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Contention-based Wireless Medium Access Control Protocols with Additional Degree of Design Freedom

Graduate School of Chosun University

Department of Computer Engineering

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Advisor: Assoc. Prof. Seokjoo Shin

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ABSTRACT

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In wireless packet networks, multiple users share a common wireless medium to transmit their packets. Should there occur two or more simultaneous transmissions from different users, the transmitted packets may interfere with each other and may not be decoded by the designated receivers. This phenomenon is commonly known as packet collisions. Over wireless packet networks, collisions are strongly undesirable because they not only waste limited transmitting power but also waste the scare wireless channel resource. Hence, every Medium Access Control (MAC) protocol that are fully responsible to coordinate the transmission of multiple users in the shared medium are focused on either eliminating or mitigating such interference.

Two classes of MAC protocols have been popularly used in wireless packet networks depending on the availability of a central entity that coordinates the transmission of multiple users. In the network

without any central entity that takes the role of coordinating the access of the users, contention-based (random access) MAC protocols are preferred over their contention-free counterpart. For example, in IEEE 802.11 Wireless Local Area Networks (WLANs), a contention-based Distributed Coordination Function (DCF) is a *defacto* MAC protocol. According to this protocol, each user senses (listen to) the wireless channel before transmitting and defers the transmission to prevent packet collisions if it detects the ongoing transmission. Since collisions can still occur if multiple users sense and initiate their transmissions at the same time, the protocol introduces a random backoff that is regulated using temporal Contention Window (CW) before each transmission to further reduce the chances of collisions. Unfortunately, it has been found that the performance of this protocol deteriorates as the number of users in the network increases.

In this dissertation, we present a simple mechanism to alleviate the problem related to the performance deterioration of DCF in both its unicast and broadcast versions. The new mechanism extends the conventional random backoff design by increasing its Degree of Design Freedom by one (i.e., by adding an additional configurable parameter in its design space). More precisely, according to the new mechanism, the Contention Slot Selection Distribution (CSSD) over the contention window is no more restricted to have only the uniform shape but is allowed to have a properly designed and adaptively tunable non-uniform shape. For the unicast DCF we design a doubly truncated Normal

CSSD with dynamically varying *kurtosis*[1] while for the broadcast DCF we adopt the static reverse-exponential CSSD. Based on theoretical and simulation based analysis, we show the benefit of the proposed mechanism in terms of most relevant performance metrics. Inclusion of the proposed mechanism in the unicast DCF not only maximizes network throughput and throughput-fairness of each user, but also reduces packet delay. Likewise, the inclusion of the proposed mechanism in broadcast DCF concurrently enhances network-throughput and reliability of the broadcasted packets. More importantly, the performance gain in terms of all of those metrics increases with increase in the number of users in the network.

Despite such a potential of the proposed mechanism in enhancing performance of DCF, it is quite challenging to adopt the proposed mechanism in Enhanced Distributed Channel Access (EDCA) protocol, a Quality of Service (QoS) extension to DCF introduced in IEEE 802.11e, because the independently tuned CSSDs of the users attempting to transmit lower priority packets may violate the CW-size differentiated relative differentiation principle adopted in EDCA. Such a violation results in frequent priority inversions (in terms of channel access) thereby reducing the perceived QoS grade of the higher priority packets, especially when the number of lower priority users is high. In the real-world sense, manifest consequences would be elongated jitter and reduced-throughput for the higher priority audio or video services

[1]Kurtosis is a measure of the peakedness of the probability distribution.

due to the increase in the lower priority data traffic load. We introduce a simple correction mechanism that manipulates the CSSDs of the lower priority users to overcome that problem and verify the efficacy of the mechanism using computer simulations.

The mechanisms that we have introduced in this dissertation for improvising the standard contention-based MAC protocols in WLAN are attractive for practical implementations due to several reasons. Firstly, those mechanisms adheres the simplicity of CW-based channel arbitration mechanism and well retain that simplicity. Secondly, those mechanisms are fully-standard compliant and backward-compatible; they neither require modifications in the standardized signalling mechanism used for transmitting a frame nor in the standardized frame structure.

Index Terms: Unicast and broadcast MAC protocols, Non-uniform contention slot selection distribution, Improvised collision avoidance, Short-term fairness, Discrete time Markov chain, Renewal reward process, Cross-layer analysis, IEEE 802.11, DCF, QoS differentiation, EDCA, Network simulator (ns-2)

ABSTRACT

DoDF (Degree of Design Freedom)를 고려한 경쟁기반 무선 매체 접속 제어 프로토콜 연구

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무선 패킷 네트워크에서는 패킷 전송을 위해 공통의 무선 자원을 다수의 사용자가 공유한다. 두 명 이상의 다른 사용자로부터 동시에 패킷이 전송되면 패킷은 서로 간섭을 일으키게 되고 수신단은 이러한 간섭에 의해 패킷을 제대로 디코딩할 수가 없다. 이러한 현상을 충돌이라고 하며, 무선 패킷 네트워크에서는 제한된 전송 전력의 낭비 뿐만 아니라 무선 채널 자원의 낭비 문제로 인해 충돌을 최대한 제어하여야 한다. 따라서 MAC 프로토콜은 다수의 사용자가 공유된 무선 자원을 통해 패킷을 전송하는 경우 이러한 간섭효과를 억제하거나 제거하여야 한다.

다중 사용자의 패킷 전송을 제어하는 중앙 제어 디바이스가 존재하는 경우에 대한 잘 알려진 두 종류의 MAC 프로토콜이 존재한다. 중앙 제어 디바이스가 없는 네트워크에서는 경쟁 기반 (임의 접근) MAC 프로토콜이 무경쟁 프로토콜에 비해 선호된다. 예를 들어 IEEE802.11 근거리 통신망 (WLAN)에서는 경쟁 기반의 Distributed Coordination Function (DCF)이 *defacto* MAC 프로토콜로 정의되어 있다. 이 프로토콜에서 각각의 사용자는 패킷 전송 전에 무선채널을 센싱하고 만일 다른 사용자가 전송 중이라면 충돌을 피하기 위하여 자신의 패킷

전송을 지연시킨다. 그러나, 다수의 사용자가 센싱을 수행하고 동시에 패킷 전송을 시도한다면 여전히 충돌은 발생할 수 있기 때문에, 충돌 확률을 줄이기 위한 목적으로 각각의 전송 이전에 경쟁 윈도우에 따른 임의 백오프 값으로 각 사용자의 전송 시점을 분산시킨다. 불행하게도 이러한 백오프 알고리즘은 네트워크에서의 사용자수가 크게 증가하는 경우에 급격히 성능이 저하된다는 단점을 가지고 있다.

본 논문에서는 DCF 기반 유니캐스트와 브로드캐스트 전송 시나리오에서 이러한 성능 저하의 문제점을 경감시킬 수 있는 단순하면서도 효과적인 메커니즘을 제안하였다. 새로운 메커니즘에서는 기존의 임의 백오프 디자인에 대해 DDoF (Degree of Design Freedom)을 1 만큼 확장하였다. 구체적으로 새로운 메커니즘에서는 경쟁 윈도우 상에서의 슬롯 선택 확률인 CSSD (Contention Slot Selection Distribution)를 기존 알고리즘에서와 같이 균일 분포가 아닌 적응적으로 튜닝이 가능한 비균일 분포를 갖도록 디자인하였다. 유니캐스트 DCF 에 대하여 본 논문에서는 다이나믹하게 변화하는 kurtosis(a measure of the peakedness of the probability distribution)를 갖는 더블 트렁케이티드 정규 CSSD 를 제안하였고, 브로드캐스트 DCF 에 대해서는 정적 역지수적 CSSD 를 제안하였다. 이론적 분석과 시뮬레이션을 기반으로 본 연구에서는 적절한 성능 평가 메트릭을 고려하여 제안 메커니즘의 우수성을 입증하였다. 유니캐스트 DCF 에서 제안 알고리즘은 패킷 지연은 감소시키고 네트워크의 처리률은 최대로 하며, 각각 사용자의 처리률-공정성 또한 최대로 제공할 수 있음을 확인하였다. 마찬가지로 브로드캐스트 DCF 에서는 네트워크의 처리률 증대와 더불어 방송된 패킷의 수신률에 대한 신뢰성도 향상시킬 수 있음을 확인하였다. 중요하게는 두 경우 모두에 있어서 네트워크의 사용자 수 증가에도 이러한 성능 메트릭이 우수함을 확인하였다.

제안 메커니즘이 단순 DCF 에서 성능 향상을 제공할 수 있음은 확인하였으나, IEEE802.11e 에서와 같이 QoS 를 제공하기 위해 확장된 EDCD(Enhanced Distributed Channel Access)에 제안 메커니즘을 적용하는 것은 문제가 있었다. 이는 낮은 우선 순위 패킷 전송을 시도하는 각 사용자의 CSSD 를 독립적으로 조절하는 것이 EDCA 에서와 같이 경쟁 윈도우 사이즈를 우선순위에 따라 분산시키는 방식에

위배되기 때문이다. 따라서, 제안 메커니즘을 그대로 EDCA 에 적용하면 채널 접속 기회 관점에서 높은 우선 순위 사용자가 지각하는 QoS 등급이 반전되는 경향이 있으며 이는 낮은 우선 순위 사용자의 부하가 높을 경우에 더욱 심각하다. 따라서 본 연구에서는 CSSD 를 조작하여 우선 순위에 따른 성능을 제공할 수 있도록 하였으며 시뮬레이션을 통해 성능을 검증하였다.

WLAN 에서와 같이 표준 경쟁 기반의 MAC 프로토콜 성능 향상을 위한 본 논문에서 제시한 메커니즘들은 실제 구현에 있어서도 장점들이 있으며 이는 다음과 같다. 첫째 제안된 메커니즘들은 경쟁 윈도우 기반의 채널 접속 메커니즘의 단순함을 그대로 상속하고 있다. 둘째 제안 메커니즘들은 표준 메커니즘과 호환성이 높고 표준에 쉽게 추가될 수 있다. 즉, 표준에서 제시된 시그널링 메커니즘의 어떠한 변형도 요구하지 않으며 표준 프레임 구조 변경을 요구하지 않는다.

Accronyms

AC	Access Category
ACK	Acknowledgement
AIFS	Arbitration Interframe Space
AWGN	Additive White Gaussian Noise
BEB	Binary Exponential Backoff
BER	Bit Error Rate
BMAC	Broadcast Medium Access Control
BSS	Basic Service Set
CBR	Constant Bit Rate
CCK	Complementary-Code Keying
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/*i*CA	CSMA with Improvised CA
CSSD	Contention Slot Selection Distribution
CTS	Clear To Send
CW	Contention Window
DBPSK	Differential Binary Phase Shift Keying
DCF	Distributed Coordination Function
DIFS	Distributed Interframe Space
DLS	Direct Link Setup
DoDF	Degree of Design Freedom
DS	Distribution System
DSSS	Direct Sequence Spread Spectrum

DTMC	Discrete Time Markov Chain
EDCA	Enhanced Distributed Channel Access
EIFS	Extended Interframe Space
ESS	Extended Service Set
ETST	European Telecommunications Standard Institute
FHSS	Frequency Hopping Spread Spectrum
FTP	File Transfer Protocol
HBV	History Backoff Value
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
HTTP	Hypertext Transfer Protocol
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
JFI	Jain's Fairness Index
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MPEG	Moving Picture Experts Group
MPR	Multi Packet Reception
NAV	Network Allocation Vector
NOAH	No Ad Hoc

OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open System Interconnection
PAR	Packet Arrival Rate
PCF	Point Coordination Function
PCMR	Push CSSD Mean Right
PDA	Personal Digital Assistants
PHY	Physical layer
QoS	Quality of Service
RHCP	Relatively High Collision Prone
RLCP	Relatively Less Collision Prone
RRP	Renewal Reward Process
RTS	Request To Send
SB-MAC	Scalable BMAC
SIFS	Short Interframe Space
SNR	Signal to Noise Ratio
TCP	Transport Control Protocol
TP	Transmission Probability
TXOP	Transmission Oppertunity
UDP	User Datagram Protocol
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Networks
WPAN	Wireless Personal Area Networks

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1 Introduction

1.1 Background

Wireless networking technology provides flexible network connectivity to the network entities without being physically connected by means of any cables or wires. Ever since the seminal packet-based wireless networking technology, popularly known as ALOHANET [1], was operated for the first time at the University of Hawaii, albeit on an experimental basis, the recent decades have witnessed tremendous developments and diversifications in the wireless networking technologies thereby resulting in multiple wireless networks with different communication scope, range and applications. Some of the representative examples are Wireless Metropolitan Area Networks (WMANs) [2], Wireless Local Area Networks (WLANs) [3], and Wireless Personal Area Networks (WPANs) [4].

As the Internet is becoming more and more prevalent in people's life, the use of various wireless networks including WLAN to access the Internet has become more popular. Although WLANs were originally conceived for the mere replacement of wired-LAN, they are now one of the most preferred access technologies at homes, enterprizes, and public hot-spots. This paradigm shift happens due to the decreasing cost of WLAN networking equipments, the gradual increment in WLAN data rates [5] [6], and the proliferation of laptops, smart phones, and Personal Digital Assistants (PDAs).

By 2012, some analysts are forecasting that more than one billion such WLAN devices will be shipped globally every year [7]. Owing to such increase in the number, the Industrial, Scientific, and Medical (ISM) radio band over which most of the WLANs operate is going to be more crowded. More precisely, the user density per channel in the ISM band is going to increase because each WLAN selects the wireless channel(s) from the pool of total[1] available channels using suitable channel selection algorithms [8].

Among many issues including compatibility and co-existence with other networks in the ISM band [9], security [10], mobility management [11], and power consumption [12], one of the fundamental issues in WLAN is how to share the assigned channel among multiple users in such a way that not only the utilization of the channel is maximized but also the transmission delay is minimized, while allowing individual users to use the channel in a fair manner. As the user density per channel increases, however, properly addressing such issues is quite challenging, especially if the channel sharing policy is user-driven. Other supplementary issues which might be equally important in some cases could be Quality of Service (QoS) provisioning and maximizing reliability of the transmission. In this dissertation, we present some protocols that address aforesaid fundamental and supplementary

[1]The number of total available channels varies from region to region due to each region's regulations on radio spectrum allocation. In particular, European and North American countries allow 13 and 11 channels, respectively, on 2.4 GHz ISM band, while Japan allow all 14 channels.

issues in simple and effective ways than the standardized protocols in IEEE 802.11 [13] do.

1.1.1 Medium Access Control Protocols

How to efficiently assign or allocate given resources between multiple entities is a fundamental problem in any resource sharing system. It arises in variety of contexts, wireless networking is not an exception.

In wireless networks, when several users want to use the common wireless resource (channel) for transmitting their packets, a well defined protocol is needed to regulate their access to the shared resource. Due to the independent transmission activities of users, a user does not have any knowledge on when another user requires the channel to transmit a packet. Thus such protocol which is popularly known as Medium Access Control (MAC) protocol is indispensable to prevent packet collisions, occurrences of simultaneous transmission from two or more users, as they waste scare wireless bandwidth and limited transmitting power. Depending on the networks characteristics (architecture, topology, targeted application etc.) various MAC protocols have been developed so far. Those MAC protocols can be broadly categorized as contention-free and contention-based [14].

Contention-free protocols are mostly based on fixed assignment of the channel resources to the users. Such fixed assignment protocols allow each user to access the channel by using a predetermined schedule.

For example, in Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA) each users are allowed to access the channel by using a predetermined time slot, frequency band and code, respectively. Since the channel access schedule is fixed, the transmission is guaranteed to be conflict-free [15]. Such predetermined assignments, however, should be tightly controlled by a coordinator (for example, base station or access point) and are not adaptive to frequent changes in traffic pattern of users. The lack of adaptiveness results in wastage of channel resources when there are quiescent users in the network, while the requirement of central coordinator hinders its usage in infrastructure-less distributed wireless networks. Demand assignment based protocols provide contention-free channel access even in absence of central coordinator. For example, in the Token Ring protocol [16], a user transmits a packet each time it receives its *token*. However, token-passing schemes rely on knowledge of the current network topology and thus it is not suitable for wireless networks where topology may change frequently.

Unlike the fixed and demand assignment based contention-free protocols, contention-based protocols randomly assign channel resources to the users whenever they have packet to transmit. Thus, packet collision is inevitable in such channel assignment policy. Therefore, the probability of collision increases with increase in the traffic load. Despite the collision prone nature of contention-based protocols, different distributed wireless networks have been using varieties of such protocols because of their simple and flexible operations.

The first contention-based protocol was ALOHA which let users to transmit their packets (lets assume each packet requires T units of time to be transmitted at a given channel rate) at completely arbitrary times. In such a protocol, collision vulnerability for a packet being transmitted is twice the packet transmission duration (i.e $2T$ units) and thus its maximum throughput[2] is low ($\approx 18\%$). Slotted variant of ALOHA [17], in which channel time is divided into discrete slots and users are allowed to transmit only at the beginning of the slot, reduces the vulnerability period to T units and thus maximizes the throughput (as high as $\approx 36\%$). To further reduce the collision vulnerability of the packet being transmitted, a new medium access scheme referred to as Carrier Sense Multiple Access (CSMA) was introduced in which users first listen for a carrier (i.e., a transmission) to find if anyone else is transmitting and act accordingly to avoid possible collisions [18]. It eventually has become the most popular and the fundamental MAC protocol for several practical wireless and wired networks, IEEE 802.3 Ethernet, IEEE 802.11 WLAN, and IEEE 802.15 WPAN, among others. In the subsequent chapters, we will elaborate it considering its adoption in WLAN, highlight the problems that it incorporates, and propose some interesting solutions to those problems.

[2] The throughput is defined as the ratio of the number of packets delivered successfully and the total number of packets possible (assuming perfect coordination).

1.1.2 Degree of Design Freedom

For a given design problem, Degree of Design Freedom (DoDF) is a measure of number of design parameters over which a designer may exert control. For a given design problem, DoDF generally has a fixed value due to the constraints associated with the design problem and the associated design objectives.

Let us consider a CSMA/CA based wireless MAC protocol design problem. Such a design problem has several fundamental design parameters that are directly associated with the CSMA and contention window-regulated Collision Avoidance (CA) mechanisms. Optionally, such a design problem may have several supplementary design parameters that would be crucial in providing various value added benefits by exploiting some special characteristics of the underlying networks, for example, cooperative diversity [19], multiuser diversity [20], Multi Packet Reception (MPR) capability [21] etc.

In this dissertation, we confine our attention to the DoDF related to the fundamental design parameters only. More precisely, we provide a new approach to enhance the performance of the conventional MAC protocol, specified in aboriginal IEEE 802.11 standard, by introducing a new design approach consisting of an additional DoDF as depicted in Table 1.1. The precise definition of all of those tabulated design parameters will be made available in the subsequent chapters.

Table 1.1: DoDF in CSMA based MAC protocols presented in this dissertation

(DoDF) Design Parameters	Remarks
(1) Carrier sense related parameter	Retained from conventional design
(2) Initial and Max CW Size	Retained from conventional design
(3) CW expand/shrink exponent	Retained from conventional design
(4) Permissible number of retries	Retained from conventional design
(5) Skewed Contention Slot Selection Distribution (CSSD) over CW	**Additional**

1.2 Contributions of Dissertation

This dissertation aims at contributing to the field of distributed wireless networking. In particular, among the seven dedicated layers of the wireless networking protocol suite, the focus of this study is on the MAC sub-layer of the data link layer. In this dissertation, we present some innovative approaches that improvise the standardized contention-based unicast and broadcast IEEE 802.11 MAC protocols in a standard-complaint way without abolishing their original simplicity.

The first contribution of this dissertation is dedicated to improvise the unicast Distributed Coordination Function (DCF) specified in IEEE 802.11. In particular, the standardized channel access arbitration mechanism in DCF, CSMA with random backoff based CA, is improvised by adding an additional DoDF to the conventional contention parameter set that is responsible for regulating the random backoff procedure. More precisely, in the improvised DCF, Contention Slot Selection Distribution (CSSD) over the contention window is allowed to have a non-uniform shape (unlike the uniformly flat distribution as per the conventional design) and adaptively tune its shape. Taking a doubly-truncated Normal CSSD as an example, we present a simple mechanism to dynamically tune its shape. By virtue of rigorous performance analyses that are carried using computer simulations in ns-2 and a newly developed analytical model, which consists of a 3D Discrete Time Markov Chain (3D DTMC) based user model and a Renewal Reward Process (RRP) based network model, we demonstrate that the improvised DCF significantly outperforms the legacy DCF in all aspects of network throughput, throughput-fairness of individual users and packet transmission delay, for the case when the network is heavily-loaded and the channel is error-free.

In our next contribution, we extend the analytical model that we develop to estimate the network throughput performance of the improvised DCF. In particular, we relax the two previously made ideal assumptions: error-free physical layer (L1) and saturated (always non empty) queue at MAC layer (L2). It is necessary to relax those ideal assumptions because the wireless medium is generally error-prone and the arrival of the packets at L2 queue is generally bursty resulting in non-saturated queue occupancy. The extended cross-layer (L1/L2) analytical model considers the effect of Rayleigh fading induced bit errors in L1 and non-saturated queue occupancy due to Poisson packet arrival at L2 queue. We further validate the extended analytical model using computer simulation is ns-2. By virtue of the validated numerical results, we show that the improvised DCF has definite benefit in terms of network throughput over the conventional DCF even in the arbitrarily loaded network with erroneous channel.

Our next contribution supplements the previous contribution, the design of the improvised unicast MAC protocol, by extending that design to support QoS. One of the fundamental basis of QoS differentiation in the IEEE 802.11e WLAN is to differentiate various channel access parameters for *initiating* and *pursuing* channel contention. More precisely, the duration of the channel access parameters (arbitration inter frame space number and contention window) for the priority classified packets are made inversely proportional to their priority levels such that the higher priority packets have smaller values for their contention parameters, which thus privilege them to possibly win contention even in the presence of the lower priority packets. However, as the number of the lower priority packets increases, frequent inventible channel access priority inversions and inter-class packet collisions degrade the perceived QoS grade of the higher priority packets. We identify that the frequency of occurrence of such problematic events would be higher if the improvised unicast MAC is directly adopted in IEEE 802.11e due to its nature of using dynamic non-uniform CSSD over the contention window. Hence, we develop a mechanism referred to as Push CSSD Mean Right (PCMR) which aims to reduce both the chances of priority inversions and inter-class packet collisions. Via computer simulations in ns-2, we demonstrate the effectiveness of the PCMR.

Finally, the last contribution of this dissertation is dedicated to improvise the broadcast DCF specified in IEEE 802.11 because the underling mechanism of arbitrating the access attempts of multiple broadcast users (using a fixed-size temporal contention window consisting of multiple contention slots having uniform selection probability) in the legacy broadcast DCF has been well understood to be inefficient in terms of broadcast reliability and network throughput, especially when the network population is large. We show that such inefficiencies can be reduced by specifying the additional DoDF (i.e CSSD over contention window) to take the reverse-exponential shape. By virtue of rigorous performance evaluation carried using a custom simulator developed in Matlab and a newly developed analytical model consisting of a 1D DTMC based user model and a RPP based network model, we demonstrate that the improvised broadcast DCF significantly outperforms the legacy broadcast DCF in terms of broadcast reliability and network throughput. The aforesaid performance metrics remain almost intact (i.e., do not falls down sharply) irrespective of contending population size making this broadcast MAC a scalable one.

Scholarly publications based on the contributions of this dissertation are listed in Appendix A.

1.3 Organization of Dissertation

The remainder of this dissertation is organized as follows. Chapter 2 presents background information on WLANs and the networking protocol suite for WLANs. Different standard unicast, broadcast, and QoS-differentiated MAC protocols for a typical IEEE 802.11 based WLAN are comprehensively discussed. In Chapter 3, an improvised unicast MAC protocol is presented. Detail analytical and simulation based analysis of the improvised unicast MAC protocol is presented to show its superiority over its conventional counterpart. In chapter 4, the analytical model to estimate the network throughput performance of the improvised unicast MAC protocol is extended to capture additional MAC and PHY layer details. Simulation results for the validation of the extended model are also presented. Chapter 5, extends the previous design of the improvised unicast MAC protocol to support QoS. Rigorous simulation based performance analysis of the improvised QoS-differentiated MAC protocol is presented to show its superiority over its conventional counterpart, refereed to as EDCA in IEEE 802.11e. In Chapter 6, an improvised broadcast MAC protocol is introduced and its performance is evaluated. Finally, Chapter 7 concludes the dissertation.

2 Wireless Local Area Networks

In this chapter, we provide brief overview of WLAN topology, WLAN protocol suite, standardization activities for WLAN, and some standarized WLAN MAC protocols that will facilitate the understanding of the contributions presented in this dissertation.

2.1 Overview of WLAN

WLAN is a flexible communication network which has emerged as an extension to, or as an alternative for, its wired counterpart. Using radio frequency or infrared technology, WLAN transmits and receives information over the wireless channel thereby minimizing the need for dedicated wired connections. Thus, WLAN provides network users the freedom of mobility and reduce network deployment costs. WLAN standardization with IEEE 802.11 and certification with *WiFi* [22] (for interoperability between 802.11 devices from different manufacturers) have led to the increased adoption of this technology at homes, offices and public area.

WLAN has been popularly used either as a *last hop* connection to the Internet or as an stand-alone *ad hoc* network. In a typical last hop WLAN in Fig. 2.1 (left), network users A, B, or C can either connect itself to the Internet or to other network users via AP, while the network users in Fig. 2.1 (right) can directly communicate with each other, as long as they lie within the radio coverage of each other.

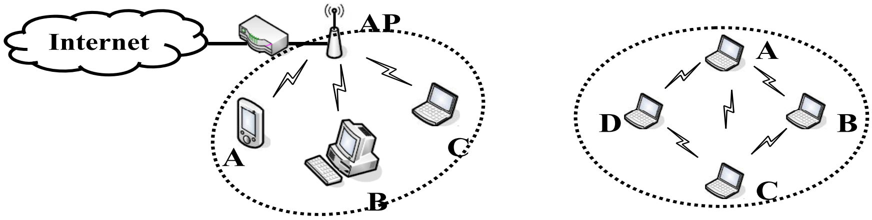


Figure 2.1: An example of WLAN: the *last hop* access network (left), and *ad hoc* network (right)

In IEEE 802.11 terminology, the last hop topology is known as Infrastructure Basic Service Set (BSS) while the AP-less *ad hoc* topology is known as Independent Basic Service Set (IBSS).

The coverage of a WLAN can be increased using multiple BSSs interconnected via a Distribution System (DS) as shown in Fig. 2.2. Such multi BSS service set is known as Extended Service Set (ESS). In ESS, the DS does not necessarily be a wired connection. In most practical ESSs, however, major portion of the DS is the Wired Ethernet [23].

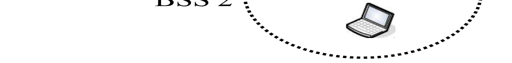


Figure 2.2: A typical example of ESS

2.2 WLAN Protocol Suite

In a general sense networking protocol suite for a communication system is a formal description of a set of rules, procedures, and formats for exchanging data among the network users. The software implementation of such protocol suite is known as a protocol stack.

The protocol stack for WLAN is based on Open System Interconnection(ISO/OSI) reference model developed by International Standard Organization (ISO) [24]. The reference model is an idealized model with seven different layers (L1-L7)[1], as shown in Fig. 2.3, where every layer is responsible for a different facet of the communications.

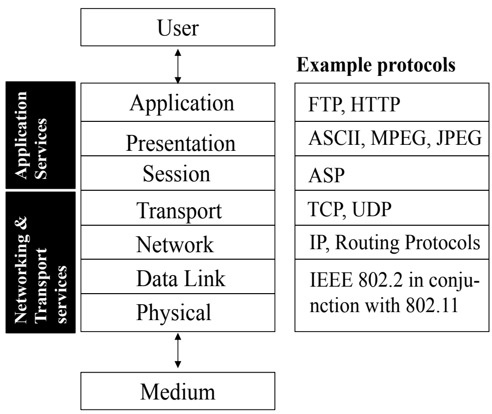


Figure 2.3: Layered architecture of the OSI reference model and some representative protocols at each layer

[1]Practical WLAN protocol stack does not necessarily confirm exactly to the seven layer structure. For example some protocols combine the functions of two or more of the layers in the model, and the boundaries between protocols may not exactly conform to the layer boundaries of the OSI model [25].

For precise function of protocols residing on each layer refer to [26] [27]. From the networking perspective, the four lower layers (L1-L4) are very important for realizing the efficient and robust communication between the networking users. In particular, L4 and L3 protocols provide end to end flow control and routing functionalities, respectively, while the L1 and L2 protocols are responsible for establishing and continuing peer-to-peer communications.

2.3 Standardization of WLAN

Similar to the evolution of wired LAN, several different WLAN technologies and standards have come and gone, for example HiperLAN from European Telecommunication Standardization Institute (ETSI) [28]. Today, there is one standard that is almost synonymous with the term WLAN, i.e IEEE 802.11 and its variants. Table 2.1 list several different IEEE standards that have already been approved or are in the process of being approved [2]. In a recent paper [29], Hiertz *et al.* has nicely surveyed the various IEEE 802.11 standardization activities. Based on that survey, in what follows, such standardization activities are briefly summarized.

The first 802.11 standard was published in 1997. It covers the issues related to the lower two layers (L1 and L2) of the networking protocol stack. It defines radio-based and Infrared (IR)-based Physical layer

[2] Sign $*$ in the table indicates the expected approval date

(PHY) technologies that provide mechanisms for making wireless

Table 2.1: List of several variants of IEEE 802.11 standard

Series	**Approval Date**	**Title**	**Remark**
802.11	1997-06-26	IEEE standard for WLAN MAC and PHY specifications	Initial standard
802.11a	1999-09-16	Higher Speed PHY extension in the 5 GHz band	54 Mbps, OFDM PHY
802.11b	1999-09-16	Higher Speed PHY extension in the 2.4 GHz band	11 Mbps, DSSS PHY
802.11g	2003-06-12	Further higher data rate extension in the 2.4 GHz	54 Mbps, OFDM PHY
802.11e	2005-09-22	MAC enhancements	Support for QoS
802.11n	2009-09-11	Enhancement for higher throughput	600 Mbps, MIMO PHY
802.11p	2010-06-30	Wireless access for vehicular environment	Closely related to IEEE 1609
802.11s	2010-09-30	Mesh networking	Transparent multihop operation
802.11z	2010-01-31	Extension to Direct Link Setup (DLS)	AP independent DLS
802.11ac	2012-12-31*	Very high throughput (below 6 GHz band)	Enhancements for greater than 1 Gbps throughput
802.11ad	2012-12-31*	Very high throughput (in 60 GHz band)	Enhancements for greater than 1 Gbps throughput

transmissions and receptions. Although IR-based PHY at 316-353 THz provides a basic data rate of 1 Mbps with an optional 2 Mbps mode, as in the case of the radio-based Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) [30] at 2.4 GHz, the IR-based PHY implementations are not popular [29]. With a slight modification to IEEE 802.3 Ethernet, IEEE 802.11 specifies a contention-based MAC protocol that operates according to a listen-before-talk manner by employing CSMA/CA scheme. In addition to the contention-based MAC, it also specifies an optional contention-free polling-based MAC protocol which, however, is not adopted by WLAN product manufacturers. Those MAC protocols are comprehensively discussed in Section 2.4.

2.3.1 Amendments in PHY Layer

Two PHY layer amendments were added to the IEEE 802.11 standard in the year 1999, namely IEEE 802.11b and IEEE 802.11a. The IEEE 802.11b provides an extension to the DSSS PHY, providing increased data rates up to 11 Mbps, using a modulation scheme known as Complementary-Code Keying (CCK) [31]. Meanwhile, the other amendment, IEEE 802.11a, defines a new radio-based PHY at 5.2 GHz that provides data rates up to 54 Mbps using a transmission technique known as Orthogonal Frequency-Division Multiplexing (OFDM)[32]. However, the IEEE 802.11a amendment have brought a serious challenge regarding its compatibility to IEEE 802.11b. In addition, the use of 5.2 GHz carrier in Europe was generally restricted, making IEEE 802.11a popular only in North America [33]. To address those issues, in 2003, a new amendment known as IEEE 802.11g was introduced. It has similar PHY specification as that of IEEE 802.11a (use of OFDM, data rate up to 54 Mbps), but it operates over 2.4 GHz carrier. In addition, it also ensures backward compatibility with the older 802.11b devices.

In 2009, a high throughput IEEE 802.11n was ratified which support up to 600 Mbps. The support of hundreds of Mbps data rates has been achieved using several advanced communications and signal processing techniques which include Multiple Input Multiple Output MIMO, higher modulation and coding, and channel bonding, among others. Moreover, upcoming IEEE 802.11ac and IEEE 802.11ad are targeting beyond gigabit rates over 5 GHZ and 60 GHz band, respectively [34].

2.3.2 Amendments in MAC Layer

Fig. 2.4 depicts the several representative MAC amendments added to the aboriginal IEEE 802.11 standard. The aboriginal 802.11 standard did not support QoS differentiation. In the year 2005, an amendment, popularly known as 802.11e, was added to it. The amendment introduces a new medium access scheme known as Hybrid Coordination Function (HCF) consisting of the following two schemes: HCF controlled channel access (HCCA) and Enhanced Distributed Channel Access (EDCA). The first scheme is an improvised variant of the

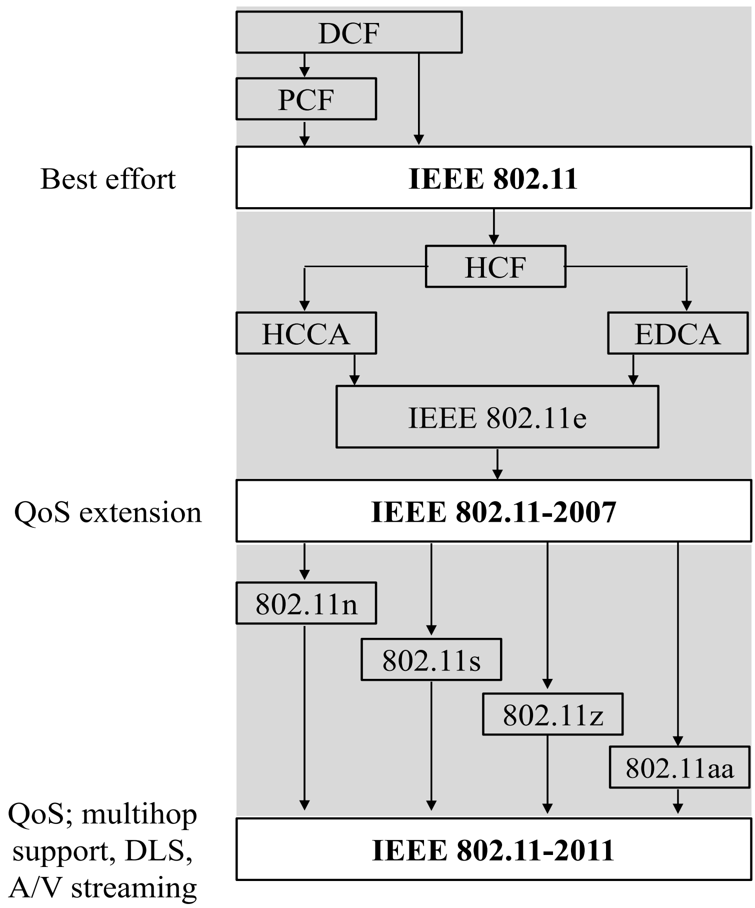


Figure 2.4: Representative IEEE 802.11 MAC amendments

contention-free polling based PCF while EDCA is the improvised variant of the best-effort DCF which provides QoS differentiation between traffic with different QoS requirements. Until recently, 802.11 devices with HCCA implementation has not appeared in the market.

Beside QoS related amendment, several amendments have been added, over the last decade, to the IEEE 802.11. IEEE 802.11n (MAC efficiency enhancement), 802.11s (multihop transmission in mesh networks), 802.11z (improvised Direct Link Setup (DLS)), and 802.11aa (effective audio/video streaming), are some representative amendments, among many others.

2.4 Standardized MAC Protocols for WLAN

IEEE 802.11 and its variants have standardized the following contention-based as well as contention-free MAC protocols to share the common wireless channel among multiple users: DCF, PCF, and HCF. Fig. 2.5 depicts the IEEE 802.11 MAC architecture consisting of those aforesaid MAC protocols. Note that ① is the mandatory MAC scheme that is used for contention services and also serve as basis for PCF and HCF, ② is an optional MAC scheme required for contention-free services for users with no QoS requirements, ③ is required for prioritized QoS service, and ④ is required for parameterized QoS service. The scope of this dissertation falls within ① and ③. Hence, in what follows, we describe them in detail.

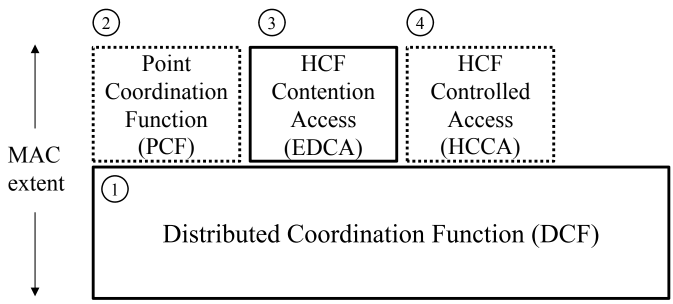


Figure 2.5: IEEE 802.11 MAC architecture

2.4.1 Unicast and Broadcast Best Effort MAC Protocols

Unicast is a type of transmission in which information is sent from a sender to only one receiver. On the other hand, broadcast is a different type of transmission in which information is sent from a sender to all users in its vicinity. For unicast best effort services, IEEE 802.11 specifies a CSMA/CA based DCF for sharing a broadcast channel among multiple users. Fig. 2.6 shows the flow chart of channel access mechanism specified in DCF. For broadcast service, a simplified DCF has been specified. The flow chart for the broadcast DCF is same as for the unicast DCF, but without the states in the black background of the figure.

DCF is a contention-based best-effort MAC protocol. As per this MAC, each user in the network determines individually when to access the channel based on CSMA/CA. This protocol comes in two flavors: the basic access mechanism and the Request-to-Send/Clear-to-Send (RTS/CTS) access mechanism. The principle to determine the transmission schedule is same regardless of the access mechanism.

The basic access mechanism requires each contending user to perform carrier sensing[3] operation to determine whether the channel is idle or busy. If the channel is found to be idle for a period of time equal to

[3]Using both the physical carrier sensing and the virtual carrier sensing. For virtual carrier sensing a timer known as Network Allocation Vector (NAV) is provisioned which is triggered by listening the *duration field* of the overheard packets.

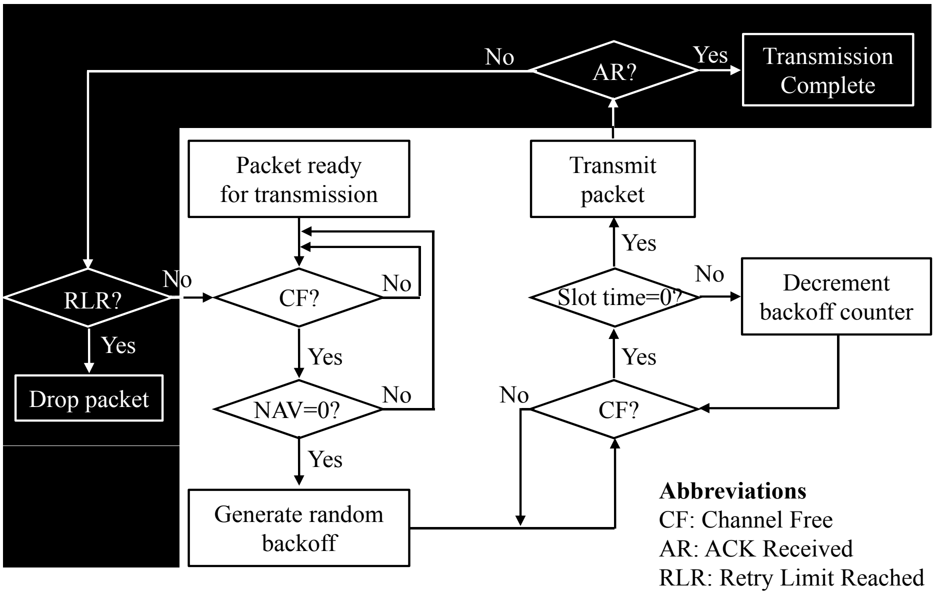


Figure 2.6: Channel access mechanism in DCF

Distributed Inter Frame Space (DIFS), the user transmits its packet. Otherwise, it waits until the channel becomes idle for DIFS period and then selects a random backoff time[4] for which it should defer its transmission. The selected value is uniformly distributed in the interval $[0, CW - 1]$, where CW is the current contention window size. Once the channel has been found to be idle for DIFS, the backoff timer is decreased by one at the elapse of every idle slot until either the channel becomes busy again or the backoff timer reaches zero. If the timer has not reached zero and the channel becomes busy, the contending user freezes its timer. When the timer is finally decremented to zero, the

[4]It is calculated in unit of physical slot duration. It represents the number of empty slots the contending user must observe on the channel before making its transmission.

user transmits its packet. If the intended receiver correctly receives the transmitted packet, it confirms the reception of the packet by sending a positive acknowledgement (ACK) after a Short Inter Frame Space (SIFS) time. If the transmitting user does not receive the ACK within a certain timeout duration, it computes backoff time for retransmission according to Binary Exponential Backoff (BEB) rules [35] and follows the similar mechanism as in its failed transmission attempt until the packet is successfully transmitted or the maximum retransmission limit is reached.

The RTS/CTS based mechanism appears as an enhancement to the basic access mechanism. It reduces contention resolution overhead in terms of channel waste time due to packet collisions by reserving the channel for data transmission using short RTS and CTS packets. A user that has a packet to transmit follows the same process exactly as in the basic access mechanism, however, when the backoff counter reaches zero, it sends a special reservation packet called RTS packet. The intended receiver responds with CTS packet after SIFS interval. Other users who overhear RTS and CTS update their NAVs accordingly. Upon receiving the CTS, the source releases its data packets after SIFS interval. The rest of the other remaining process are identical to that of the basic access mechanism.

2.4.2 QoS Differentiated MAC Protocol

The QoS differentiation mechanism in WLAN was first introduced in IEEE 802.11e. The mechanism is based on a relative differentiation framework. According to that framework, several channel access parameters of the priority-classified contending packets are differentiated according to their priorities. More precisely, the duration that the network users should sense the channel to be idle in order to *initiate* and *pursue* the contention over the shared channel (Arbitration Inter Frame Space (AIFS) and the contention window for generating random backoff, respectively) are specified in a such a way that they remain inverse-proportional to the corresponding priorities of the contending packets. That is, the higher the priority of the contending packet is, the shorter will be the AIFS and contention window. Such differentiation thus privileges the higher priority packets to finish their contention earlier for being transmitted over the shared channel, while the lower priority packets are still contending.

IEEE 802.11e EDCA is a QoS extension of DCF. EDCA maps packets from higher layers with a specific user priority value (as defined in IEEE 802.1D bridge specification [36]) into corresponding Access Category (AC) and differentiate various channel access parameters for packets belonging to different ACs, as shown in Fig. 2.7. EDCA defines the following four ACs for each user (more precisely, a station[5]

[5]In this dissertation, we use the term user and station interchangeably.

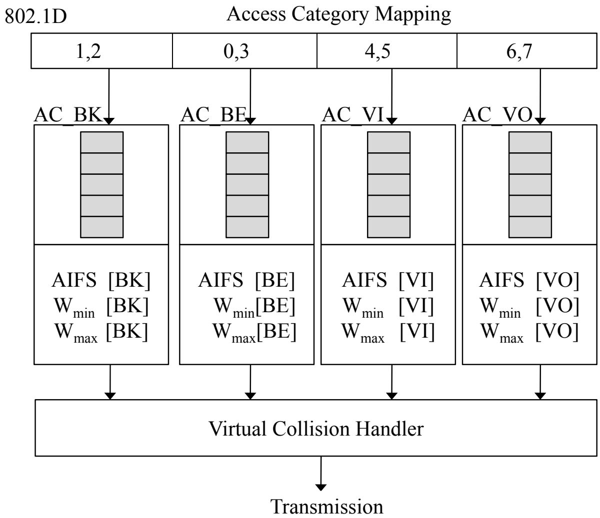


Figure 2.7: Mapping user priorities to access categories

belonging to the user): AC_VO (voice), AC_VI (video), AC_BE (best effort) and AC_BK (background). AC_VO has the highest priority, while the AC_BK has the lowest priority.

Each AC accomplishes the differentiated channel access for the packets in its queue in the similar fashion as DCF does, but with differentiated channel access parameters. The parameter for initiating the channel contention, namely AIFS[AC], and the parameters for pursuing the channel contention, namely the initial and maximum contention window sizes (W_{min}[AC] and W_{max}[AC]), are made inversely proportional to their priority levels. In other words, for the ACs of higher priorities, their AIFS[AC] and CW[AC] are smaller than those of lower priority ACs. Therefore, the higher priority ACs can decrement their relatively smaller backoff counters while lower priority ACs are still waiting their AIFS to finish. Thus higher priority ACs are likely to win contention and access the medium earlier.

Upon gaining access to the channel, each AC may transmit multiple packets as long as the total access duration does not exceeds the AC-specific Transmission Opportunity (TXOP) duration.

2.5 Concluding Remarks

In this chapter, we have provided a brief overview of WLAN and some of its representative standardization activities. We have reviewed two fundamental contention-based MAC protocols for best-effort and QoS-differentiated services. Even though those protocols suffers from some serious problems, especially when the traffic load increases in the network, they have become *de facto* MAC for all commercially available WLAN products. In the subsequent chapters, we will highlight their most crucial problems and present our innovative solutions to those problems.

3 Improvised Contention-based Unicast MAC

In this chapter, we propose an interesting concept to improvise the conventional contention-based unicast MAC specified in IEEE 802.11. Theoretical and simulation based analysis are presented to show its superiority over its conventional counterpart.

3.1 Motivation

As described in the previous chapter, DCF is the *de-facto* contention-based MAC protocol to share the common broadcast channel among multiple users within a WLAN. It has adopted a CSMA/CA scheme to arbitrate access attempts of multiple contending users. It works fairly well for light traffic load [37]. As the number of contending users increases, however, DCF does not perform well because it incurs high overheads in terms of channel-waste-time due to frequent packet collisions and channel-idle-time due to random backoff delays. As a consequence, the packet transmission delay is increased [38] while the network throughput as well as throughput fairness [39] of contending users are decreased [40],[41]. Hence, designing a MAC protocol that can simultaneously provide the following desirable properties: (i) high network throughput, (ii) low packet transmission delay, and (iii) throughput fairness among contending users, is still a fundamental research problem.

In this chapter, we present a solution to address the aforesaid problem. Our solution simply improvises the conventional CSMA/CA by exploiting an additional DoDF to control the Transmission Probability (TP) of contending users during ongoing collision resolution process. In particular, in the improvised scheme which we refer to as CSMA/iCA, the shape of CSSD over CW is adaptively tuned, which used to be flat (uniformly distributed) in the conventional scheme. The CSSD tuning mechanism is designed to meet the following attributes: (i) compensating the long backoff delay in the failed access by provisioning re-access with the shorter backoff delay, and (ii) mitigating collisions as much as possible to reduce collision resolution overheads. In subsequent sections, we will show that the former attribute enhances the throughput fairness of competing users, even in short time-scale, while the later attribute enhances network throughput and reduces transmission delay.

3.2 The Improvised MAC: CSMA/iCA

3.2.1 Overview

The conventional CSMA/CA constitutes of two fundamental mechanisms: carrier sensing along with a collision avoidance and resolution mechanism. These mechanisms jointly regulate how the common broadcast channel is shared by multiple users in a distributed manner. The carrier sensing mechanism allows contending users to access the channel only when it is found to be unoccupied while the random backoff based collision avoidance and resolution mechanism controls the TP of each contending user using a CW consisting of multiple contention slots.

The proposed CSMA/iCA can be understood as an enhancement to the legacy counterpart pertaining to the collision avoidance and resolution mechanism, while the carrier sensing mechanism is kept as it is. In the conventional collision avoidance and resolution mechanism, the TP of each contending user is controlled by changing CW size according to BEB algorithm upon witnessing success or failure of the most recently transmitted packet. On the other hand, in the proposed scheme, TP is controlled not only by changing CW size but also by adaptively changing the shape of CSSD over CW. In other words, a non-uniform CSSD is specified over CW, instead of specifying the statically flat (uniformly distributed) CSSD as in the legacy collision avoidance and resolution mechanism, whose shape is regularly tuned during ongoing collision resolution process.

To dynamically tune the shape of CSSD, we formulate mapping relations wherein the shape of CSSD is reflected as the functions of CW and a new parameter referred to as History Backoff Value (HBV). The parameter HBV is the backoff value with which a contending user started its backoff for the previously transmitted packet. Details of the mapping functions will be made available in the subsequent subsection.

The improvised collision avoidance feature of CSMA/iCA can be understood from both local perspective of individual contending user

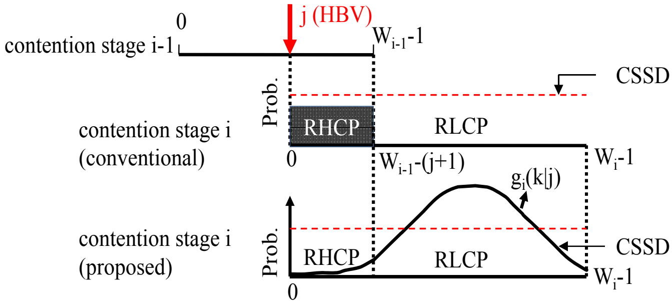


Figure 3.1: Adaptive tuning of CSSD in i-th contention stage according to HBV j in the $(i-1)$-th contention stage

and global perspective of the common broadcast channel (i.e. collective perspective of all users in the network). From the local perspective, the improvised collision avoidance looks simple. It consists of two straightforward processes: classification and prioritization of the contention slots over CW. Contention slots over CW are classified into two sets based on HBV, Relatively High Collision-Prone (RHCP) and Relatively Less Collision-Prone (RLCP), and slots belonging to RLCP set are prioritized by tuning CSSD as shown in Fig. 3.1. An illustrative example in Section 3.2.3 would be helpful to understand this concept. From the global perspective, the improvised collision avoidance logically divides the contending users into several smaller groups such that the collision chances of the transmitted packets among the intra-group users as well as the inter-group users are reduced as illustrated with an example in Section 3.2.3.

The proposed CSMA/iCA can be easily incorporated in the standard DCF as shown in Fig. 3.2 without abolishing the original sim-

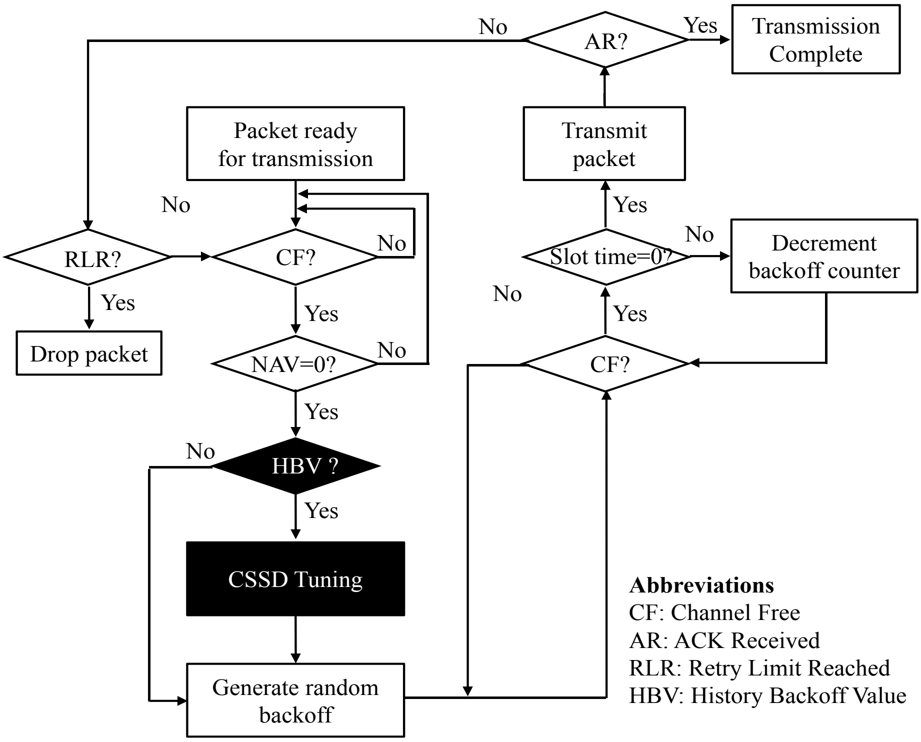


Figure 3.2: Channel access mechanism in the improvised DCF

plicity of DCF. Note that, in the figure, only the operations presented in the black-colored box are appended while the rest other operations are same as in Fig. 2.6.

3.2.2 Operational Mechanism of CSMA/iCA

Let us denote CSSD over a CW containing k number of slots with $g(k|j)$, where j is the HBV. We design $g(k|j)$ to be a doubly-truncated Normal distribution [42]. For contention stage i, $i \in [1, m]$, it takes the shape defined by the following relation:

$$g_i(k|j) = \begin{cases} \frac{h_i(k)}{\int_{T_{i,l}}^{T_{i,r}} h_i(k)dk}; & T_{i,l} \leq k \leq T_{i,r}, \\ 0; & \text{elsewhere}, \end{cases} \tag{3.1}$$

where m is the maximum allowed retry limit; $h_i(k)$ is the normal probability distribution function with mean μ_i and standard deviation σ_i; $T_{i,l}$ and $T_{i,r}$ are the truncation points at the left and the right, respectively. In (3.1), $h_i(k)$ is normalized with $\int_{T_{i,l}}^{T_{i,r}} h_i(k)dk$ so as to converge $\sum g_i(k|j)$ over the CW to 1. The shape of CSSD $g_i(k|j)$ thus can be uniquely characterized with quad-tuples $\{\mu_i, \sigma_i, T_{i,l}, T_{i,r}\}$.

To adaptively tune the CSSD during ongoing collision resolution process, we need to specify the value of the quad-tuples $\{\mu_i, \sigma_i, T_{i,l}, T_{i,r}\}$ for each contention stage i. So, we formulate two simple mapping relations to specify the first two tuples while utilize BEB algorithm to specify the values of the last two tuples. The two mapping relations

$$\begin{aligned} \mu_i &= f_{i,1}(j, W_i) \quad \text{and} \\ \sigma_i &= f_{i,2}(j, W_i) \end{aligned} \tag{3.2}$$

are designed to be the functions of CW size W_i and HBV j in contention stage $i-1$, where

$$f_{i,1}(j, W_i) = \lfloor (W_i - 1) \cdot (1 - \psi_i(j)) \rfloor, \quad \psi_i(j) \in [0, 1], \tag{3.3}$$

and

$$f_{i,2}(j, W_i) = \begin{cases} \left(\frac{W_i \cdot (1+2\cdot\psi_i(j))}{4}\right)^{\frac{1}{2}} & 0 \le \psi_i(j) \le 0.5 \\ \left(\frac{W_i \cdot (3-2\cdot\psi_i(j))}{4}\right)^{\frac{1}{2}} & 0.5 < \psi_i(j) \le 1. \end{cases} \tag{3.4}$$

The $\psi_i(j)$ in (3.3) and (3.4) is the HBV j normalized with the CW size in previous contention stage $i-1$, i.e., $\psi_i(j) = \frac{j}{W_{i-1}-1}$, $\forall j \in [0, W_{i-1}-1]$. The linear function $f_{i,1}$ in (3.3) shifts μ_i of the CSSD over CW (i.e., peak of the distribution) towards the RLCP slots. In such situation, a RLCP slot "near" the slot pointed by the value of μ_i is more likely to be selected. Note that it is σ_i which determines how close will be the selection near the slot pointed by μ_i. The smaller is the σ_i value, the nearer will be the selection. The last two tuples can simply be updated considering the backoff algorithm being used. For example, in case of the BEB algorithm they can be updated as follows:

$$T_{i,z} = \begin{cases} 0; & z = l, \\ min[2^i W_0 - 1, W_{max} - 1]; & z = r, \end{cases} \tag{3.5}$$

where W_0 and W_{max} are the initial CW size and the maximum-allowed CW size, respectively.

Shape of the CSSD $g_i(k|j)$ for contention stage $0 < i \le m$ is tuned by specifying the values of the quad-tuples $\{\mu_i, \sigma_i, T_{i,l}, T_{i,r}\}$ obtained from (3.3),(3.4) and (3.5). For the initial contention stage (i.e., $i = 0$), CSSD is kept flat (uniform distribution) over the CW as in the conventional scheme because HBV is not available at that stage.

3.2.3 Characteristics Feature of CSMA/iCA

CSMA/iCA has two types of characteristic features: *explicit* and *implicit*. Explicit features are those that can be perceived in the context of a single access attempt, while implicit feature is realizable only when evolution of back-to-back access attempts from multiple contending users is considered.

A. Classified-Collision Avoidance: Classified-collision avoidance is an explicit feature of CSMA/iCA. By "classified-collision avoidance" we refer to the avoidance of a particular type of collision that would possibly occur if the accesses are made using the contention slots in the overlapped portion of the adjacent CWs [43], [44]. The following example illustrates this feature.

Let us assume that a group of users that are in their $(i-1)$-th contention stage are contending for getting access to the channel. Let us further assume that $G1(\geq 2)$ number of users from the group select the same contention slot j_{G1} in the window $[0, 31]$ and the rest $G2$ STAs select their contention slots larger than j_{G1}. In this scenario, collision occurs at j_{G1}. After EIFS, the collided users double their CW and randomly select any slot in their expanded CW for the next access. Note that some part of the expanded CWs of the $G1$ users, overlaps with CWs of the $G2$ users. In this situation, if the collided $G1$ users select any of the slots from the overlapped portion, it is more likely that they would collide with any of the $G2$ users because the $G2$ users have already picked up the slots in that portion before the $G1$ users have initiated their i-th contention resolution round. Hence, it is desirable to minimize slot selection probability in the overlapped portion, in order to enhance the collision avoidance feature.

According to the proposed scheme, all the collided $G1$ users tune their CSSD by calculating the quad-tuples $\{\mu_i, \sigma_i, T_{i,l}, T_{i,r}\}$ based on their HBV j_{G1}. For a special case when $j_{G1} = 0$, the quad-tuples are updated to $\{\mu_i = 63, \sigma_i = 4, T_{i,l} = 0, T_{i,r} = 63\}$. The resulting shape of CSSD according to the updated quad-tuples is shown in Fig. 3.3 (case when $\psi_i = 0$). From the figure one can see that the selection likelihood of the contention slots in overlapped portion (filled rectangle) is very low. Thus, collision chances among $G1$ and $G2$ users are lowered.

B. Collision mitigation through partitioning of contending pool: It is an implicit feature of CSMA/iCA. By "collision mitigation through partitioning of contending pool" we refer to the process that logically divides a large pool of contending users into multiple groups containing smaller number of users in such a way that collision chances among intra-group and inter-group users will be reduced.

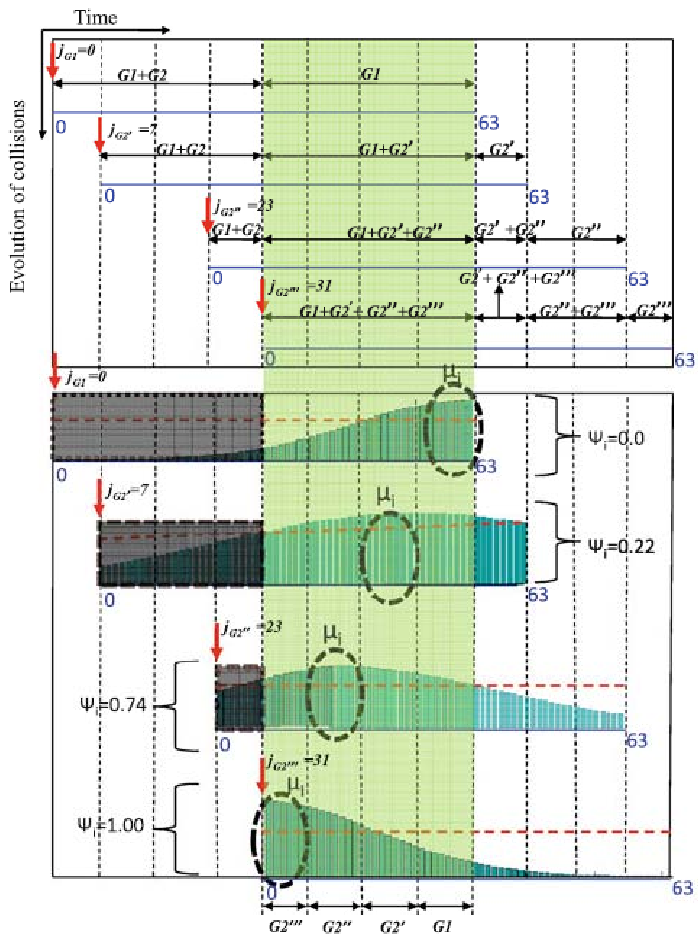


Figure 3.3: An explanatory illustration of the characteristics features of CSMA/iCA

Recall the previous example. Let us further assume temporal evolution of successive collisions of the $G2$ users as shown in Fig. 3.3 (in the figure collisions are indicated with downward pointing arrows). For example, some $G2'$ users among $G2$ users make their transmission using a slot $j_{G2'} = 7$ which results in a collision. Similarly, transmissions of some $G2''$ users among the remaining $(G2-G2')$ users collide at slot $j_{G2''} = 23$ and transmissions of some $G2'''$ users among the remaining $(G2 - G2' - G2'')$ users collide at $j_{G2'''} = 31$.

In the legacy collision resolution mechanism, upon identifying collisions at $j_{G1} = 0$, $j_{G2'} = 7$, $j_{G2''} = 23$ and $j_{G2'''} = 31$, the users involved in the collision double their CWs to 64 where the expanded CWs have flat CSSD. For such window expansion, the broadcast channel perceive the access arbitration of the contending users as shown in Fig. 3.3 (top). In the figure, the number of users that can access the channel by selecting any of the contention slots within a marked fraction (double arrowed horizontal line) of the expanded CW is indicated. For example, after all considered collision instances, $(G1+G2'+G2''+G2''')$ users compete for each of the contention slots within the fraction of the expanded CW highlighted with the grey rectangle.

On the other hand, if the collision resolution is carried as per the proposed scheme, the shape of CSSDs over the expanded CWs are dynamically updated based on respective HBVs utilizing (3.3), (3.4), and (3.5). Bottom part of Fig. 3.3 depicts the shape of the tuned CSSDs. In the figure, the dotted ellipses corresponds to the region where selection of the contention slots are more likely. As such, the total (G1+G2) users gets logically divided into multiple groups containing $G1$, $G2'$, $G2''$, and $G2'''$ users where collision chances among inter-group users will be reduced because the peaks of the CSSD of those smaller groups (dotted ellipse in the figure) are sufficiently apart. Furthermore, intra-group collision chances will also be reduced because the logically divided groups contain smaller number of users.

C. Backoff Delay Equalization: Backoff delay equalization is an explicit feature of CSMA/iCA. By "backoff delay equalization" we refer to the process of compensating the longer backoff delay in the failed access attempt by probabilistically provisioning shorter backoff delay for the next access and vice versa. Thus, average backoff delay becomes more or less equal for all contending users over the extended period of time.

Recall the previous example. For the $G2'''$ users, backoff delay in the failed access was as high as 31 slots. To compensate such larger delay, the proposed scheme, tunes the CSSD over the expanded CW by updating the quad-tuples to $\{\mu_i = 0, \sigma_i = 6.93, T_{i,l} = 0, T_{i,r} = 64\}$. The tuned CSSD is shown in the bottom of Fig. 3.3 (when $\psi = 1$). From the figure one can see that the earlier contention slots in the expanded CW are more likely to be selected. Hence, the higher backoff delay in the previously failed access attempt possibly gets compensated with the smaller backoff delay in the current access attempt.

3.3 Performance Analysis of CSMA/iCA

3.3.1 Analytical Throughput Estimation Model

In this section, we present an analytical model to estimate the throughput of CSMA/iCA. The model consists of two sub models: a user model and a network model. As to be described in subsequent subsections, the user model is based on three dimensional DTMC which takes into account the channel arbitration details of CSMA/iCA. The output of the user model along with the network population size and the timing details of the signalling mechanisms of the IEEE 802.11 DCF are used as inputs to the RRP based network model to estimate the throughput.

3.3.1.1 3D DTMC based User Model

A 3D DTMC for CSMA/iCA is formulated based on the seminal 2D DTMC [40] of the conventional CSMA/CA. We made the same assumptions as in [40] that in the state of equilibrium packet transmission fails[1] with a constant and independent probability p, and all the N contending users always have packets to transmit.

Since an additional dimension is added in the DTMC to track every possible HBVs (unlike assuming HBVs to be available a *priori* in our previous work [45]), the number of states in the 3D DTMC increases exponentially in comparison to the seminal 2D DTMC with finite retry

[1]Note that we consider the channel to be ideal and thus transmission failures are only due to collisions.

limit. For example, for the standard contention parameters in IEEE 802.11b DCF, $m = 6$, $W_0 = 32$, and $W_{max} = 1024$, the 2D DTMC has only $\sum_{i=0}^{6} W_i = 3,040$ states, but in the 3D DTMC the number of states increases to $\sum_{i=0}^{6} \frac{W_i(W_i+1)}{2} = 1,224,688$. Despite the complexity of the 3D DTMC, we next focus on obtaining its steady state solution.

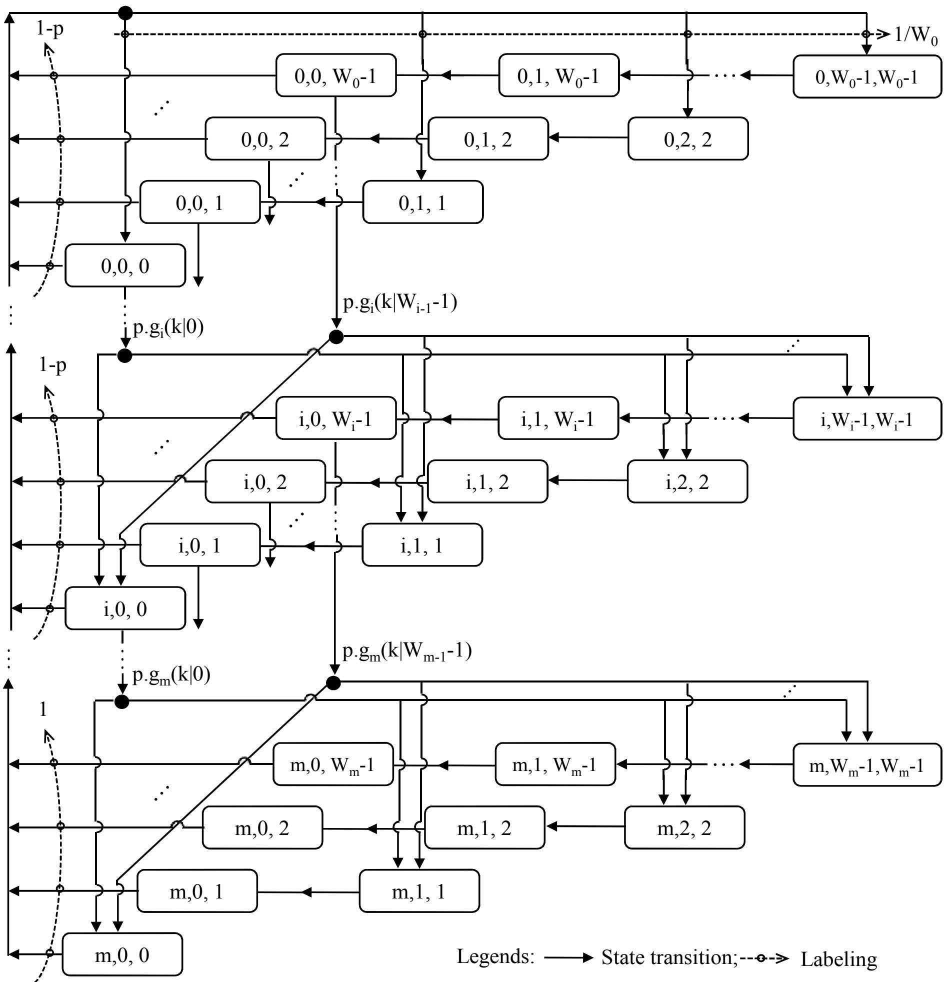


Figure 3.4: 3D DTMC of CSMA/iCA

For a tagged user, let $b(t)$ and $c(t)$ be stochastic processes that represent the current value of the backoff counter and the originally selected backoff value, respectively, for the contention stage $s(t)$ at any slot time t. Note that $c(t)$ is introduced to track the selected backoff value at each contention stage. Since all processes $\{s(t), b(t), c(t)\}$ can only take integer-value, they can be represented with a DTMC with states (i, j, k), where $i \in [0, m]$; $k \in [0, W_i - 1]$; and $j \leq k$, as depicted in Fig. 3.4. By adopting the conventional notation for transition probabilities, $P\{i_1, j_1, k_i | i_0, j_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = j_1, c(t+1) = k_1 | s(t) = i_0, b(t) = j_0, c(t) = k_0\}$ for the transition from state (i_0, j_0, k_0) to state (i_1, j_1, k_1), the possible one-step transitions in the 3D DTMC and their corresponding transition probabilities can be written as follows:

1. $P\{i, j, k | i, j+1, k\} = 1;$

   $i \in [0, m],\ j \in [0, W_i - 2],\ k \in [0, W_i - 1],$

2. $P\{0, j, k' | i, 0, k\} = \frac{(1-p)}{W_0};$

   $i \in [0, m-1],\ k \in [0, W_i - 1],\ k' \in [0, W_i - 1],\ j = k',$

3. $P\{i, j, k' | i-1, 0, k\} = p \cdot g_i(k'|k);$

   $i \in [1, m],\ j \in [0, W_i - 1],\ k' = j, k \in [0, W_{i-1} - 1],$

4. $P\{0, j, k' | m, 0, k\} = \frac{p}{W_0} + \frac{1-p}{W_0};$

   $k' \in [0, W_0 - 1],\ j = k',\ k \in [0, W_m - 1].$

The above expressions account, respectively, for:

1. Probable transitions when the slot is idle in contention stage i; contention stage i remains the same, the history of the originally selected backoff value k is copied, and backoff counter j is decremented by 1.

2. Probable transitions after a successful packet transmission in contention stage i; contention stage i is reset to 0, CW is reset to W_0, and slot k' is selected randomly (uniformly).

3. Probable transitions after an unsuccessful packet transmission in contention stage $i-1$; contention stage $i-1$ is increased by 1, CW is doubled, and any of the slot k' is selected randomly when $g_i(k'|k)$ is given.

4. Probable transitions after either successful or unsuccessful packet transmission in contention stage m; contention stage is reset to 0, CW is reset to W_0 and any slot k' is selected randomly.

Let stationary distribution (i.e., $\lim_{t\to\infty} P\{s(t) = i, b(t) = j, c(t) = k\}, \forall i \in [0, m]$, $\forall k \in [0, W_i - 1]$, $j \leq k$) of the 3D DTMC be $b_{i,j,k}$. This denotes the probability of the tagged user to be in state (i, j, k). To facilitate the analysis, we define a compound state (i, j, X), for the given i and j, representing all the states having $k \geq j$. Let $\mathbb{B}_{i,j,X}$ be the probability of being in the compound state (i, j, X) which is equivalent to $(b_{i,j,j} \bigcup b_{i,j,j+1} \cdots \bigcup b_{i,j,W_i-1})$. It should be noted that the inter-contention stage transitions can happen only from the compound state $\mathbb{B}_{i,0,X}$ $\forall i \in [0, m]$. Hence, the probability of the user to be in the compound state $(i, 0, X)$ can be expressed with the probability of the user to be in the state $(i-1, 0, X)$, i. e.,

$$\mathbb{B}_{i,0,X} = p \cdot \mathbb{B}_{i-1,0,X}, \; 0 < i \leq m. \tag{3.6}$$

Since the chain is regular, the value of $\mathbb{B}_{i,j,X}$ for $0 < i \leq m$, can be written as

$$\begin{aligned} \mathbb{B}_{i,j,X} &= p \cdot \mathbb{B}_{i-1,0,X} \sum_{y=j}^{W_i-1} \sum_{z=0}^{W_{i-1}-1} g_i(y|z) \\ &= p^i \cdot \mathbb{B}_{0,0,X} \sum_{y=j}^{W_i-1} \sum_{z=0}^{W_{i-1}-1} g_i(y|z) \end{aligned} \tag{3.7}$$

Similarly, for the case $i = 0$, $\mathbb{B}_{0,j,X}$ can be written as

$$\mathbb{B}_{0,j,X} = \frac{W_0 - j}{W_0} \cdot \left[\mathbb{B}_{m,0,X} + (1-p) \sum_{l=0}^{m-1} \mathbb{B}_{l,0,X} \right]. \tag{3.8}$$

Using (3.6), (3.8) can be simplified to

$$\begin{aligned} \mathbb{B}_{0,j,X} &= \frac{W_0 - j}{W_0} \left[\mathbb{B}_{m,0,X} + (1-p) \frac{1-p^m}{1-p} \mathbb{B}_{0,0,X} \right] \\ &= \frac{W_0 - j}{W_0} \mathbb{B}_{0,0,X}. \end{aligned} \tag{3.9}$$

Equations (3.7) and (3.9) express $\mathbb{B}_{i,j,X}$ for $0 \leq i \leq m$ as a function of $\mathbb{B}_{0,0,X}$ and p. Hence, $\mathbb{B}_{0,0,X}$ can be determined by imposing the following normalization condition:

$$
\begin{aligned}
1 &= \sum_{i=0}^{m} \sum_{j=0}^{W_i-1} \mathbb{B}_{i,j,X} \\
&= \sum_{j=0}^{W_0-1} \mathbb{B}_{0,0,X} \frac{W_0 - j}{W_0} + \sum_{i=1}^{m} \sum_{j=0}^{W_i-1} \mathbb{B}_{i,0,X} \sum_{z=0}^{W_{i-1}-1} \sum_{y=j}^{W_i-1} g_i(y|z).
\end{aligned}
\tag{3.10}
$$

After simplifying (3.10), $\mathbb{B}_{0,0,X}$ is obtained to be

$$
\mathbb{B}_{0,0,X} = \left[\sum_{j=0}^{W_0-1} \frac{W_0 - j}{W_0} + \sum_{i=1}^{m} \sum_{j=0}^{W_i-1} \sum_{z=0}^{W_{i-1}-1} \sum_{y=j}^{W_i-1} p^i g_i(y|z) \right]^{-1}. \tag{3.11}
$$

Since the transmission can happen from any of the compound state $\mathbb{B}_{i,0,X}$, the probability that a station transmits in a randomly chosen slot time can be expressed as

$$
\tau = \sum_{i=0}^{m} \mathbb{B}_{i,0,X} \quad = \quad \mathbb{B}_{0,0,X} \frac{(1 - p^{m+1})}{1 - p}. \tag{3.12}
$$

From (3.12), it is evident that the transmission probability τ depends on the collision probability p. The probability p that a transmitted packet encounters a collision is the probability that at least one of the $N - 1$ remaining users transmit in the same time slot. With the assumption that all users have the homogeneous τ, the collision probability p can be written as

$$p = 1 - (1 - \tau)^{N-1}. \tag{3.13}$$

Rearranging (3.12) and (3.13) the following nonlinear system can be defined and solved numerically, which gives the value of the two unknowns τ and p:

$$\begin{cases} \tau - \mathbb{B}_{0,0,X} \frac{(1-p^{m+1})}{1-p} = 0, \\ p - 1 + (1 - \tau)^{N-1} = 0. \end{cases} \tag{3.14}$$

Based on the solution of the nonlinear system in (3.14), the performance of the network can be estimated. In the next section we will present the network model that we adopt in the current analysis.

3.3.1.2 RRP based Network Model

We use RRP based network model to estimate the long-run average normalized throughput (throughput efficiency) ξ. It is the fraction of time that the channel is used to successfully transmit payload bits.

Let us consider that transmission attempts from N contending users, each of which transmits packet with probability τ derived in the previous subsection, are independent events which repeat over time. The outcome space for every attempt is $\{I, S, C\}$, where I corresponds to the event that there is no access attempt (the channel is idle), S corresponds to the event that the attempt was successful, and C corresponds to the event that the attempt ended in collision. Considering the outcome space for the events, inter event duration T can be estimated as

$$E[T] = \sum_{\forall x \in (I,S,C)} P_x T_x, \tag{3.15}$$

where P_x is the probability that the outcome of the event is x and T_x is the duration for which x lasts. With the assumption that all N contending users can hear each others' transmission (i.e. connected single-hop network), P_x can be obtained as follows:

$$P_x = \begin{cases} (1-\tau)^N; & x = I, \\ \binom{N}{1}\tau(1-\tau)^{N-1}; & x = S, \\ 1-(P_I + P_S); & x = C. \end{cases} \tag{3.16}$$

Note that T_x for both the basic and RTS/CTS access mechanisms, T_x^{bas} and $T_x^{r/c}$, can be obtained following the signaling mechanisms specified for DCF in [13]. See [38] for the calculation of T_x^{bas} and $T_x^{r/c}$.

For the given N, nonlinear system in (3.14) can be solved numerically to get the values τ and p. Based on these values, P_x $\forall x \in (I, S, C)$ in (3.16) can be calculated. Considering T_x values, either for the basic or the RTS/CTS access mechanism, $E[T]$ in (3.15) can be obtained. Upon estimation of $E[T]$, throughput efficiency ξ can be calculated by considering the reward R per renewal event T as follows:

$$\xi = \frac{E[R]}{E[T]}, \tag{3.17}$$

where $E[R]=P_S \cdot T_D$ and T_D is the time required to transmit the payload. The presented throughput estimation model is independent of physical layer parameters and can be applied to all IEEE 802.11 PHY standards.

3.3.2 Validation of Throughput Estimation Model

We simulate, using ns-2 simulator [46], the uplink packet transmission scenario in a typical BSS where an AP is located in the center of the network area ($100m \times 100m$) and N stationary users are uniformly distributed over the network area. The MAC and the PHY parameters are set as specified in Table 3.1; among the three available channel rates, $1Mbps$ is selected. All users transmit UDP packets of $1024Bytes$ to AP. The packet sending rate of each user is kept sufficiently high such that the MAC queue never remains empty. No Ad-Hoc Routing Agent (NOAH) [47] is used to bypass the effect of routing in the network's performance. Under such simulation conditions, we observe the throughput efficiency for the increasing number of contending users. Fig.3.5 depicts the observed throughput efficiency.

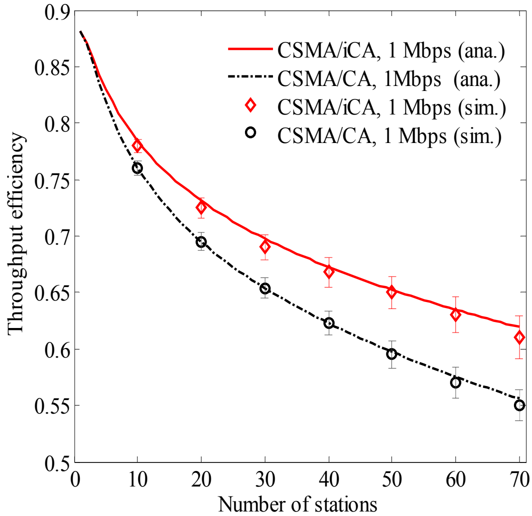
Table 3.1: PHY/MAC parameters in IEEE 802.11b.

Parameters	**Values**
Slot time	20 μs
DIFS	50 μs
SIFS	10 μs
MAC header	224 $bits$
PHY header	192 $bits$
RTS packet	160 $bits$ +PHY Header
CTS packet	112 $bits$ + PHY header
ACK packet	112 $bits$ + PHY header
Channel data rate	1, 5.5, and 11 $Mbps$
Control rate	1 $Mbps$
Minimum CW	32
Maximum CW	1024
Retransmission limit	6

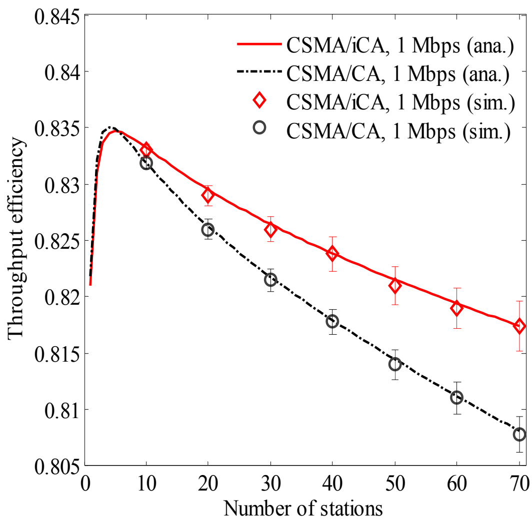
From Fig. 3.5 one can make two major observations: validation of the throughput estimation models and comparison of throughput efficiencies of CSMA/CA and CSMA/iCA based DCF. With regard to model validation, it shows that the considered analytical models predict throughput efficiencies with adequate accuracy; analytical results (lines) well agree with simulation results[2] (markers) for both basic and

[2]Each presented simulated results are the average of the 30 iterated simulation runs ± standard deviation.

RTS/CTS access mechanisms.



(a)



(b)

Figure 3.5: Throughput efficiency of DCF with CSMA/CA and DCF with CSMA/*i*CA: (a) Basic access mechanism, (b) RTS/CTS access mechanism

With regard to throughput efficiency comparison, it shows that the throughput efficiency of the CSMA/iCA is significantly higher throughout the considered range of contending population size. More interestingly, the gain in throughput efficiency (difference between the throughput efficiency of CSMA/iCA and CSMA/CA divided by the throughput efficiency of CSMA/CA) increases as the number of contending users increases. This increase in the gain is mainly due to the reduction of the collision resolution overhead in terms of channel waste time due to collisions.

3.4 Performance Results

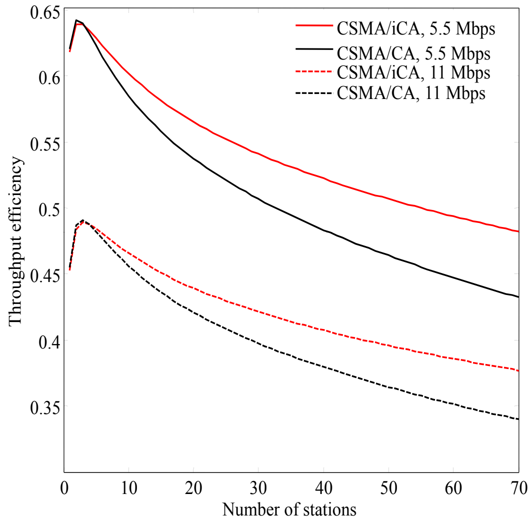
In this section, we compare the performance (throughput, packet transmission delay, and throughput fairness) of the proposed CSMA/iCA with the legacy CSMA/CA in a IEEE 802.11b WLAN considering various channel rates and packet sizes.

3.4.1 Throughput Efficiency

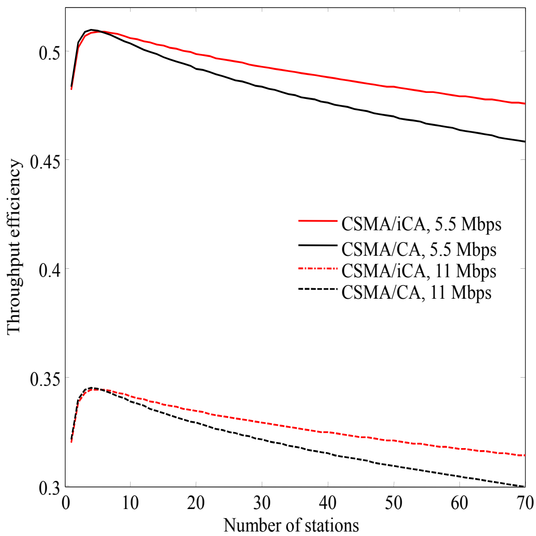
We compare the throughput efficiency of the proposed CSMA/iCA and the legacy CSMA/CA using both analysis and simulation. Analytical framework in [38] is used for the analysis of CSMA/CA and the framework that we present in the previous section is used for the analysis of CSMA/iCA. Analytical results are validated using simulation results obtained from *ns*-2. Upon validation, we use the validated models to further analyze the throughput efficiency for different configurations of channel rate (R_D) and payload size (L_D).

Fig. 3.6 depicts the throughput efficiency of CSMA/iCA and CSMA/CA for two different channel rates: $5.5Mbps$ and $11Mbps$. Because of the channel rate independent fixed control overheads (channel idle time due to random backoff, transmission of preambles at the lowest available rate etc.), the throughput efficiency of both CSMA/CA and CSMA/iCA decreases as the channel rate increases. Nevertheless, throughput efficiency of CSMA/iCA is higher than that of CSMA/CA for both the basic and the RTS/CTS access mechanism regardless of the channel rates.

Note that the throughput efficiency of the RTS/CTS mechanism (for both CSMA/iCA and CSMA/CA) is even lower than that of the basic access mechanism when the channel rates are higher, $5.5Mbps$ and $11Mbps$. This is contradictory to the performance at the lower rate of $1Mbps$; at the lower channel rate, RTS/CTS mechanism outperforms basic mechanism (see Fig. 3.5). Because of such inefficiency at the higher rates, RTS/CTS is barely used in practice. With reference to Fig. 3.5 and Fig. 3.6, it can be concluded that CSMA/iCA outperforms CSMA/CA in terms of throughput efficiency irrespective of channel rate, contending population size, and underlying access mechanism.



(a)



(b)

Figure 3.6: Throughput efficiency of DCF with CSMA/CA and DCF with CSMA/iCA for different channel rates: (a) Basic access mechanism, (b) RTS/CTS access mechanism

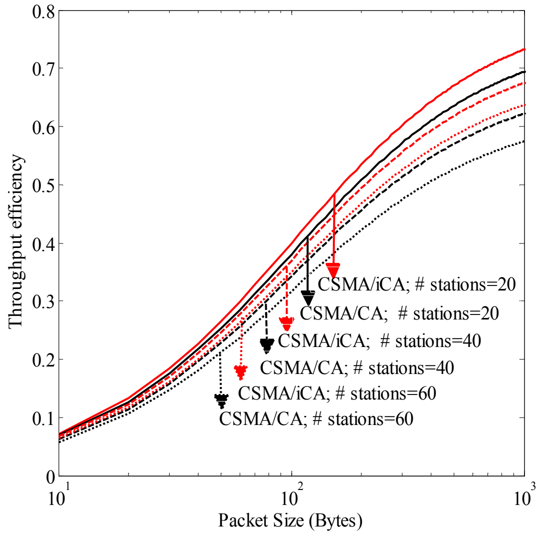
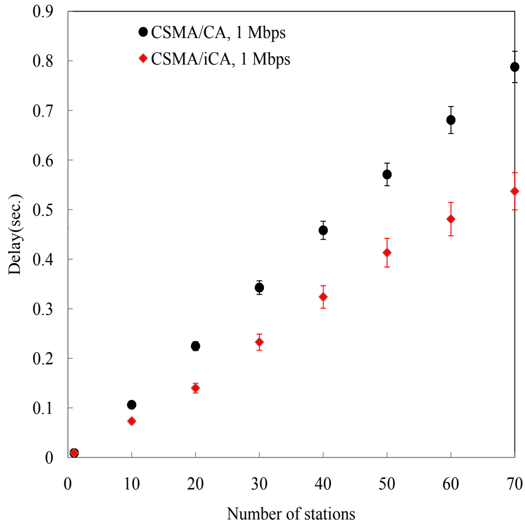


Figure 3.7: Throughput efficiency of DCF with CSMA/CA and DCF with CSMA/iCA, in basic access mechanism, for different payload size

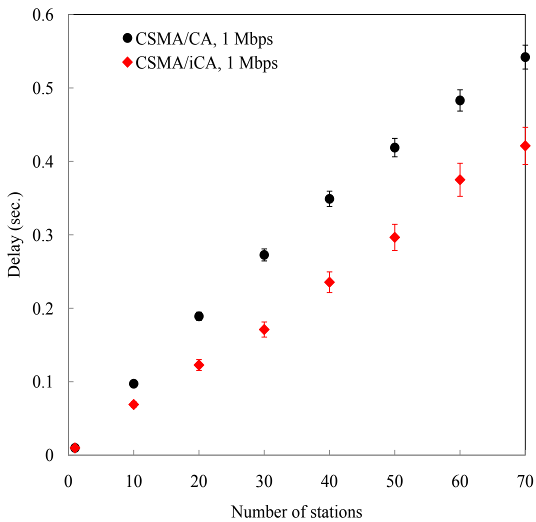
The positive gain in the throughput efficiency due to CSMA/iCA, which has hitherto been characterized considering fixed payload size of $1024 Bytes$, remains positive for a wide range of payload sizes as shown in Fig. 3.7. Note that for a given contending population size, the gain in throughput efficiency due to CSMA/iCA increases with the increase of the payload size.

3.4.2 Packet Delay

Under the given simulation conditions, we compare the delay performance of CSMA/iCA to that of CSMA/CA. Note that the delay for the successfully transmitted packet is defined to be the time interval from the instant a packet is at the head of its MAC queue ready for transmission, until the acknowledgement for this packet is received.



(a)



(b)

Figure 3.8: Average packet delay performance of DCF with CSMA/CA and DCF with CSMA/*i*CA: (a) Basic access mechanism, (b) RTS/CTS access mechanism

Fig. 3.8 depicts the increase in average packet delay for the increasing population size. Under any access mechanisms, either basic or RTS/CTS, average packet delay of both medium access schemes (CSMA/CA and CSMA/iCA) increases almost linearly as the contending population increases. It is due to the increase in the number of collisions which thus requires multiple retransmissions before making a successful transmission. It is note worthy to mention that the rate of the linear increase is delay is significantly lower in case of CSMA/i CA for both basic and RTS/CTS access mechanisms. For example, for the worst contention situation in the considered simulation scenario, CSMA/iCA under basic and RTS/CTS access mechanism offers 31.1% and 21.56% reduction in the delay, respectively.

3.4.3 Fairness

Finally, we compare quantitative fairness performance of CSMA/CA and CSMA/iCA via simulation experiments. For this evaluation, we consider the following scenario. Initially, 10 users are contending for getting access opportunity. Within every $20s$ interval, 10 new users join the network. Thus, with the increase in the simulation time, the number of contending users goes on increasing up to 60. In other words, there are $10(t+1)$ users at the end of interval $[20t, 20(t+1)]s$, where $t = 0, 1, ..., 5$. Every contending user generates UDP packets of $512Bytes$. Channel data rate is considered to be 11 $Mbps$. Simulations are performed for the duration of 2 minutes.

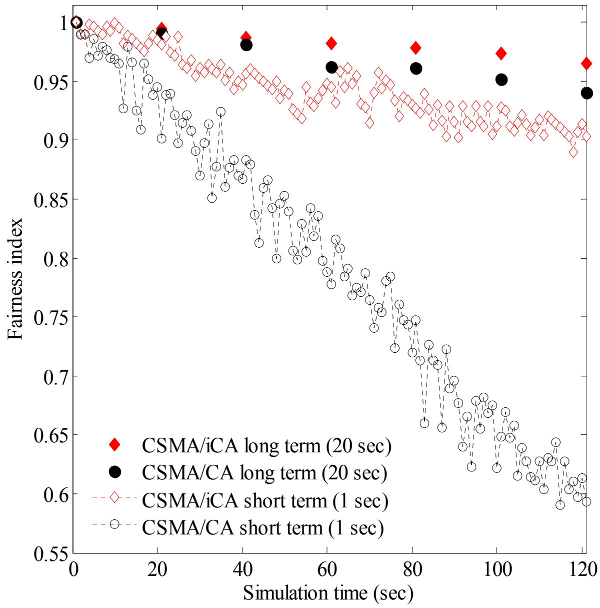


Figure 3.9: Quantitative short-term and long-term fairness of DCF with CSMA/CA and DCF with CSMA/*i*CA

Fig. 3.9 depicts simulation results in terms of Jain's Fairness Index (JFI) [39]. Note that JFI is a widely used performance indicator to quantify the fairness over different time scales in many resource sharing systems. JFI is always bounded between 0 and 1, and the closer the value is to 1, the more fairly the system operates. We analyze short-term and long-term JFI for the increasing number of contending users considering time scales of $1s$ and $20s$, respectively. From the figure it is evident that CSMA/CA can provide adequate long-term fairness (JFI ≥ 0.94) for the entire considered contending users. Long term fairness of the proposed CSMA/*i*CA is even better. Note that the long-term fairness of DCF with the legacy CSMA/CA doesn't guarantee short-term fairness. Its short-term fairness deteriorates with the increasing number of the contending users. On the other hand, DCF with CSMA/iCA well maintains the short-term fairness at around 0.9 even for the maximum number of the considered contending users.

3.5 Related Works

Contention-based MAC protocols does not perform well as the number of contending users increases in the network due to the high overheads associated with collision avoidance and collision resolution mechanisms. Numerous approaches have been suggested so far to reduce such overheads which thus helps in enhancing the performance of the underlying MAC protocols. To distinguish those approaches from the proposed approach in this paper, we categorize them into the following two cases.

A. Common design goals but different operational mechanism

1. Reservation based backoff: One approach of enhancing collision avoidance procedure is to use reservation based backoff as in [48] and [49]. In such scheme, user announces its future backoff information using the currently transmitted frame. All users that overhear this information can avoid collisions by excluding the same backoff duration when selecting their backoff value. However, this requires modifications in the standard frame structure to carry the future backoff information. The scheme in [50] realizes reservation-based backoff without the need to announce future backoff value. Its operation is too simple, deterministic backoff after successful transmission (for example stick to the same backoff value that resulted success) and random backoff otherwise. By doing so, it logically mimics the contention-free time division multiple access scheme by scheduling all the users that made successful transmission. Nevertheless, the new entrants in the network may pose collision threats to the previously scheduled pseudo contention-free users.

2. Optimal Contention Window: Optimizing the CW, as in [51] and [52], in accordance with contending population size is a smart approach to reduce collisions in the network. The main challenge associated with that is to estimate the contending population size since contending users are unaware of this information *a priori*. Schemes in [53] and [54] can be used to estimate the population size. Nevertheless, the precise estimation of the number of contending users, especially in small time-scale, is difficult. The calculated so-called optimal CW based on the erroneous estimation, in reality, would not be optimal. Hence, these schemes have practical limitations. Scheme in [55] known as Idle sense is an approach to use constant CW without the priori information of the contending population size. Idea of Idle Sense is to make the CW of the contending users equal to achieve fairness among them. Each user estimates the number of consecutive idle slots between two transmission attempts and uses the value to compute its CW. Due to such CW adjustment, mean number of the consecutive idle slots of users converge to the common value (target value) and thus the fairness among the users is maximized. This scheme, however, can not offer significant throughput gain.

3. Fast Contention Resolution: Note that the CW-assisted temporal collision resolution process slows down as the number of the contending users increases. Hence, to accelerate the resolution process, schemes like Fast Collision Resolution Algorithm (FCRA) [56] and Implicit Pipelined Scheduling (IPS) [57] have been proposed. FCRA uses smaller CW for the STAs with successful packet transmissions and reduces the backoff timers quickly (exponentially) when the predetermined fixed number of consecutive idle slots is detected. Since this scheme favors users that have recently made successful transmission, unfairness may arises among the contending users, especially when the maximum allowed back-to-back transmissions are not limited. Multi-round contention in [58] and [59] also offer fast contention resolution, but with different operational mechanism. They basically split the contention cycle into smaller contention tournaments and repeatedly eliminate a portion of contending users in each tournament until the wining user is selected. However, for elimination at each contention tournament, they need to transmit a tone signal (energy-pulse) which is undesirable in terms of energy efficiency since wireless user devices are basically energized using small batteries with limited power resource.

B. Common design goals with partially similar operational mechanism

1. Non uniform CSSD: Until recently, little attention has been paid to exploit potential benefits that can be achieved by using non-uniform CSSD over CW. Cai et al. [60] proposed a distributed channel access algorithm where an optimized polynomial CSSD is used over a fixed size CW. It has been shown to enhance network throughput. However, the optimization of the CSSD over CW requires global knowledge of the contending population size, which is not available in the contending users. Likewise, Tay et al. [61] discussed the potential benefit of using a reverse-exponential CSSD over CW, especially considering the event-centric traffic in wireless sensor networks. This scheme can not be directly applied to WLANs where traffic is well-known to be bursty. Unlike the schemes in [60] and [61] where the CSSD remain static over a fixed size CW, in the proposed scheme the CSSD is dynamically tuned during ongoing collision resolution process without requiring to optimize CW size.

3.6 Concluding Remarks

In this chapter, we have presented an improvised DCF in which the conventional CSMA/CA is replaced with a new CSMA/iCA. The key technique that we have introduced in CSMA/iCA is the usage of adaptively configurable non-uniform CSSD over the contention window during ongoing collision resolution process. We have shown, both by theoretical and simulation based analysis, that CSMA/iCA not only offers significant improvement in network throughput and throughput fairness of competing network users, but also reduces the packet transmission delay. Despite such a potential of CSMA/iCA, it is not suitable for being used in QoS differentiated MAC protocols like EDCA. In Chapter 5, we will elaborate the unsuitability problem and propose a simple remedy.

4 Cross Layer Analysis of the Improvised Unicast MAC

In this chapter we extend the analytical model that we develop in Chapter 3 to estimate the network throughput performance of the improvised DCF. In the extended model we consider the more realistic cross layer (L1-L2) settings.

4.1 Motivation

In Chapter 3, a 3D DTMC was developed to analytically characterize the access mechanism of of CSMA/iCA. Based on the steady-state solution of the 3D DTMC, throughput efficiency was analytically estimated using a RRP based network model. To simplify the analysis, following assumptions were made: Physical layer (L1) is error-free and MAC queue (L2) is saturated (always non empty). These assumptions, however, do not accurately hold in the real-world WLANs since the wireless medium is generally error-prone and the arrival of the packets at L2 queue is generally bursty resulting in non-saturated queue occupancy. Thus, the estimated throughput, in such typical L1/L2 settings, is not complete to understand the actual performance benefit that CSMA/iCA can offer under the realistic network settings.

In this chapter, we relax those ideal L1 and L2 assumptions and present a cross-layer (L1/L2) performance analysis of CSMA/iCA. The new cross-layer analytical model considers the effect of Rayleigh fading induced bit errors in L1 and non-saturated queue occupancy due to Poisson packet arrival at L2. The new cross-layer analysis provides a general analytical model for which the model in Chapter 3 is a special case when the packet error probability due to channel noise is zero and the probability of packet availability at L2 queue is 1.

4.2 Framework for Cross Layer Analysis

Figure 4.1 depicts the high-level framework of the cross-layer analytical model. It consists of two sub-models as in the previous model of Chapter 3: a user model and a network model. As to be described in the subsequent sections, the user model which is based on 3D DTMC takes into account the channel arbitration process of CSMA/iCA considering the influence of bit errors on L1 and Packet Arrival Rate (PAR) at L2 queue. The output of the user model along with network population size and the timing details of the signalling mechanisms of IEEE 802.11 DCF are used as inputs to the RRP based network model to estimate the performance of interest.

4.2.1 L1/L2 Considerations

We consider a WLAN with N contending users where their channel access opportunities are arbitrated according to the improvised DCF in which CSMA/CA is replaced with CSMA/iCA.

We consider a $M/M/1/K$ queue at L2 of each user station. Packets

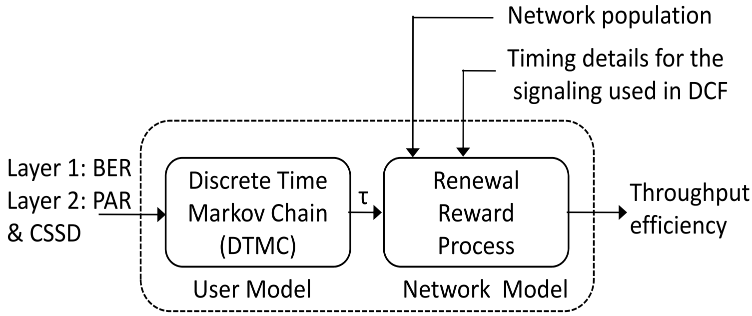


Figure 4.1: High-level framework for the cross-layer performance analysis

arrive at the queue in a Poisson manner with exponentially distributed inter-packet arrival time with mean rate λ_a and are serviced at the rate λ_s[1]. Hence, the probability q that the queue remains non empty can be expressed as

$$q = 1 - \frac{1 - \lambda_a/\lambda_s}{1 - (\lambda_a/\lambda_s)^{K+1}}. \tag{4.1}$$

Regarding L1, we consider it to be noisy; the transmitted packets might possibly experience bit errors. Note that probability of bit errors primarily depends on the utilized modulation technique and the channel characteristics. In this current work, we have considered Differential Binary Shift Keying (DBPSK) and a typical Rayleigh faded channel. For DBPSK, probability of bit error, p_b, over Additive White Gaussian Noise (AWGN) channel is [62]

$$p_b(\gamma) = \frac{1}{2}\exp(-\gamma), \tag{4.2}$$

[1]For a given WLAN configuration, λ_s can be calculated as discussed in the last paragraph of Section 4.2.4.

where γ is the received instantaneous Signal to Noise Ratio (SNR). In Rayleigh faded channel, γ is a random variable with the following probability distribution function

$$f(\gamma) = \frac{1}{\gamma_0} \exp(\frac{-\gamma}{\gamma_0}), \tag{4.3}$$

where γ_0 is the average SNR. Thus, bit error probability for DBPSK-modulated Rayleigh faded channel can be estimated as

$$\begin{aligned} p_b &= \int_0^{\infty} p_b(\gamma) f(\gamma) d\gamma \\ &= \int_0^{\infty} \frac{1}{2} \exp(-\gamma) \frac{1}{\gamma_0} \exp(\frac{-\gamma}{\gamma_0}). \end{aligned} \tag{4.4}$$

Note that (4.4) reflects the bit error probability of a IEEE 802.11b STA operating in its lowest available channel rate (1 $Mbps$). For the other available channel rate options, 5.5 and 11 $Mbps$, p_b can be calculated as elaborated in [63]. Based on p_b in (4.4), packet error probability in L2 can be calculated. To calculate the packet error probability in L2, we assume that the bit errors are identically and independently distributed (*i.i.d*) over the whole packet. Due to such assumption of *i.i.d* bit errors, packet error probability for a packet x can be expressed as

$$p_e^x = 1 - (1 - p_b)^{L_x}, \tag{4.5}$$

where x is a type of the packet (either DATA or ACK) and L_x is the length of x in number of bits. It is noteworthy to mention that packet error probability should take into account both packet error probabilities of DATA and the subsequent ACK (recall the two way DATA-ACK exchange in the basic access mechanism of DCF). Assuming independence between bit errors of DATA and ACK packets, effective packet error probability observed at L2 can be written as

$$p_e = p_e^{data} + p_e^{ack} - p_e^{data} p_e^{ack}. \tag{4.6}$$

Note that packet transmission fails not only due to channel errors, but also due to collisions. Collision happens with the following probability when more that one users transmit at the same time

$$p_c = 1 - (1 - \tau)^{N-1}, \tag{4.7}$$

where τ is the transmission probability of each contending user. Finally, assuming independence between the chances of packet collision and packet error, the overall transmission failure probability for the considered L1/L2 settings can be expressed as

$$\begin{aligned} p_{eq} &= p_c + p_e - p_c p_e \\ &= 1 - (1 - \tau)^{N-1}(1 - p_e). \end{aligned} \tag{4.8}$$

4.2.2 Extended 3D DTMC User Model

In this section, we extend the 3D DTMC in Chapter 3 to consider L1 channel errors, as in [64], and unsaturated L2 queue occupancy. Fig. 4.2 shows the extended 3D DTMC.

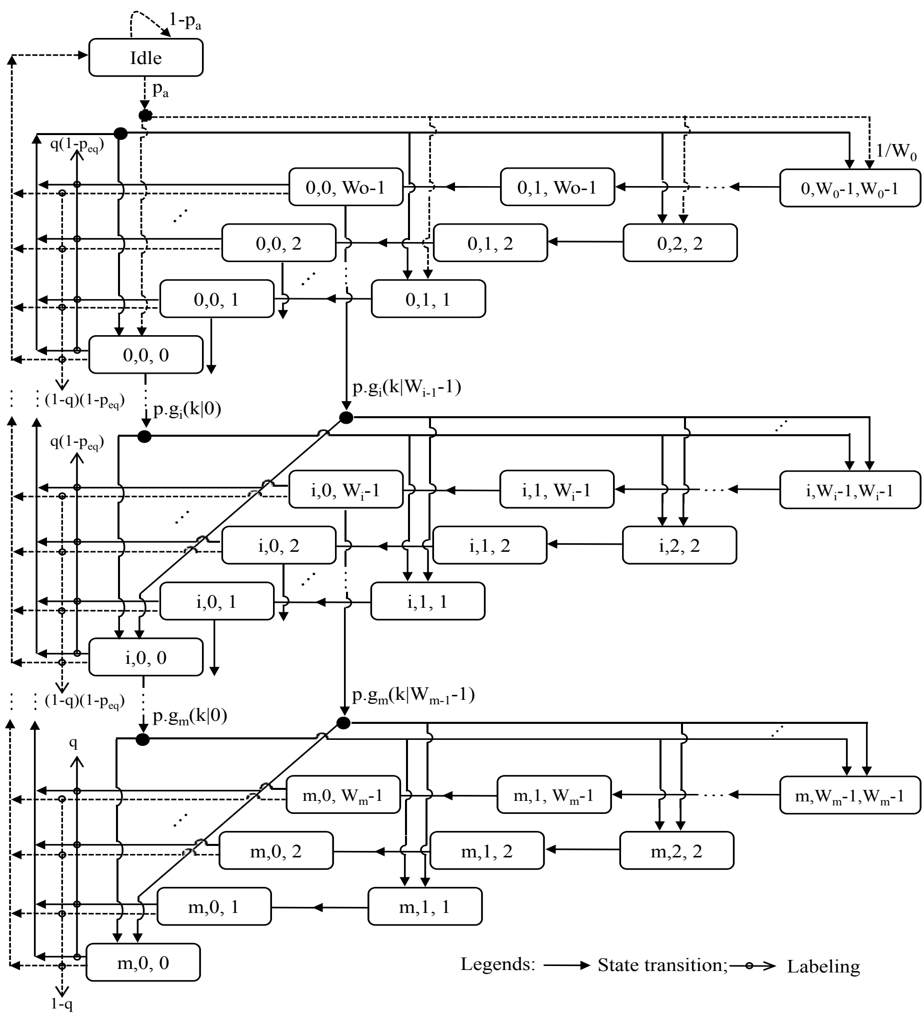


Figure 4.2: Extended 3D DTMC of CSMA/iCA considering L1 channel errors and unsaturated L2 queue

In the 3DTMC, at any time t, a tagged contending user can be in any of the states (rounded rectangles in the figure), (i, j, k) or $Idle$ where $i \in [0, m]$ is the contention stage, j is the current value of the backoff counter, and k is the backoff value with which the contention was initiated in the stage i.

In the extended 3D DTMC, two types of transitions can happen: intra-contention stage transition and inter-contention stage transition. Intra-contention stage transition happens within any stage i when an idle slot is detected and $j \neq 0$. If j is zero and an idle slot is detected, the tagged user transmits its packet. Based on the result of transmission attempt, success or failure, inter-contention stage transition takes place. In the figure, both intra and inter-contention stage transitions are marked with a line with a filled arrow head. By adopting the conventional notation $\{i_1, j_1, k_1|i_0, j_0, k_0\}$ to denote the transition from (i_0, j_0, k_0) to (i_1, j_1, k_1) with probability $P\{i_1, j_1, k_1|i_0, j_0, k_0\}$, all the possible one-step transitions in the extended 3D DTMC and their corresponding probabilities can be written as follows:

1. $P\{i, j, k|i, j+1, k\} = 1;$

   $i \in [0, m],\ j \in [0, W_i - 2],\ k \in [0, W_i - 1],$

2. $P\{0, j, k'|i, 0, k\} = \frac{q(1-p_{eq})}{W_0};$

   $i \in [0, m-1],\ k \in [0, W_i - 1],\ k' \in [0, W_i - 1],\ j = k',$

3. $P\{0, j, k'|m, 0, k\} = \frac{qp_{eq}}{W_0} + \frac{q(1-p_{eq})}{W_0};$

$k' \in [0, W_0 - 1],\ j = k',\ k \in [0, W_m - 1],$

4. $P\{i, j, k'|i-1, 0, k\} = p_{eq} g_i(k'|k);$

   $i \in [1, m],\ j \in [0, W_i - 1],\ k' = j, k \in [0, W_{i-1} - 1],$

5. $P\{I|i, 0, k\} = (1-q)(1-p_{eq});$

   $i \in [0, m-1], k \in [0, W_i - 1],$

6. $P\{I|m, 0, k\} = 1 - q;$

   $k \in [0, W_m - 1],$

7. $P\{0, k, k'|I\} = \frac{p_a}{W_0};$

   $k \in [0, W_{i-1} - 1], k' = k,$

8. $P\{I|I\} = 1 - p_a.$

The above expressions account, respectively, for:

1. Probable transitions when an idle slot is detected in stage i; contention stage i remains the same, backoff counter j is decremented by 1, and the history of the originally selected backoff value k is copied.

2. Probable transitions when L2 queue is found to be non empty upon making a successful packet transmission during contention stage i ; contention stage i is reset to 0, CW is reset to W_0, and slot k' is selected randomly (uniformly) over W_0.

3. Probable transitions when L2 queue is found to be non empty after making either a successful or a failed packet transmission in contention stage m; contention stage m is reset to 0, CW is reset to W_0, and slot k' is selected randomly (uniformly) over W_0.

4. Probable transitions after making an unsuccessful packet transmission in contention stage $i-1$; contention stage $i-1$ is increased by 1, CW is doubled, and slot k' is selected randomly following $g_i(k'|k)$.

5. Probable transitions when L2 queue is empty after a successful packet transmission in contention stage i; user enters into *Idle* state and waits for new packet to arrive.

6. Probable transitions when L2 queue is empty after either a successful or a failed packet transmission in contention stage m; user enters into *Idle* state and waits for new packet to arrive.

7. Probable transitions when a new packet arrives in the empty L2 queue; backoff procedure is invoked with the initial contention window W_0. Note that $p_a = 1 - e^{-\lambda P_I \cdot T_I}$ where definition of P_I and T_I are available in (4.19) and (4.20).

8. Probable transitions when no new packets arrive in the empty L2 queue.

4.2.3 Steady State Solution of the 3D DTMC

Let the stationary distribution of a tagged user to be in state (i, j, k) and state *Idle* be $b_{i,j,k}$ and b_I, respectively. Furthermore, let (i, j, X) be a compound state representing all the states having $k \geq j$ for the given i and j, and $\mathbb{B}_{i,j,X}$ be the probability of being in the compound state (i, j, X). Mathematically, $\mathbb{B}_{i,j,X}$ is equal to $(b_{i,j,j} \bigcup b_{i,j,j+1} \cdots \bigcup b_{i,j,W_i-1})$. In Fig. 4.2, note that the inter-contention stage transitions can occur only from the compound state $\mathbb{B}_{i,0,X}$ $\forall i \in [0, m]$. Hence, the probability of being in compound state $(i, 0, X)$ can be expressed as a function of the probability being in state $(i-1, 0, X)$, i. e.,

$$\mathbb{B}_{i,0,X} = p_{eq} \cdot \mathbb{B}_{i-1,0,X}, \; 0 < i \leq m. \tag{4.9}$$

Since the extended 3D DTMC is regular, $\mathbb{B}_{i,j,X}$ for $0 < i \leq m$ can be written as

$$\begin{aligned} \mathbb{B}_{i,j,X} &= p_{eq} \cdot \mathbb{B}_{i-1,0,X} \sum_{y=j}^{W_i-1} \sum_{z=0}^{W_{i-1}-1} g_i(y|z) \\ &= p_{eq}^i \cdot \mathbb{B}_{0,0,X} \sum_{y=j}^{W_i-1} \sum_{z=0}^{W_{i-1}-1} g_i(y|z). \end{aligned} \tag{4.10}$$

Similarly, for the case $i = 0$, $\mathbb{B}_{0,j,X}$ can be written as

$$\mathbb{B}_{0,j,X} = \frac{W_0 - j}{W_0} \cdot \left[q\mathbb{B}_{m,0,X} + q(1 - p_{eq}) \sum_{l=0}^{m-1} \mathbb{B}_{l,0,X} + p_a b_I \right]. \tag{4.11}$$

Likewise, b_I can be written as

$$b_I = (1-q)(1-p_{eq})\sum_{l=0}^{m-1}\mathbb{B}_{l,0,X} + (1-q)\mathbb{B}_{m,0,X} + (1-p_a)b_I \quad (4.12)$$

which can be further simplified to

$$\begin{aligned} p_a b_I &= (1-q)(1-p_{eq})\frac{1-p_{eq}^m}{(1-p_{eq})} + (1-q)p_{eq}^m\mathbb{B}_{0,0,X} \\ \therefore b_I &= \frac{1-q}{p_a}\mathbb{B}_{0,0,X}. \end{aligned} \quad (4.13)$$

Using (4.13), (4.11) can be simplified to

$$\begin{aligned} \mathbb{B}_{0,j,X} &= \frac{W_0-j}{W_0}\cdot\left[q(1-p_{eq})\sum_{l=0}^{m-1}p_{eq}^l\mathbb{B}_{0,0,X} + q\mathbb{B}_{m,0,X} + \frac{p_a(1-q)}{p_a}\mathbb{B}_{0,0,X}\right] \\ &= \frac{W_0-j}{W_0}\cdot\mathbb{B}_{0,0,X}. \end{aligned} \quad (4.14)$$

Equations (4.10) and (4.14) express $\mathbb{B}_{i,j,X}$ for $0 \leq i \leq m$ and equation (4.12) expresses b_I as a function of $\mathbb{B}_{0,0,X}$. Hence, $\mathbb{B}_{0,0,X}$ can be determined by imposing the following normalization condition:

$$\begin{aligned} 1 &= b_I + \sum_{i=0}^{m}\sum_{j=0}^{W_i-1}\mathbb{B}_{i,j,X} \\ &= \frac{1-q}{p_a}\mathbb{B}_{0,0,X} + \sum_{j=0}^{W_0-1}\mathbb{B}_{0,0,X}\frac{W_0-j}{W_0} + \sum_{i=1}^{m}\sum_{j=0}^{W_i-1}\mathbb{B}_{i,0,X}\sum_{z=0}^{W_{i-1}-1}\sum_{y=j}^{W_i-1}g_i(y|z). \end{aligned} \quad (4.15)$$

Upon simplifying (4.15),

$$\mathbb{B}_{0,0,X} = \left[\frac{1-q}{p_a} + \sum_{j=0}^{W_0-1}\frac{W_0-j}{W_0} + \sum_{i=1}^{m}\sum_{j=0}^{W_i-1}\sum_{z=0}^{W_{i-1}-1}\sum_{y=j}^{W_i-1} p_{eq}^{i} g_i(y|z)\right]^{-1} \quad (4.16)$$

Since packet transmission can happen from any of the compound state $\mathbb{B}_{i,0,X}$, the probability that the tagged STA transmits in a randomly chosen slot can be expressed as

$$\tau = \sum_{i=0}^{m}\mathbb{B}_{i,0,X} = \mathbb{B}_{0,0,X}\frac{(1-p_{eq}^{m+1})}{1-p_{eq}}. \quad (4.17)$$

By solving a nonlinear system formed by pair of equations in (4.17) and (4.8), two unknowns τ and p_{eq} can be obtained. With the known τ, the WLAN throughput can be estimated using the RRP based network model in the following subsection.

4.2.4 Extended RRP based Network Model

Let us consider that transmission attempts from N contending users, each of which transmits packet with probability τ derived in the previous subsection, are independent events and they repeat over time. The outcome space for such events is $\{I, S, C, E_d, E_a\}$, where the notations have the following interpretations, I: no access attempt (channel is idle); S: attempt is successful and the reception is error free as well; C: attempt ended in a collision; E_d: attempt is successful but the reception is not error free; and E_a: attempt is successful and the reception is error free but the returned acknowledgement is suffered from channel error. Considering the outcome space for such repetitive events, inter event duration T can be estimated as follows:

$$E[T] = \sum_{x \in (I,S,C,E_d,E_a)} P_x T_x, \tag{4.18}$$

where P_x is the probability that event x happens and T_x is the duration for which the event x lasts. With the assumption that all N contending users can hear each others transmission, P_x can be obtained as follows:

$$\begin{aligned}
P_I &= (1-\tau)^N, \\
P_S &= N\tau(1-\tau)^{N-1}(1-p_e^{data})(1-p_e^{ack}), \\
P_C &= 1-(1-\tau)^N - N\tau(1-\tau)^{(N-1)}, \\
P_{E_d} &= N\tau(1-\tau)^{N-1}p_e^{data}, \\
P_{E_a} &= N\tau(1-\tau)^{N-1}(1-p_e^{data})p_e^{ack}.
\end{aligned} \tag{4.19}$$

T_x for the basic access mechanism can be obtained by considering the signaling mechanisms specified for DCF in [13] as follows:

$$
\begin{aligned}
T_I &= Physical\ Slot\ Duration, \\
T_S &= DIFS + T_H + T_D + SIFS + T_A, \\
T_C &= T_H + T_D + EIFS, \\
T_{E_d} &= T_C, and\ T_{E_a} = T_S, \qquad (4.20)
\end{aligned}
$$

where time required to transmit H bits of header, L_D bits of data (D), and L_A bits of acknowledgement (A) are $T_H = \frac{H_{MAC}}{R_D} + \frac{H_{PHY}}{R_C}$, $T_D = \frac{L_D}{R_D}$, and $T_A = \frac{L_A + H_{PHY}}{R_C}$, respectively, for the given data rate R_D and control rate R_C *bits/second*. It should be noted that $EIFS = SIFS + T_A + DIFS$. For the given N, nonlinear system formed by (4.8) and (4.17) can be solved numerically to get the values of two unknowns τ and p_{eq}. Based on these values, P_x $\forall x \in (I, S, C, E_d, E_a)$ in (4.19) can be calculated. T_x in (4.20) can be obtained for the given L_D. Upon obtaining both P_x and T_x, $E[T]$ in (6.11) can be obtained. Once $E[T]$ is estimated, ξ can be calculated by considering the reward R per renewal event T as follow:

$$
\xi = \frac{E[R]}{E[T]}, \qquad (4.21)
$$

where $E[R]$=$P_S \times L_D$.

Note that the extended 3D DTMC can be utilized to estimate ξ of the saturated WLAN as well. For this, q in (4.16) should be assigned 1.

Let the solution of non-linear system in (4.8) and (4.17) for saturated WLAN be τ_s and corresponding $E[T]$ in (6.11) be $E[T_s]$. For the known τ_s and $E[T_s]$, λ_s in (4.1) can be obtained as follows:

$$\lambda_s = \frac{\tau_s(1-\tau_s)^{N-1}}{E[T_s]}. \tag{4.22}$$

4.3 Performance Results

4.3.1 Model Validation

We validate the accuracy of the theoretical results obtained via the proposed analytical model by comparing them to the simulation results obtained from ns-2 [46]. For doing that we not only implemented the CSMA/iCA for IEEE 802.11 DCF in ns-2 (version 2.29) but also modified the signal reception model because the conventional PHY layer implementation does not take into account the effect of bit error on the transmitted packets. In the modified signal reception model, bit error on the transmitted packets are accounted (when determining the success or failure of a received signal) as described in [65], along with the three conventional SNR based thresholds: carrier sense threshold (CSThresh), receive threshold (RxThresh), and capture thresh (CPThresh).

A typical infrastructure BSS is considered where the AP is located in the center of a circular network area of radius 20m. Users are randomly located over the circumference of the network area. All users transmit 1024 Bytes UDP packet to the AP. The inter-packet arrival time at each user is exponentially distributed with mean rate of λ_a packets/s. NOAH routing [47] is used to bypass the effect of routing in the network's performance. The considered MAC parameters are summarized in Table 4.1. Regarding the propagation model, the *shadowing* model is adopted. The path loss exponent is considered to be 3.6. CSThresh and RxThresh are considered to be -94dBm and -95dBm, respectively, while the transmission power is considered to be 0.03162 watt. It is worth mentioning that we have fixed the value of CPThresh to relatively very higher value than its default value of 10dB because in our simulation we do not want to *capture* any packets in the situations when simultaneous transmissions happen, as our analytical model does not consider the case related to capture effect. Under the aforesaid simulation settings, we observe the throughput for the the two different scenarios: (i) varying number of saturated users (whose queue has always packet to transmit) under a given bit error rate and (ii) varying packet arrival rate for a given number of users. Each simulation experiment for a particular scenario was run for 100s after a 10s initialization. All of the presented throughput values are the average of the 10 values obtained from independently repeated simulation experiments.

Table 4.1: PHY and MAC parameters considered for the cross layer analysis of CSMA/CA and CSMA/iCA based DCFs

Parameters	**Values**
Slot time	20 μs
DIFS	50 μs
SIFS	10 μs
MAC header	224 $bits$
PHY header	192 $bits$
ACK packet	112 $bits$ + PHY header
R_D and R_C	1 $Mbps$
Minimum CW	32
Maximum CW	1024
Retransmission limit	6
Channel model	DBPSK modulated Rayleigh-faded channel
Queue length (K)	50
Packet arrival rate	Variable (0-50 packets/sec)
Packet length	$512, 1024 Bytes$
Number of users (N)	Variable (up to 70)

Simulation results along with the results from the analytical model are shown in Fig. 4.3. In particular, Fig. 4.3(a) depicts the throughput when there were varying number of saturated users (5 to 30) for a special case when bit error rate over the channel was 4.9995×10^{-5}.

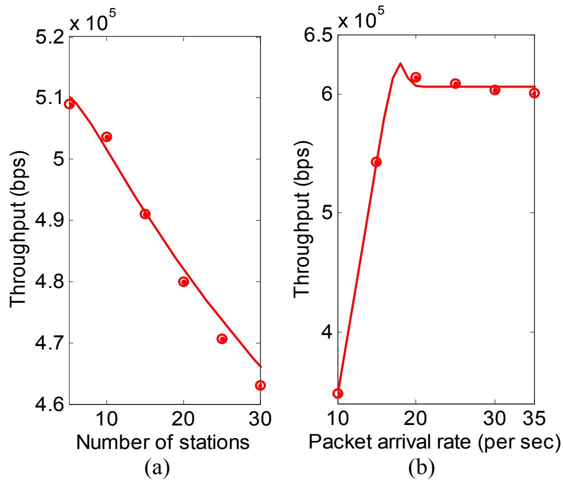
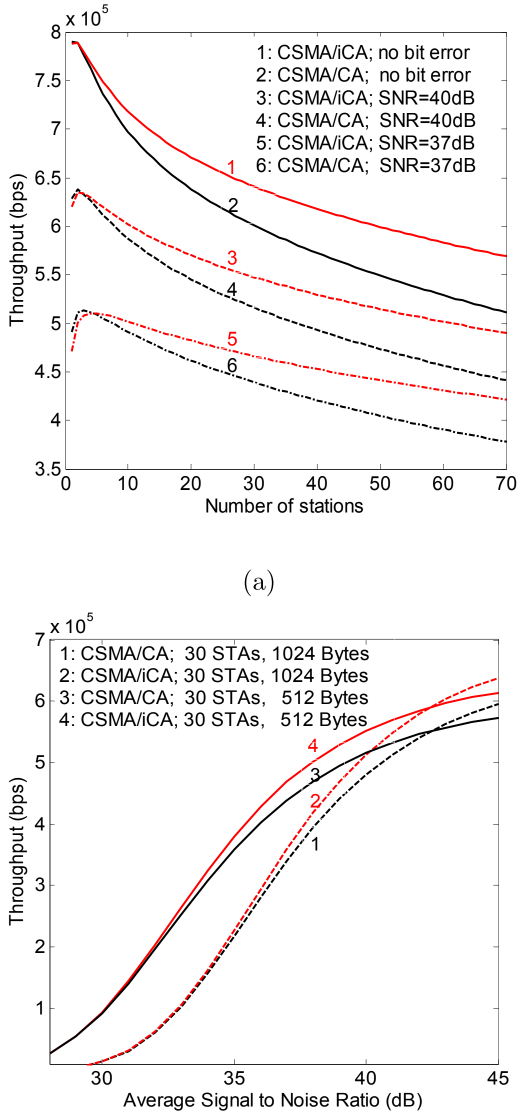


Figure 4.3: Theoretical and simulated throughput of the CSMA/iCA based DCF: (a) Varying number of users, (b) Varying packet arrival rates

Fig. 4.3(b) depicts the throughput for the case of varying packet arrival rates (10 to 35 packets/s) when there were 10 users and the bit error rate was 9.9743×10^{-5}. Simulation results for these two scenarios adequately match with the corresponding theoretical results.

4.3.2 Effects of channel error and PAR

Once the accuracy of the analytical throughput estimation model for CSMA/iCA based WLAN had been validated, it was used to generalize the results for different network and channel conditions. The results are compared with the corresponding results of the conventional CSMA/CA based WLAN. For both WLANs, we firstly analyze the effect of Rayleigh fading induced L1 bit errors on the throughput considering a special scenario in which each contending user has



(a)

(b)

Figure 4.4: Effect of channel errors in a saturated WLAN: (a) Fixed channel error with increasing traffic load, (b) Varying channel error for a fixed traffic load

saturated L2 queue, and then we generalize that result for the case when the contending users do not necessarily have saturated L2 queue. It is a well established fact that channel errors degrade the performance of any wireless networks. Fig. 4.4 depicts the trend how channel errors degrade throughput of CSMA/CA and CSMA/iCA based saturated WLANs. As can be noted in Fig. 4.4(a), for a given number of contending users with fixed-size homogeneous packets (1024 Bytes), throughput of both WLANs decreases as BER increases (correspondingly, SNR decreases). Since channel error not only depends on the SNR but also on the size of the transmitted packets, Fig. 4.4(b) further elaborates Fig. 4.4(a) by including additional case studies for different packet sizes.

Fig. 4.5 compares the throughput of CSMA/iCA and CSMA/CA based WLANs over an error-prone channel (average SNR of 37dB) for the broad range of packet arrival rates. In both WLANs, for the given number of contending users, as the packet arrival rate at each contending user increases, the network throughput linearly increases up to their respective maximum achievable throughput limits and settles as a plateau thereafter. Lets denote the arrival rate that resulted the plateau be a critical arrival rate. For the arrival rates less than the critical arrival rate, CSMA/iCA based WLAN offers similar throughput as CSMA/CA based WLAN does. Interestingly, CSMA/iCA based WLAN offers higher throughput for the arrival rates greater than or equal to critical arrival rate. This result implies that as the network traffic load increases, either due to the increase in the number of con-

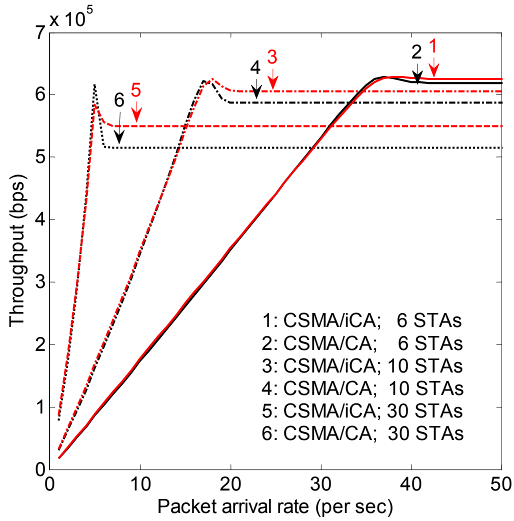


Figure 4.5: Throughput of DCF with CSMA/CA and DCF with CSMA/iCA under different packet arrival rates

tending users or due to the high packet arrival rate at each contending users, CSMA/iCA based WLAN performs better.

4.4 Concluding Remarks

In this chapter, we have presented an analytical model to estimate throughput of a CSMA/iCA based DCF considering cross-layer (L1/L2) details. The presented analytical model not only takes into account the improvised collision avoidance feature of CSMA/iCA but also the effects of channel errors and packet arrival rate at contending users. Through numerical results, we have shown that CSMA/iCA consistently offers throughput benefit over CSMA/CA in arbitrary channel and traffic conditions. Simulation results adequately confirm the validity of the presented analytical model.

5 QoS Extension to The Improvised Unicast MAC

In this Chapter, we present a simple scheme to support QoS differentiation in CSMA/iCA based MAC protocol. Rigorous simulation analysis is presented to support the suitability of the proposed scheme in provisioning QoS over a WLAN.

5.1 Motivation

Recall the QoS differentiation mechanism specified in IEEE 802.11e EDCA. As previously discussed in Chapter 2, Section 2.4. 2, that mechanism is based on relative differentiation principle. It has been well understood that such a mechanism performs fairly good when the AC specific traffic load is fairly light or moderate. As the AC-specific traffic load increases, however, its performance deteriorates because occurrence probability of undesirable events like inventible priority inversions[1][66] and inter-priority class packet collisions[2][67],[68],[70] increases.

Consider the AIFS and CW settings for two ACs, higher priority I and lower priority I+1, depicted in Fig. 5.1. In perspective of AC I, due to the shorter AIFS[I], the level of contention over the W[I]

[1]Lower priority packet win contention in presence of co-contending higher priority packets

[2]Collisions among the packets belonging to different priority classes of different users

varies over CZ1 zone and CZ2 zone because in CZ1 only the traffic belonging to AC I contends while in CZ2 traffic belonging to both AC I and AC I+1 contend. Therefore, if AC I selects its backoff value in CZ2 zone, following three events can possibly happen: (1) It may win contention, (ii) It may loose contention (i.e priority inversions), or (iii) It may collide with AC I+1 packets (inter-AC packet collision). The probability of occurrence of either the second or the third event increases with increase in traffic load belonging to AC I+1. The occurrence probability of the second or third event is even higher if the CSMA/CA in EDCA is replaced with CSMA/*i*CA. The cause for that is rooted to the CSSD tuning mechanism in CSMA/*i*CA. Since users independently tune their CSSDs, there would be higher chances that the relative differentiation principal gets violated, especially when the tuned CSSDs of the lower priority users have their peak somewhere near the left end of the contention window (for example, CZ2 zone in Fig. 5.1).

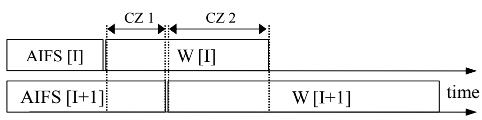


Figure 5.1: AIFS and CW settings for two ACs with different priorities

Increase in occurrence of such events degrades the perceived QoS grade of the higher priority packets. In the real-world sense, manifest consequences would be elongated jitter and reduced throughput for the higher priority audio or video services due to increase in the lower priority data traffic load [69]. Hence in this chapter, we propose a simple solution to alleviate the aforesaid problems in CSMA/*i*CA based EDCA.

5.2 QoS Extension to CSMA/*i*CA based EDCA

5.2.1 Overview

As previously elaborated with a simple illustration in the previous Section, number of priority inversions and inter-AC packet collisions increases in CSMA/CA based EDCA with increase in lower priority traffic. The modified EDCA that replaces CSMA/CA with CSMA/*i*CA is further inefficient when it comes to differentiating priority due to the dynamically changing CSSDs of users. We present a simple solution, named as Push CSSD Mean Right (PCMR), to address the aforesaid problem. As the name suggests, PCMR pushes the mean (i.e first order moment) of the CSSDs of the lower priority users towards the right of the contention window by a certain amount that would be sufficient to minimize the chances of priority inversions and inter-priority class packet collisions. Through computer simulations we show the effectiveness of PCMR in CSMA/iCA based EDCA for provisioning QoS in a typical WLAN with heterogeneous traffic.

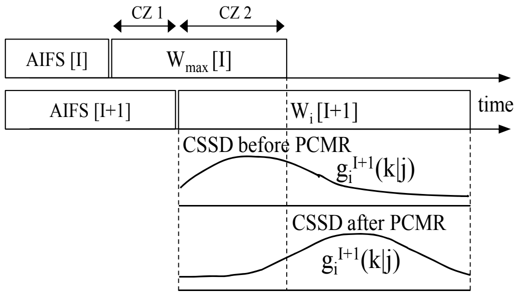


Figure 5.2: Illustration of the PCMR operation

5.2.2 PCMR Operation

As the name suggests, the PCMR operation simply pushes CSSD distribution of the low priority users towards the right direction of the contention window. As such, contention of the lower priority users over a certain fraction of the contention window of high priority users (CZ2 region in Fig. 5.1) gets hugely reduced. In what follows, we elaborate the PCMR operation.

Recall the definition of CSSD in Eq. 3.1. Let us denote the CSSDs of the high and low priority users as $g_i^I(k|j)$ and $g_i^{I+1}(k|j)$, respectively. Since, the proposed PCMR applies only to the lower priority users, the tuning mechanism of $g_i^I(k|j)$ is same as previously discussed in Section II. The tuning mechanism for $g_i^{I+1}(k|j)$ is slightly revised by appending the PCMR operation on top of the existing tuning mechanism. Let us denote the quad-tuples obtained after revised CSSD tuning mechanism with $\{\mu_i^*[I+1], \sigma_i[I+1], T_{i,l}[I+1], T_{i,r}[I+1]\}$.

The revised CSSD tuning operation is as follow: (1) During ongoing collision resolution process calculate the quad-tuples $\{\mu_i, \sigma_i, T_{i,l}, T_{i,r}\}$ for the lower priority users, denoted as $\{\mu_i[I+1], \sigma_i[I+1], T_{i,l}[I+1], T_{i,r}[I+1]\}$, according to eqn. (3.3), (3.4) and (3.5); and (ii) Update $\mu_i[I+1]$ to $\mu_i^*[I+1]$ based on the following relation:

$$\mu_i^*[I+1] = \mu_i[I+1] + \triangle_i[I+1], \tag{5.1}$$

where

$$\triangle_i[I+1] = \begin{cases} 0, & \mu_i[I+1] > \mathcal{Z}, \\ \mathcal{Z}, & \mu_i[I+1] \leq \mathcal{Z}, \end{cases} \tag{5.2}$$

and

$$\mathcal{Z} = W_{max}[I] + AIFS[I] - AIFS[I+1]. \tag{5.3}$$

Figure 5.2 illustrates how a CSSD of a low priority user (in the i-th contention stage) gets shifted towards right by the PCMR operation.

It is noteworthy to mention that the proposed solution is presented and discussed considering only two priority levels for the sake of presentation clarity. The extension of the proposed solution to the case of multiple priority levels is trivial.

5.3 Performance Analysis of QoS Differentiated CSMA/*i*CA

In this section, we present simulation results to compare the performance of CSMA/*i*CA based EDCA and CSMA/CA based EDCA. The first two parts elaborate the used simulator and considered simulation scenarios, while the last part discusses the simulation results.

We perform all simulation experiments in the network simulator (ns-2.28) available in [71], upon modifying it to incorporate both the CSMA/*i*CA and PCMR.

5.3.1 Simulation Scenario and Parameters

We simulate a static, single-hop, and channel-error free WLAN (equipped with IEEE 802.11b radio) over an area of 100×100 m^2 where all uniformly lactated users are sending fix-sized UDP packets (1024 Bytes unless otherwise specified) to a common destination (lets say access point). The access point has no other traffic destined to the users beside acknowledgement for the received packets. The PHY and MAC layer parameters of the network are presented in Table 5.1.

Table 5.1: PHY and MAC parameters considered for the analysis of QoS differentiated MAC protocols

Parameters	**Values**
Physical layer	DSSS
Slot time (σ)	20 μs
SIFS	10 μs
MAC header	224 *bits*
PHY header	192 *bits*
ACK packet	112 *bits* + PHY header
Channel data rate	11 *Mbps*
Control rate	1 *Mbps*
AIFS[VO]	$2 \times \sigma$ +SIFS
AIFS[BE]	$3 \times \sigma$ +SIFS
CW_{min}[VO]	7
CW_{min}[BE]	15
CW_{max}[VO]	15
CW_{max}[BE]	128
Voice payload	200 *Bytes* (Scenario 2)

We consider two different experiment scenarios, lets say Scenario 1 and Scenario 2, to examine the following two fundamental properties of the two QoS differentiated MAC protocols: (i) how well these protocols differentiate achievable throughput of different traffic categories?, and (ii) how well these protocols attempt to protect the higher priority traffic when the lower priority traffic significantly increases in the network?

In Scenario 1, we consider a situation where all the users in the network have heterogeneous Constant Bit Rate (CBR) traffic destined to the access point. The users either have a high priority voice or low priority data packet. There are equal number of voice and data users in the network. The incoming bit rate of both data users and voice users are set to a value higher than the channel data rate so that all the users in the network remain saturated[3]. On the other hand, in Scenario 2, we consider that the network consists of a single high priority user with 64 kbps CBR voice traffic (equivalent to the rate of G.711 codec) and varying number of saturated users with low priority data traffic.

5.3.2 Simulation Results and Discussion

All of the presented simulation results are computed by averaging the results from 10 repeated simulation experiments which last for 2 minutes after initialization of 5 seconds.

Scenario 1: Figure 5.3 depicts normalized throughput of the high and the low priority users in Scenario 1, where normalized through-

[3]Saturated users are those users which have packet ready at their MAC queue for transmission all the time.

put is the ratio of the aggregate throughput per traffic class to the channel rate. From the figure, it is evident that the modified EDCA (consisting of CSMA/iCA and PCMR) maintains clear throughput differentiation between the two different priority user groups as the conventional EDCA does, regardless of the number of users in each group. That is, in both protocols, the normalized throughput of high priority users is significantly higher than that of the low priority users. It is noteworthy to mention that the modified EDCA improvises the normalized throughput of users in each priority group.

As the number of users in each group increases, the normalized throughput of higher priority users falls sharply in case of the conventional EDCA. The modified EDCA reduces such loss in the throughput. This can be partly attributed to the inclusion of the PCMR in the modified EDCA which attempts to probabilistically separate the contention region of higher priority users from that of low priority users. Such separation thus prevents the higher priority packets from being collided with the packets from low priority users.

For any number of users in Fig. 5.3, sum of the corresponding normalized throughput points in the curve A and curve C is higher than that of curve B and curve D. This implies that the modified EDCA also offers higher network throughput than that of the conventional EDCA for a given channel resource.

Scenario 2: Figure 5.4 depicts throughput of the higher priority voice

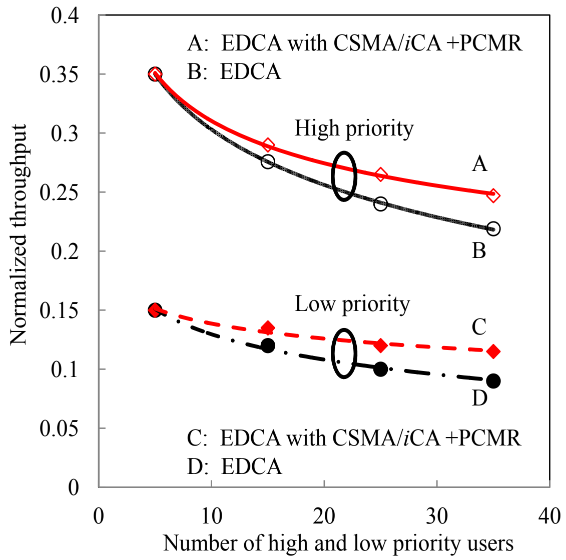


Figure 5.3: Throughput differentiation between the high and low priority traffics by CSMA/CA based EDCA and CSMA/*i*CA based EDCA

user versus increasing number of lower priority users in the network. For the conventional EDCA and the modified EDCA without PCMR, the throughput of the voice user starts to sharply decrease with increase in number of lower priority users. For example, the throughput of the voice user sharply reduced to 50 kbps and 37 kbps, respectively, when the number of lower priority users reaches 30 in the network. It is worth noting that the throughput of voice user under the modified EDCA without PCMR is significantly lower (~ 43 %) than the ideally achievable throughput (for example using absolute priority differentiation). Once the PCMR is incorporated in the modified EDCA, the throughput of the voice user is so impressive. It remains within the 90% of the ideal throughput.

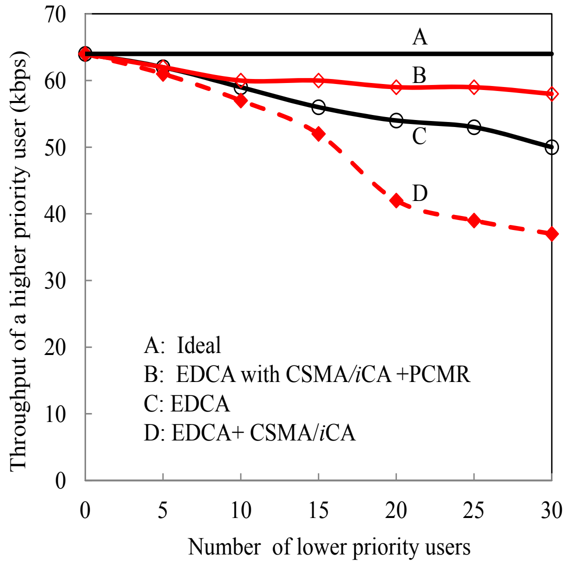


Figure 5.4: Throughput of a higher priority user in the presence of increasing number of lower priority users

5.4 Concluding Remarks

In this chapter, we have addressed a critical problem related to supporting QoS in the modified EDCA where CSMA/CA has been replaced by CSMA/iCA. For that, we have presented a simple solution referred to as PCMR which simply pushes the mean of adaptively changing non-uniform CSSDs of lower priority users towards the right of their contention window in order to probabilistically separate their contention from the high priority users. Through computer simulation we have shown the usefulness of the proposed solution in provisioning QoS among the heterogeneous traffic over WLAN.

6 Improvised Contention-based Broadcast MAC

MAC-layer broadcasting is a fundamental network-wide communication primitive that provides an operational platform for many other higher-layer protocols in distributed wireless networks [72]. A very common example is the route discovery mechanism in general-purpose multi-hop ad hoc networks [73]. With the advent of different special purpose *ad hoc* networks like sensor networks [74] and vehicular *ad hoc* networks [75], the scope of broadcasting has been widened to incorporate mechanism to disseminate sensed or monitored physical phenomena of interest.

6.1 Motivation

DCF, defined in Section 9.2.7 of the IEEE 802.11 protocol specification [13], has been used as a *de facto* MAC for broadcast applications in distributed wireless networks. Hereafter, it will be referred to as a B-MAC. Note that in B-MAC, the recipients do not acknowledge reception as in a unicast MAC. Therefore, there is no MAC layer recovery or retransmission. For this reason, IEEE 802.11 has specified a fixed contention window for broadcast traffic which is equal to the initial (minimum) contention window specified for unicast traffic.

Recall that the efficiency of the access arbitration method used in B-MAC depends on two factors: the number of contending users and

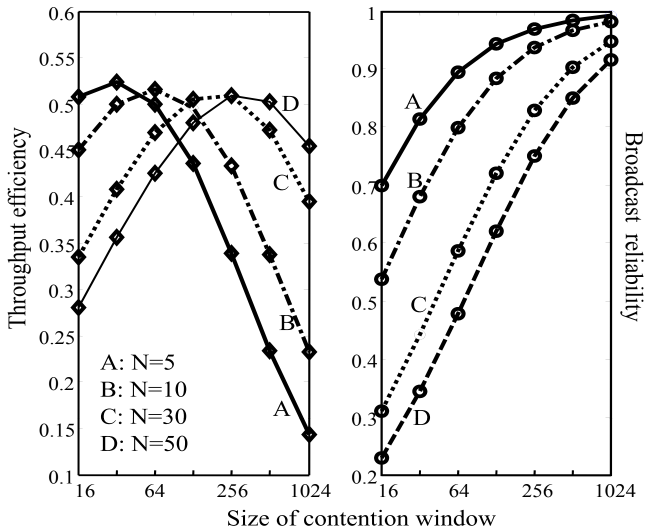


Figure 6.1: Throughput-reliability tradeoff in B-MAC

the size of contention window. For a given (specified) contention window size, collision probability increases with an increase in the contending population size. Using a large contention window could be a trivial approach to reduce collisions. This approach, however, has counterproductive implications in the network performance.

Figure 6.1 shows the performance of IEEE 802.11a distributed networks for varying contention window sizes. It is evident that, for a given contending population size, both throughput efficiency and broadcast reliability increase with an increase in contention window size up to a certain threshold, let the size be called the critical contention window. Beyond this critical value of contention window, throughput is traded off against reliability. In other words, throughput starts to decrease even though broadcast reliability manages to increase.

Note that even though the usage of a large contention window (larger than the critical window) maintains graceful throughput efficiency, especially when the number of users is high, it is still not a good strategy to use such a large window because it severely elongates transmission delays, which is strongly undesirable for delay-sensitive broadcast traffics. Hence, in this chapter we present an interesting approach to improvise the legacy B-MAC in order to eliminate such an undesirable throughput-reliability tradeoff. Hereinafter, we refer the improvised B-MAC to as scalable B-MAC.

6.2 Scalable Broadcast MAC (SB-MAC)

An ideal prerequisite for any MAC to be scalable would be its ability to maintain the performances of interest (e.g., network throughput efficiency and broadcast reliability) intact, irrespective of any increase in contending population size. Note that both these performance indicators are inversely proportional to the number of collisions, while the number of collisions itself is directly proportional to the contending population size. Hence, from the perspective of MAC layer, collisions should be lowered as much as possible to attain scalability.

Note that the most readily available design choice to enhance the collision avoidance efficiency of B-MAC is to increase the size of contention window. This implies that the number of DoDF available for adjusting the contention window is one. SB-MAC adds a second DoDF (referred to as CSSD over the contention window) to reduce the number of collisions in the network, irrespective of the contending population size.

6.2.1 Operational Procedure of SB-MAC

The operational procedure of the SB-MAC is exactly same as that of B-MAC, except for the following two changes:

- First, the way of choosing the random further-deferral (backoff) duration upon performing carrier sense is slightly different because the legacy uniform CSSD over the contention window has been replaced with the reverse-exponential CSSD [76], [77], in (6.1)

$$q_k = \frac{1-\alpha}{1-\alpha^W} a^{W-(k+1)}; \quad k \in [0, W-1], \tag{6.1}$$

  where k is any contention slot within the window and α is a design variable (an additional DoDF) which is bounded over the open interval (0,1). Note that $\lim_{\alpha \to 1} \frac{1-\alpha}{1-\alpha^W} a^{W-(k+1)} = \frac{1}{W}$. In other words the distribution in (6.1) mimics the legacy uniform CSSD when $\alpha \to 1$.

- Second, the requirement to freeze the backoff counter upon sensing the channel to be busy is relaxed. In other words, if the channel is detected to be busy during an ongoing backoff cycle, the backoff counter is reset, and the next backoff cycle is initiated.

6.2.2 Performance Analysis of SB-MAC

In this subsection, an analytical model is presented to estimate the performances of interest: network throughput efficiency and broadcast reliability. The model consists of two sub-models: a newly developed 1D DTMC user model that incorporates the details of SB-MAC channel arbitration, and the RRP based network model in Chapter 3, that estimates the performances of interest based on the solution obtained from the 1D DTMC user model.

6.2.2.1 1D DTMC User Model

Figure 6.2 shows the DTMC for the user model which characterizes the backoff procedure of the SB-MAC for a given contention window size W. The DTMC is formulated based on the assumption that the packet arrival rate at the transmission buffer is high enough that the buffer will never be empty.

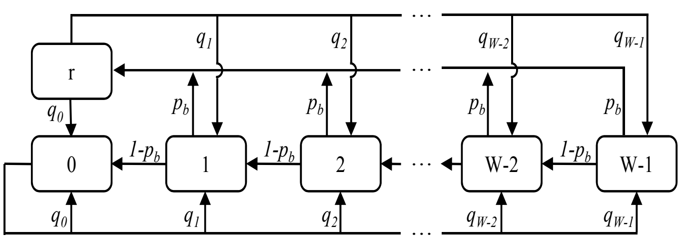


Figure 6.2: Representation of the channel access arbitration of the SB-MAC using a 1D DTMC

In the DTMC there are all together $W + 1$ number of states; state 0 to $W - 1$ correspond to the backoff counter values of the tagged user, while an auxiliary state r corresponds to the situation where the backoff counter has been reset. Using conventional state transition notations, all possible transitions in the DTMC and their corresponding transition probabilities can be written as follows:

$$\begin{aligned}
&\text{(a)} \quad P\{k|k+1\} &&= 1 - p_b; &&k \in [0, W-2],\\
&\text{(b)} \quad P\{r|k\} &&= p_b; &&k \in [1, W-1],\\
&\text{(c)} \quad P\{k|0\} &&= q_k; &&k \in [0, W-1],\\
&\text{(d)} \quad P\{k|r\} &&= P\{k|0\}; &&k \in [0, W-1].
\end{aligned}$$

The first expression corresponds to the event that the backoff timer is decreased by one upon detecting the channel to be idle, while the second expression corresponds to the event that the backoff counter is reset upon finding the channel to be busy. In these expressions, p_b is the probability that the channel is found to be busy. Its mathematical definition is given in (6.9). The last two expressions correspond to the events that a random slot is selected for initiating the backoff procedure upon completing the previous backoff cycle (backoff counter reached zero) and upon resetting the backoff counter (channel is detected to be busy) respectively. The transition probabilities are equal in those last two expressions.

In the DTMC, let the stationary distribution of the probabilities that a tagged user is in state $k, k \in [0, W-1]$, and r be b_k and b_r respectively. It will be shown that a closed-form solution exists for this DTMC. Note that

$$b_k = \begin{cases} \frac{1-\alpha}{1-\alpha^W}\alpha^{W-(k+1)}\{b_0+b_r\} + (1-p_b)b_{k+1}; & 0 \le k \le W-2, \\ \frac{1-\alpha}{1-\alpha^W}\{b_0+b_r\}; & k = W-1 \end{cases} \tag{6.2}$$

and

$$\begin{aligned} b_r &= p_b(b_1 + b_2 + \cdots + b_{W-1}) \\ &= p_b(1 - b_0 - b_r) \\ &= \frac{p_b(1-b_0)}{1+p_b}. \end{aligned} \tag{6.3}$$

To express (6.2) with a single expression for all k, it can be rewritten in a different style. For the special case when W is 4, b_k for $k \in [0,3]$ can be rewritten, after few steps of manipulations, as follows:

$$\begin{aligned} b_3 &= \left(\frac{\alpha}{1-p_b}\right)^0 (1-p_b)^0 z, \\ b_2 &= \left[\left(\frac{\alpha}{1-p_b}\right)^0 + \left(\frac{\alpha}{1-p_b}\right)^1\right](1-p_b)^1 z, \\ b_1 &= \left[\left(\frac{\alpha}{1-p_b}\right)^0 + \left(\frac{\alpha}{1-p_b}\right)^1 + \left(\frac{\alpha}{1-p_b}\right)^2\right](1-p_b)^2 z, \\ b_0 &= \left[\left(\frac{\alpha}{1-p_b}\right)^0 + \left(\frac{\alpha}{1-p_b}\right)^1 + \left(\frac{\alpha}{1-p_b}\right)^2 + \left(\frac{\alpha}{1-p_b}\right)^3\right] \\ &\cdot\ (1-p_b)^3 z, \end{aligned} \tag{6.4}$$

where $z = \frac{1-\alpha}{1-\alpha^4}(b_r + b_0)$. Therefore, jointly considering the relations in (6.3) and (6.4), a recursive relation of b_k in (6.2) can simply be expressed as follows:

$$b_k = \frac{b_0 + p_b}{1 + p_b} \frac{1 - \alpha}{1 - \alpha^W} (1 - p_b)^{W-(k+1)} \sum_{j=k}^{W-1} \left(\frac{\alpha}{1 - p_b} \right)^{W-(j+1)}. \quad (6.5)$$

From (6.3) and (6.5), it is evident that the probability of being in any of the states in the DTMC can be represented as a function of b_0. Therefore, b_0 can be obtained using the following normalization condition:

$$\sum_{k=0}^{W-1} b_k + b_r = 1. \quad (6.6)$$

Upon solving (6.6),

$$b_0 = \frac{(\Upsilon - p_b) - (\Upsilon - 1)(1 + p_b)}{(\Upsilon - p_b)}, \quad (6.7)$$

where

$$\Upsilon = \frac{1 - \alpha}{1 - \alpha^W} . \frac{1}{\alpha - (1 + p_b)} \cdot \left[\frac{\alpha^{W+1} - 1}{\alpha - 1} + \frac{(1 - p_b)^{W+1} - 1}{p_b} \right]. \quad (6.8)$$

The probability of transmission (τ) of the tagged user in a generic slot is equal to b_0 because it is allowed to transmit only when its backoff counter reaches zero. Then, given the parameter τ, the probability p_b that the channel remains busy when there are N contending users in the network is given by:

$$p_b = 1 - (1 - \tau)^N. \tag{6.9}$$

Rearranging (6.7) and (6.9), the following nonlinear system can be defined and solved numerically to get the values of the two unknowns τ and p_b:

$$\begin{cases} \tau - b_0 = 0 \\ p_b - 1 + (1 - \tau)^N = 0 \end{cases} \tag{6.10}$$

6.2.2.2 RRP based Network Model

Given the transmission probability τ, performances of interest, including network throughput efficiency and broadcast reliability, can be calculated using the renewal reward process based network model in which the packet transmission process is approximated by a renewal process. In such an approximation, transmission attempts from N contending users, each of which transmits packet with probability τ, are considered to be independent events which repeat over time. The outcome space for every attempt is $\{I, S, C\}$, where I corresponds to the event that there is no access attempt (the channel is idle), S corresponds to the event that the attempt was successful, and C corresponds to the event that the attempt ended in a collision. Considering the outcome space for the events, the inter event duration T can be estimated as follows:

$$E[T] = \sum_{\forall x \in (I,S,C)} P_x T_x, \tag{6.11}$$

where P_x is the probability that the outcome of the event is x and T_x is the duration for which x lasts. With the assumption that all N contending users can hear each others transmission (i.e. connected single-hop network), P_x can be obtained as follows:

$$P_x = \begin{cases} (1-\tau)^N; & x = I, \\ N\tau(1-\tau)^{N-1}; & x = S, \\ 1 - P_I - P_S; & x = C. \end{cases} \tag{6.12}$$

Moreover, T_x can be obtained as in [78] considering the signaling mechanism specified for broadcast DCF in [13]:

$$T_x = \begin{cases} \sigma\ ; & x = I, \\ (L_H + E[PL])/R_d + DIFS + \delta\ ; & x = S \text{ or } C, \end{cases} \tag{6.13}$$

where σ is the duration of a physical slot, $E[PL]$ is the expected payload length, L_H is the time required to transmit header (both PHY and MAC header), R_d is the raw data rate of the channel, and δ is the propagation delay.

For a given N, nonlinear system in (6.10) can be solved numerically to get two unknowns τ and p_b. Based on these values, P_x in (6.12) can be calculated. For a given $E[P]$, T_x in (6.13) can be obtained. Once both P_x and T_x have been obtained, $E[T]$ in (6.11) can be calculated. Upon estimation of $E[T]$, network throughput efficiency ($\Im$) can be calculated using the expected reward $E[R]$ per renewal event duration $E[T]$ as follows:

$$\Im = \frac{E[R]}{E[T]}, \tag{6.14}$$

where $E[R] = P_s \cdot E[PL]$. Likewise, the broadcast reliability ($\Re$), the probability that the transmitted packet does not collide with other packets, can be calculated easily using the following relation when the probability of success (P_s) in the renewal packet transmission process is known:

$$\Re = \frac{P_s}{N\tau}. \tag{6.15}$$

6.3 Performance Results and Discussions

6.3.1 Model Validation

A custom discrete-event simulator is developed in MATLAB which can adequately represent the channel access arbitration details of the legacy B-MAC. By making some necessary changes, it is used to simulate SB-MAC. Note that the analytical model derived in the previous section is independent of any specific PHY-layer technology. Hence, detailed PHY implementations have intentionally been ignored in the simulator as developed here.

For the purpose of model validation, the numerically obtained results have been compared with the simulation results. For both numerical analysis and simulation, a channel error-free distributed network with no hidden-terminals has been used consisting of a varying number of broadcast users, each having a never-empty MAC queue (this situation literally corresponds to the case of saturated packet arrival). Note that collisions are the only reason of packet loss in the aforementioned settings. Unless otherwise stated, the following are the default parameters (with corresponding values in parentheses) used in the current study: channel rate (6 $Mbps$); standard contention window size (16); physical slot duration (9 μs); PHY header (20 μs); MAC header (28 $Bytes$); DIFS (34 μs); payload PL (128 $Bytes$); and propagation delay (1μs).

Table 6.1: Comparison of analytical and simulation results of SB-MAC

N	**W**	**PL**	α	$\Im$		$\Re$	
				Ana.	**Sim.**	**Ana.**	**Sim.**
5	16	128	0.4	0.4939	0.487	0.9012	0.907
			0.6	0.4989	0.491	0.8947	0.903
			0.8	0.5121	0.509	0.8705	0.881
20	16	128	0.4	0.5107	0.502	0.8241	0.828
			0.6	0.5122	0.504	0.8104	0.815
			0.8	0.5098	0.497	0.7446	0.749
40	32	256	0.4	0.6379	0.629	0.8899	0.893
			0.6	0.6397	0.631	0.8864	0.891
			0.8	0.6465	0.640	0.8691	0.871
60	32	256	0.4	0.6425	0.639	0.8785	0.882
			0.6	0.6440	0.639	0.8746	0.879
			0.8	0.6493	0.641	0.8536	0.858

As can be noted in Table 6.1, the simulated results show good match with the analytical results for all configurations of contention window size, contending population size, α, and payload length. This confirms that the analytical model as developed here is accurate enough to be used for quick and easy numerical performance analysis.

6.3.2 Comparison of SB-MAC and B-MAC

Once the accuracy of the analytical model had been validated, it was used to generalize the results ($\Im$ and $\Re$) for different network parameters. The generalized results were then compared with the corresponding performance results of B-MAC considering two different cases: (1) Standard contention window, and (2) Non standard contention window.

Case 1: Standard Contention Window: Recall that α is the protocol parameter in SB-MAC. It can be assigned any value greater than zero and less than one. The selection of α value, however, has immediate implications for the performances of interest, $\Im$ and $\Re$, as shown in Fig. 6.3 and Fig. 6.4.

From Fig. 6.3, it is apparent that when there are few number of users in the network, roughly on the order of contention window size, it is beneficial to use higher value of α because it can maintain higher $\Im$. For example, among the considered α values, 0.2 to 0.8, $\Im$ attains its maximum when α is 0.8 and the number of contending users is less

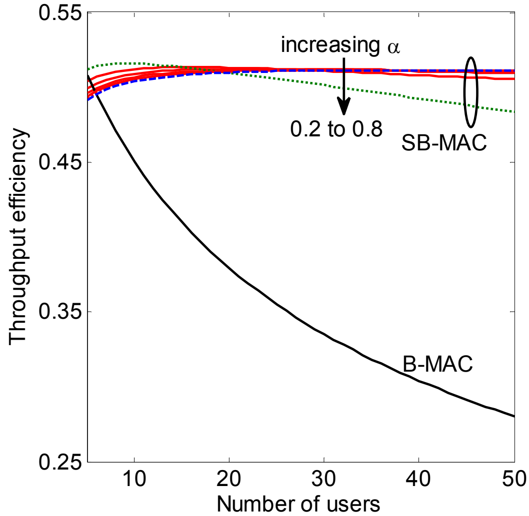


Figure 6.3: Network throughput efficiency of SB-MAC and B-MAC under various number of contending users.

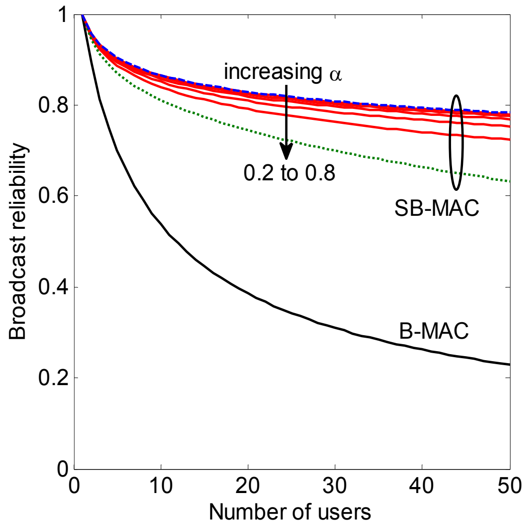


Figure 6.4: Broadcast reliability of SB-MAC and B-MAC under various number of contending users.

than or roughly equal to the size of contention window (16). As the ratio of contending users over contention size increases, it is beneficial to use lower values for α to maintain a graceful $\Im$.

As shown in Fig. 6.4, it would be desirable to use lower α value to enhance $\Re$ in SB-MAC. The lower the value of α, the higher will be the chance of selecting collision-free earlier contention slot. For example, among the various α values considered, reliability is best when α is 0.2. The desirability of lower α values for better $\Re$ is common to $\Im$ as well, expect for the case when the contending population size is less than (or in the order of) the size of the contention window used.

Beside the SB-MAC performance in terms of $\Im$ and $\Re$, Fig. 6.3 and Fig. 6.4 also show these performance for the B-MAC. Contrary to the performance trend in SB-MAC, both $\Im$ and $\Re$ in B-MAC severely decrease with an increase in contending population size. A simple comparison reveals that the SB-MAC performs better over the entire range of considered contending population, irrespective of the values specified for α. It is interesting to highlight that the performance gain that SB-MAC offers over B-MAC increases with increase in contending population size. For example, SB-MAC offers an enhancement of approximately 230% in $\Re$ along with 75% enhancement in $\Im$ when the number of contending users is three times the size of the contention window.

Case 2: Non-standard Contention Window:$\Im$ and $\Re$ of B-MAC are compared with that of SB-MAC considering various non standard contention window sizes, up to either four times smaller or larger than that of the standard contention window (16), and a typical α value (0.2). Recall that, in Fig. 6.1, $\Im$ of B-MAC linearly increases with respect to contention window size (for a given number of user) until it reaches the critical threshold. Beyond that threshold it starts to decrease. Similar critical threshold exists for SB-MAC as well, as can be noted in Fig. 6.5, but it is relatively smaller than that of B-MAC. For example, when there are 50 users in the network, the critical window for B-MAC is almost 16 times larger than the standard contention window. In case of SB-MAC, it is nearly of the same order as the standard contention window. From Fig. 6.5 it is evident that the performance of SB-MAC in terms of $\Im$ is superior than that of B-MAC for any number of user population size, especially for the contention windows that are equal or smaller than the critical contention window size. Unlike $\Im$, $\Re$ of SB-MAC monotonically increases, regardless of the number of users, with increase in the contention window sizes as can be noted in Fig. 6.6. It is noteworthy to mention that $\Re$ of SB-MAC is higher than that of B-MAC for any cases of contention window and user population sizes.

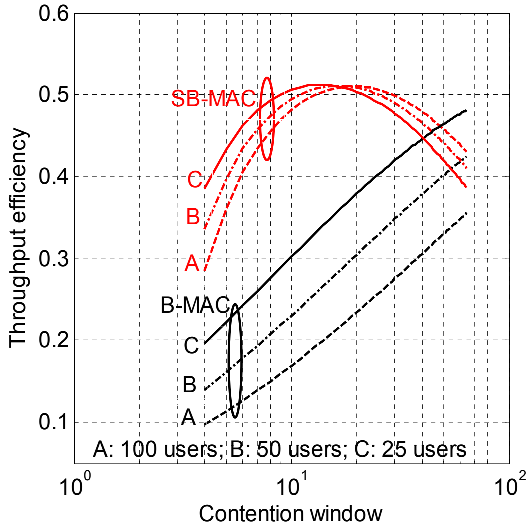


Figure 6.5: Network throughput efficiency of SB-MAC and B-MAC under various contention window size configurations

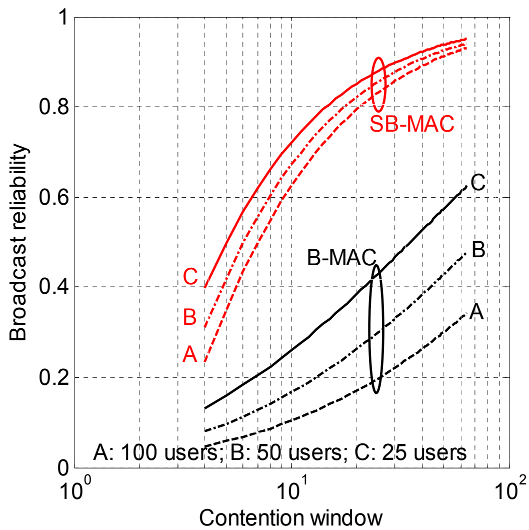


Figure 6.6: Broadcast reliability of SB-MAC and B-MAC under various contention window size configurations

6.4 Concluding Remarks

Unlike the throughput-centric design objectives in unicast contention-based MAC protocols, their broadcast counterparts should have reliability-centric design objective because they do not necessarily have MAC layer retransmission mechanisms for the lost packets. From the perspective of a MAC layer, broadcast reliability issues can be addressed by reducing the number of packet collisions as much as possible. Recently, it has been noted that the number of collisions in broadcast CSMA/CA networks can be significantly reduced by using a well scaled reverse-exponential CSSD to conduct the backoff procedure. In this chapter, a simple and accurate analytical model has been developed to characterize the channel access arbitration according to this approach. The model was validated using computer simulations, and it was then used to demonstrate the performance gains available from this approach in terms of easily understandable performance indicators such as network throughput efficiency and broadcast reliability.

7 Conclusions

In this dissertation, we have presented some innovative approaches to enhance the performance of the contention-based wireless MAC protocols standardized in IEEE 802.11. In particular, we have improvised both the best-effort and QoS-differentiated MAC protocols that have been specified in IEEE 802.11 by introducing and engineering the additional DoDF related to the CSSD. The remarkable attributes of the proposed improvisation approaches are that they adhere and retain the simplicity of the original CW-based channel arbitration mechanism and does not require any changes in the standard signaling mechanism used for transmitting a frame and the standard frame structure (format). Such attributes make the proposed improvisation approaches attractive for practical implementation in the real-worls WLANs. In what follows, we summarize those approaches in the order they have appeared in the dissertation.

In Chapter 3, we have presented a scheme to improvise the standardized channel access arbitration mechanism in unicast DCF, which is based on CSMA with random backoff based CA, by adding an additional DoDF to the conventional contention parameter set that is responsible for regulating the random backoff procedure. More precisely, the uniformly flat static CSSD over the CW in the legacy scheme is allowed to have adaptively tunable non-uniform shape where the CSSD tuning operation is triggered every time the collision event is observed. Detail theoretical analysis using a newly developed analytical model, 3D DTMC based user model coupled with a RRP based network model, and simulation based analysis using ns-2 have revealed that the improvised DCF enhances the performance of a typical saturated and an error-free WLAN equipped with IEEE 802.11b radio in all aspects of network throughput, packet transmission delay, and throughput fairness of individual users. In Chapter 4, we have shown that the improvised DCF maintains its throughput superiority in terms of network throughput even in error-prone and arbitrarily loaded non-saturated WLAN, considering the Rayleigh-faded channel and Poisson packet arrival at MAC queue.

In Chapter 5, we have devised a simple mechanism, referred to as PCMR, to adopt the approach presented in Chapter 3 in QoS differentiated MAC protocol specified in IEEE 802.11e because that approach does not looks lucrative in EDCA as the independently tuned CSSD by users may frequently violate the underlying relative differentiation principle and may bring undesirable and counterproductive consequences in regards to QoS provisioning among heterogeneous services. We have shown that by using PCMR on top of modified EDCA, EDCA in which the non-uniform CSSD tuning mechanism is applied, better throughput differentiation between the heterogeneous traffic categories can be achieved. Moreover, we have shown that the throughput share of the higher priority traffic (for example voice service) can be retained as close to the ideal value even if the traffic belonging to the low priority service category (for example data service) significantly increases in the network.

Finally, in Chapter 6, we have introduced a scheme to improvise the standardized channel access arbitration mechanism in the conventional broadcast DCF. The conventional broadcast DCF suffers from the similar throughput degradation problem as its unicast counterpart does, especially when the network density increases. Moreover, due to the plurality of destinations in broadcast applications, the provision of acknowledging the reception of the broadcasted packets has been dropped since simultaneously acknowledging the reception of the broadcasted packets from several destinations is not feasible, while individually acknowledging the reception, on the other hand, may hugely wastes the channel resources. Therefore, broadcast reliability (in terms of successful reception at destinations) also quickly decreases with an increase in number of contending broadcast users. We have show that such issues related to inverse relationship of network throughput efficiency and broadcast reliability with contending population size can be partially addressed from MAC layer by reducing number of collisions as much as possible. In particular, we have shown based on the validated theoretical analysis that by using a configurable reverse-exponential CSSD (with configurable parameter α, $\alpha \in [0,1]$) over the temporal CW in a typical single hop and error-free IEEE 802.11a network, approximately 230% enhancement in broadcast reliability along with 75% enhancement in network throughput can be achieved when the number of contending users is three times more than the size of the default CW and α equals to 0.2.

Even though, in this dissertation, we have introduced and engineered the concept of DoDF related to CSSD in context of 802.11 WLANs, we speculate that the concept can be easily incorporated in other CSMA/CA based networks including WPANs and WBANs, among others.

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Appendix A: Representative Publications

1. Following are the representative journal publications based on the contributions of this dissertations:

S. Pudasaini, S. Shin, and K. Kim, "Carrier Sense Multiple Access with Improvised Collision Avoidance and Short Term Fairness," *Springer Wireless Networks*, in Press. [SCI]

S. Pudasaini, M. Kang, S. Shin, and J. Copeland, "COMIC: Intelligent Contention Window Control for Distributed Medium Access," *IEEE Communications Letters*, vol. 14, no. 7, pp. 656-658, 2010. [SCI]

S. Pudasaini, and S. Shin, "Cross-Layer Analysis of CSMA/iCA based Wireless Local Area Networks," *Springer Wireless Personal Communications*, Accepted, In Press. [SCI-E]

S. Pudasaini, S. Shin, and K. Kim, "Throughput and Reliability Analysis of a Scalable Broadcast MAC for Distributed Wireless Networks," *EURASIP Journal on Wireless Communications and Networking*, Submitted June 2011, Revised on November 2011, Second Revision March 2012. [SCI-E]

2. Following are the representative conference publications based on

the contributions of this dissertations:

S. Pudasaini, A. Thapa, M. Kang, and S. Shin, "Intelligent Contention Window Control Scheme for Distributed Medium Access," in *Proc. IEEE Consumer Communications and Networking Conference (CCNC)*, pp. 1-2, January 2010. [Short paper]

S. Pudasaini, and S. Shin, "Cross Layer Analysis of CSMA/*i*CA based Wireless Local Area Network," in *Proc. 3rd International Conference on Ubiquitous and Future Networks (ICUFN)*, pp. 246-251, June 2011. [Best paper award]

S. Pudasaini, and S. Shin, "QoS Provisioning in CSMA/*i*CA based Medium Access Control Protocol for WLAN," in *Proc. 4th International Conference on Ubiquitous and Future Networks (ICUFN)*, pp. 1-6, July 2012. [Invited]

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Subodh Pudasaini

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논문제목	한글 : DoDF (Degree of Design Freedom)를 고려한 경쟁기반 무선 매체 접속 제어 프로토콜 연구 영어 : Contention-based Wireless Medium Access Control Protocols with Additional Degree of Design Freedom				

본인이 저작한 위의 저작물에 대하여 다음과 같은 조건아래 -조선대학교가 저작물을 이용할 수 있도록 허락하고 동의합니다.

\- 다 음 -

1. 저작물의 DB구축 및 인터넷을 포함한 정보통신망에의 공개를 위한 저작물의 복제, 기억장치에의 저장, 전송 등을 허락함
2. 위의 목적을 위하여 필요한 범위 내에서의 편집・형식상의 변경을 허락함. 다만, 저작물의 내용변경은 금지함.
3. 배포・전송된 저작물의 영리적 목적을 위한 복제, 저장, 전송 등은 금지함.
4. 저작물에 대한 이용기간은 5년으로 하고, 기간종료 3개월 이내에 별도의 의사 표시가 없을 경우에는 저작물의 이용기간을 계속 연장함.
5. 해당 저작물의 저작권을 타인에게 양도하거나 또는 출판을 허락을 하였을 경우에는 1개월 이내에 대학에 이를 통보함.
6. 조선대학교는 저작물의 이용허락 이후 해당 저작물로 인하여 발생하는 타인에 의한 권리 침해에 대하여 일체의 법적 책임을 지지 않음
7. 소속대학의 협정기관에 저작물의 제공 및 인터넷 등 정보통신망을 이용한 저작물의 전송・출력을 허락함.

동의여부 : 동의(o) 반대( )

2012년 07월 10일

저작자: 수보드 푸다사이니 (서명 또는 인)

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