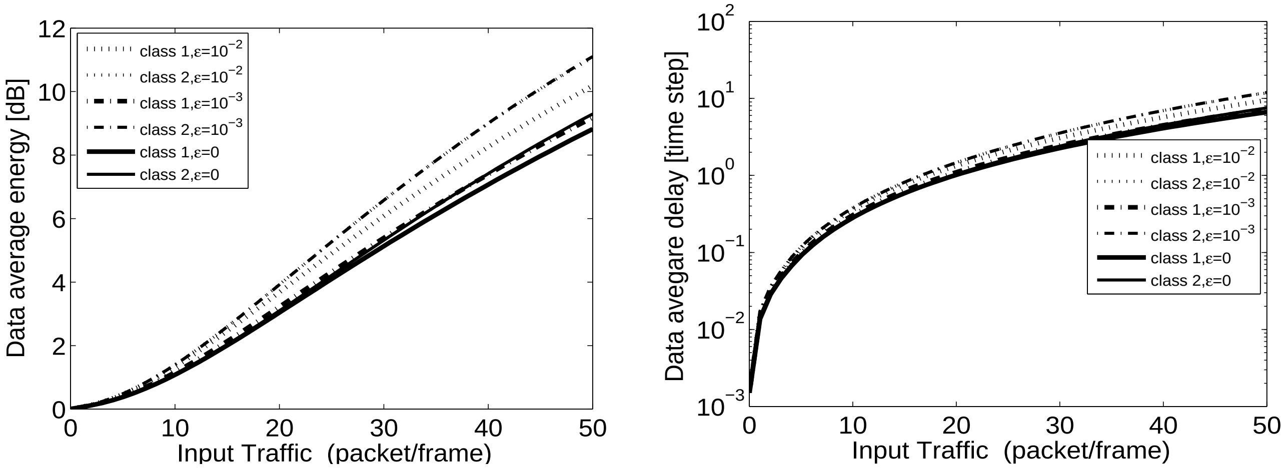


(a) Data channels throughput

(b) Data channels acceptance probability

Figure 6.16: Data channels throughput and acceptance probability for QoS support model

reached is for the high priority traffic with low BER. The average data channel delay is shown in Fig. 6.17b. The shortest delay is reached when we the BER is low and the longest delay when the BER is high. The shortest delay is for the high priority traffic. This model proved that the BER has an impact of the performance. Better throughput, better acceptance probability, shorter delay and less energy are obtained when the channel condition is better and vise versa. Therefore not only collisions degrades the performance but also the channel condition.



(a) Data channels average energy

(b) Data channels average delay

Figure 6.17: Data channels average energy and delay for QoS support model

6.5 Chapter Summary

In this chapter we developed a model for the uplink channel utilization with quality of service support in WLANs. We also studied the net acceptance probability for this model.

The uplink channel utilization reaches full channel utilization when we have only one channel which is a special case for IEEE802.11a and the utilization starts to go down as we have more channels. We also assured that high priority class get better performance, so quality of service is achieved. In a similar way we assured the net acceptance probability for the high priority class get better performance in all types of traffic. We also concluded that as the number of data channels get higher the net acceptance probability is getting close to the requests acceptance probability. Therefore, all granted requests will get their data transmitted. This model can be applied to different wireless standards. In our quality of service support model high priority traffic gets better access chance and the low priority is not ignored when high priority class requesting access. This work is published in [15].

In the request mechanism and data transmission channels in wireless networks that supports quality of service, we studied the impact of varying several parameters such as the requesting channels and the data channels. The requests performance in dependant only on the number of requesting channels whereas the data channel performance is depended on both. As the number of requesting channels increases the performance of the requests improved and vise versa. The data channel performance improved as the number of data channels increase. However, we can not allocate many number of requests channels since that is affects the data channels. So, the balance point between the number of requesting channels and data channels is a challenge. We noticed that the single channel wireless standard performs badly compared to multichannel standards. We assured the quality of service for high class traffic in the request and data transmission channels. This work has been submitted to [20]. Finally, we developed a model for the wireless channel when the error is considered in both the request channel and data channel. The users may not get access due to two reasons either a collision or the channel error. This model gives a better understanding for the reason that the users can not send their data. From our results, we get better performance when the BER is low. This model supports quality of service. We assured that the high class traffic has better performance than the low priority traffic. Therefore, not only the collision has a bad impact on the performance but also the channel condition. This work will be submitted to [17]

Chapter 7

Contributions Summary and Future Work

This chapter summarizes the major research work and propose future work. In our research work we presented several models in the medium access control in wireless local area network. We do not envision that our proposed approaches will replace the current models nor work in isolation from other techniques. Our approaches can compliment existing models to enhance the medium access control performance. We could not cover all possible ways that leads to an optimal medium access control frame performance. Nonetheless, we hope that our proposed approaches for better medium access control perfromnace could help wireless local area network users for better services.

7.1 Summary

This section summarizes the research work presented in the dissertation.

In the first part of the research work, presented in Chapter 3 and Chapter 4, we proposed single class model. In this model a Markov chain model is presented for the user. In this work we showed the impact of the allocated random access channel on the medium access control frame. We proposed different backoff strategy models.

Furthermore, we proposed cross-layer model for a single class and considered the channel error. In chapter 4, we extended our cross-layer model to study the uplink channel utilization for the single channel WLANs and mutli channel WLANs and studied the impact of channel error in the request and data transmission channels.

In the second part of the research work presented in Chapter 5 and Chapter 6, we proposed a quality of service support model in wireless local area network. The impact of packet priority probability is shown. We enhance this model by applying our backoff strategy models which we proposed in chapter 3. Moreover, a cross-layer design for the quality of service model is developed and we studied the impact of various parameters. In chapter 6, we extended our QoS support model to study the uplink channel utilization for data transmission channels for WLANs, we studied the request mechanism and finally we studied the impact of channel error in the request and data channels.

7.2 Contributions

The contribution of this research work can be summarized as follow.

7.2.1 Single Class Backoff Strategy Investigation

For our first contribution, we proposed four backoff strategy models for the random access channels. In these models we used a Markov chain analysis to model a user and monitor the impact of varying the number of channels. In the proposed backoff strategy models the collided users adapt one of the proposed backoff strategy models. We compare these models and we also compare them with the known backoff models. Our proposed models showed better performance compared to the known ones. We found out that the complementary backoff strategy model outperforms other models since the collided users reduce there retransmission probabilities as the traffic increases. This model is enhanced by proposing a cross-layer model for single class random access channels. In this enhancement, we considered the error in the transmission state. Since the wireless channel is not always error free then the data transmission always prone to corruption. Our model is a cross-layer model and as the users got its requests guarantee then in the transmission state we applied an error control model. The average number of retransmission is studied and shown that as the amount of data is large then the average number of retransmission is higher. We also studied the efficiency of our model. This work has been published in [13] and [14].

7.2.2 Uplink Channel Utilizations for Single Class

In the second contribution, we developed a model for the channel uplink utilization for data transmission channels. In this model we showed the channel utilization for the single channel WLANs and the multichannel WLANs. We also have shown the net acceptance probability for WLANs. Furthermore, as we have more access data channels the net acceptance probability is close to the requests acceptance probability. Thus, most of the requests granted their data to be transmitted. We proved that the single channel access WLANs such as IEEE802.11a is completely utilized very early in the traffic line however other multichannel access WLANs can handle more traffic and the channels are not completely utilized. This work has been published in [15]. We studied the request and data transmission mechanism. In this study we varied the number of request and data channels. As the number of data channels increases the performance improved. However, a balance point between the request and data channel is an issue. This work has been published in [16]. We enhanced our proposed model by considering the channel in the request and data channel. Users may not get access due to two reasons, collision and channel error. The performance is better when the channel condition is better (i.e. low BER). This work has been submitted to [17].

7.2.3 Quality of Service Support Model

In the third contribution, we proposed a quality of service support model in wireless local area network. In this model we classify our users as high and low priority users. We assign each class certain number of random access channels. In our results we show that the hight priority class traffic got better acceptance probability. We studied the impact of the packet priority probability. The high priority class traffic get better acceptance probability even if most packets are coming from this class. We extended our model to consider the error in the transmission states. This a cross-layer model with quality of service support. We applied our proposed backoff strategy models on this proposed model. It is shown that the complementary backoff probability model outperforms other developed model as the collided users reduce there retransmission probability as the offered load increases. It is also shown that the average retransmissions probability increases as the number of packets increase, and it is zero as the channel is error free. The efficiency reaches 100% when the channel is error free and reduces as the average error increases. This work have been published in [18] and [19].

7.2.4 Uplink Channel Utilization with QoS Support

In the fourth contribution, we studied the uplink channel utilization for the data transmission channel with quality of service support. We showed that single channel WLANs get very high uplink channel utilization in low traffic load. We also showed that high priority traffic uplink channel utilization is lower so the channel can handle more traffic compared to low priority traffic. We also compared the performance in terms of net acceptance probability. We proved that when we have single channel that net acceptance probability is low compared to the multiple channel access WLANs. Furthermore, as we have more access data channels the net acceptance probability is close to the requests acceptance probability. Thus, most of the requests granted their data to be transmitted. This work has been published in [15]. We studied the request and data transmission mechanism with quality of service support. This work has been submitted to [20]. This model is enhanced by considering the error in the requesting channel. The users may not get access by either collision in the request channel or due to channel error. The performance is greatly affected by the error in the request channels. The performance is better when the BER is low. This work has been submitted to [21].

7.3 Directions for Future Work

We can not claim that our proposed models solve the problems of contention in the random access, nor the proposed model provides the better scheme for the quality of service support. However, this work is a contribution in this area. This research work can be extended along the following research directions.

7.3.1 Different Traffic Models

Reducing contention on the random access phase by our proposed model has been improved. However, different traffic models can be used to test our proposed models when we have mixture of traffic flows. By doing that the proposed models will be more general to adapt many traffic models.

7.3.2 Applying Backoff Strategies to Different Traffic

Our proposed backoff strategy also shown good performance but more work in this direction would be more beneficial and the selection of which backoff strategy is applied to what type of traffic.

7.3.3 Study Other Parameters

Our quality of service support models showed that we can provide quality of service to certain class of traffic. However, more investigation and study on all parameters is highly recommended to select what is the most significant parameter on the type of traffic.

7.3.4 Different Channel Types

Our proposed error control protocol show great efficiency when the channel has small error, however, as the error increases the efficiency reduced. Hence, more development on the channel model can provide better efficiency when the error is higher. Also, the average number of retransmission can be reduced as of the number of retransmitted packets increases.

7.3.5 Ad-hoc Multihop Networks

We applied our models on a single hop wireless network with omnidirectional antenna. This work can be extended to a multihop wireless local area network with mobile terminal equipped with directional antenna. That will help to reduce the interference caused by the omnidirectional antenna and increase the spatial reuse .

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