A DISTRIBUTED AIR-TIME FAIR MAC FOR MULTI-RATE IEEE 802.11 NETWORKS USING MULTIPLE DISTRIBUTED COORDINATION FUNCTIONS

A THESIS

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By

Fırat Karataş

July 2010

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

A DISTRIBUTED AIR-TIME FAIR MAC FOR MULTI-RATE IEEE 802.11 NETWORKS USING MULTIPLE DISTRIBUTED COORDINATION FUNCTIONS

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July 2010

In a multi-rate IEEE 802.11 network, the conventional Distributed Coordination Function (DCF) Medium Access Control (MAC) aims to ensure max-min throughput fairness and equal channel access in scenarios with multiple nodes, while failing to satisfy air-time fairness. Consequently, nodes that have relatively poor channels or longer packets to transmit invade the channel substantially more than others, hence decreasing the throughput of nodes which have better channels or shorter packets. This phenomenon is known as the performance anomaly problem in the existing literature. In this thesis, we propose a novel distributed air-time fair algorithm to cope with the performance anomaly problem without having to change the conventional IEEE 802.11 DCF MAC. In the proposed algorithm, each node in the system runs multiple instances of the conventional IEEE 802.11 DCF back-off algorithm where the number of instances for the particular node is calculated independently from other nodes using only local information such as packet lengths and transmission rates. Both analytical and simulation-based results are provided to validate the effectiveness of the distributed air-time fair algorithm we propose.

Keywords: IEEE 802.11 Distributed Coordination Function (DCF) MAC, air-time fairness, multi-rate wireless network, performance anomaly

ÖZET

ÇOKLU HIZ ORANLI IEEE 802.11 AĞLARINDA ÇOKLU DAĞITILMIŞ KOORDİNASYON FONKSİYONU (DKF) KULLANARAK KANAL YAYIN SÜRELERİNİ EŞİTLEMEK

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Elektrik ve Elektronik Mühendisliği Bölümü Yüksek Lisans
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Çoklu hız oranlı IEEE 802.11 ağlarında, bilinen IEEE 802.11 Dağıtılmış Koordinasyon Fonksiyonu (DKF) Çoklu Erişim Kontrol (ÇEK) mekanizması en büyük ve en küçük iş/zaman oranının eşitliğini ve birden fazla kullanıcılı senaryolarda eşit kanal erişim sayısını, kanal yayın sürelerini eşitleyemeden sağlamaktadır. Buna bağlı olarak, diğerlerine göre daha kötü kanalları kullanan ya da gönderilecek paket uzunlukları daha fazla olan kullanıcılar, diğer kullanıcılara göre ciddi anlamda kanalı daha fazla işgal etmekte ve bunun sonucunda da daha iyi kanalı kullanan veya daha kısa paketlere sahip olan kullanıcıların iş/zaman oranı düşmektedir. Bu olay literatürde, performans anormalliği problemi olarak tanımlanmıştır. Bu tezde, dağıtılmış, kanal yayın sürelerini eşitleyerek performans anormalliği problemini çözen ve klasik IEEE 802.11 DKF ÇEKinde bir değişiklik yapılmasını gerektirmeyen yeni bir algoritma sunmaktayız. Sunulan algoritmada sistemdeki her kullanıcı, birden fazla klasik IEEE 802.11 DKF geri sayma algoritması - kaç tane algoritma kullanılacağı her kullanıcı tarafından, diğer kullanıcılardan bağımsız bir şekilde, sadece paket uzunluğu ve kanal erişim hızı gibi yerel bilgiler ışığında hesaplanmaktadır - çalıştırmaktadır. Bütün analitik ve simülasyon tabanlı sonuçlar, önerilen bu dağıtılmış kanal yayın sürelerini eşitleyen algoritmanın verimliliğinin doğruluğunu ispatlamaktadır.

Anahtar Kelimeler: IEEE 802.11 Dağıtılmış Koordinasyon Fonksiyonu (DKF) Çoklu Erişim Kontrol (ÇEK), kanal yayın süresi eşitliği, çoklu hız oranlı kablosuz ağ, performans anormalliği

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Dedicated to my parents and my brother…

Chapter 1

INTRODUCTION

1.1 IEEE 802.11 Introduction

IEEE 802.11 is the most commonly deployed suite of protocols for wireless local area networks (WLAN). The goal of WLANs is to meet networking demand of users for which wired setup is hard, expensive, or infeasible. IEEE 802.11 standards are announced by IEEE working groups of WLAN standards. The first IEEE 802.11 standard was introduced in 1997 [3] with later announcements of 25 further standards, some of which are finalized and some still have active working groups.

IEEE 802.11 WLANs are designed to offer services that are already available in wired Local Area Networks (LANs) that satisfy the reliable data transfer requirements and ensure continuous network connection [4]. Although there are similarities between conventional wired LANs and WLANs, wired LANs are connected via a wire which is a guided transmission medium and WLANs are connected via air which is an unguided medium. Another important difference between wired LANs and WLANs is mobility; wired LANs do not support mobility because all the stations in the network are connected via wire, but WLANs

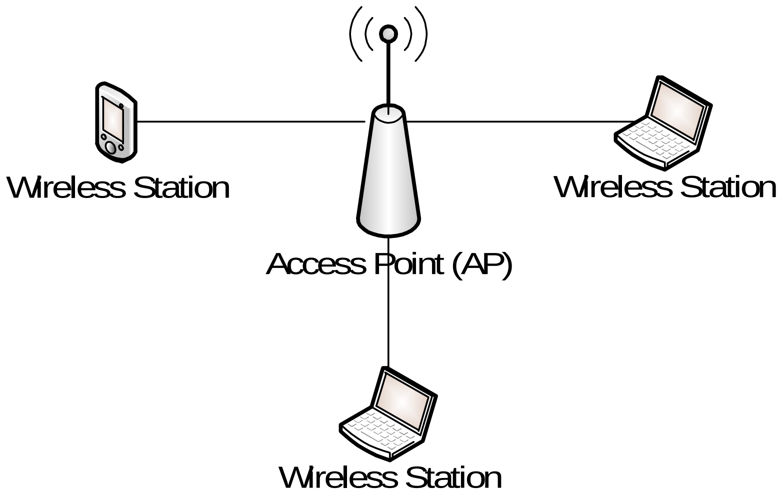


Figure 1.1: A Basic Service Set (BSS)

support mobility because stations can move freely. However, there is a drawback of this flexibility; most of the today's equipment use air as transmission medium and WLANs can interfere with existing equipment (if the same frequency band is used) leading to potential physical layer problems, for instance a moving station can lose connection to its base station [5].

The nodes of IEEE 802.11 WLANs are called stations (STA); stations use wireless medium, which is air, and they can be mobile. Stations can be an access point (AP) or a wireless station (a user in the wireless network). Wireless networks are built by STAs, and basic IEEE 802.11 WLANs are setup by an AP and wireless STAs that are connected to an AP. This basic set of stations is named as Basic Service Set (BSS) [6]. In some cases, there might be no AP in the set and then it is called Independent Basic Service Set (IBSS). The main difference between BSS and IBSS is the control mechanism; in BSS all the STAs are coordinated by AP, but in IBSS there is no such control mechanism and IBSS is an ad-hoc network. If more than one BSS is connected with each other, it is called Extended Service Set (ESS) [2].

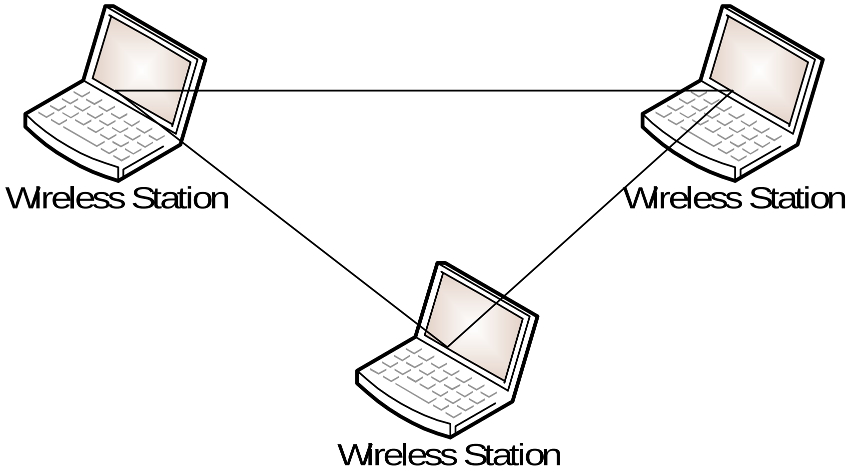


Figure 1.2: An Independent Basic Service Set (IBSS)

The speeds that are supported by IEEE 802.11 WLANs are approaching wired LANs; the most common wired LAN is Ethernet (IEEE 802.3) and it supports speeds up to 10Gb/s, but the most widespread speed is 100Mb/s and WLANs try to meet this standard speed [7]. In the first version of IEEE 802.11 standard, the standard supported only two different transmission data rates by using DSSS (Direct Spread Spectrum Spread). The data rates of the first version are 1Mb/s and 2Mb/s, but in response to growing bandwidth demands, the second version of IEEE 802.11 offered higher transmission speeds by using successive extensions of DSSS which is HR-DSSS (High Rate/Direct Spread Spectrum Spread) on the 2.4GHz frequency band. For IEEE 802.11b, the data rates are 1Mb/s, 2Mb/s, 5.5Mb/s and 11Mb/s [8]. Depending on the extensions and developments in the physical layer, IEEE 802.11 reaches the transmission speed of 54Mb/s in IEEE 802.11a and IEEE 802.11g standard [9],[10]. OFDM (Orthogonal Frequency Division Multiplexing) is used in IEEE 802.11a on the 5GHz band and in IEEE 802.11g on the 2.4GHz band instead of DSSS. Different users of the same 802.11 multi-rate network can use different transmission rates based on their channel conditions. Moreover, a single user can experience varying channel conditions and it can opt to adaptively change its transmission rate in response to channel

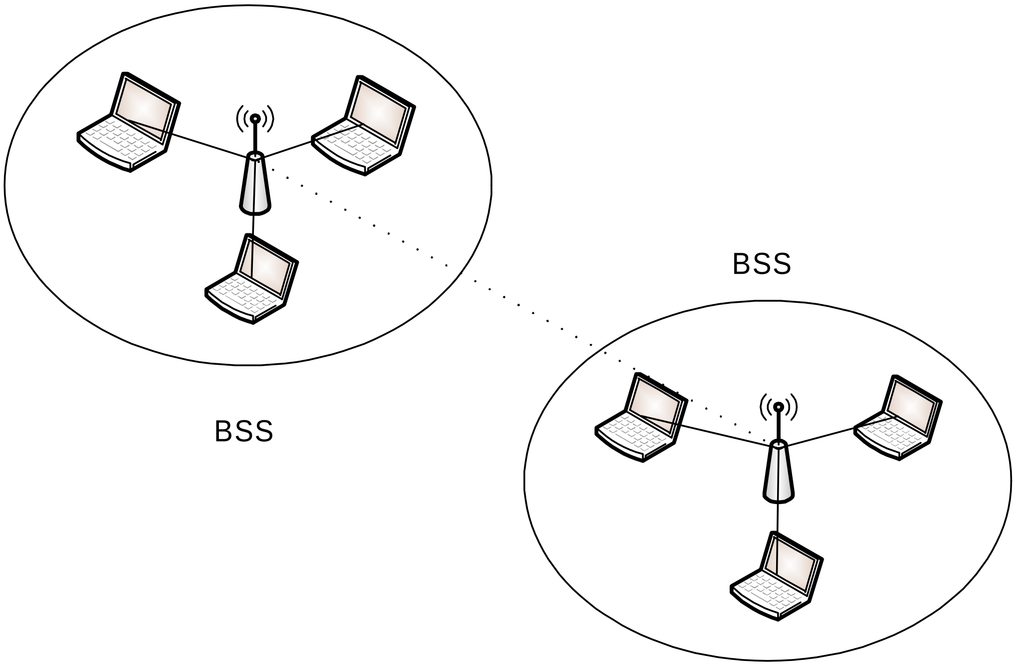


Figure 1.3: An Extended Service Set (EBS)

IEEE 802.11 Type	Operating Frequency
IEEE 802.11a	5GHz
IEEE 802.11b	2.4GHz
IEEE 802.11g	2.4GHz

Table 1.1: IEEE 802.11a/b/g Operating Frequencies

variations. For example, if the signal strength of a user momentarily drops, the user can choose to lower its data transmission rate in order to reduce the packet loss probability.

1.2 Multiple Access Control Protocols (MAC)

In wireless networks, the medium is shared by all the users in the system. Hence there must be a protocol to handle the multiple access mechanism of the medium. This problem is solved by Multiple Access Control Protocols (MAC). There are two major types of multiple access mechanisms: conflict free access protocols and contention based access protocols. The difference between these two types

IEEE 802.11 Types	Transmission Data Rates in Mbps							
IEEE 802.11a	6	9	12	18	24	36	48	54
IEEE 802.11b	1		2		5.5		11	
IEEE 802.11g	6	9	12	18	24	36	48	54

Table 1.2: IEEE 802.11 Transmission Data Rates

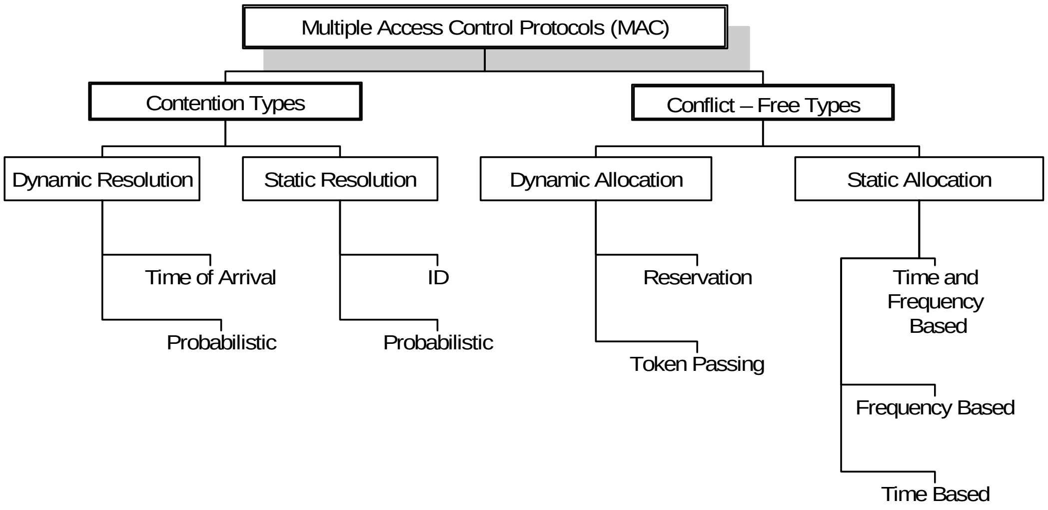


Figure 1.4: Multiple Access Control Protocols (MAC) [1]

of the protocols is the idea of guaranteed successful transmission. In the case of conflict-free type of protocols, when a transmission is done, it is ensured as successful; because it is guaranteed that only one node in the system can transmit so there are not any collisions. On the other hand, in contention-based access protocols, if a transmission is done, there is no guarantee that it would be successful since when a node transmits, another node in the system may also transmit leading to collisions and an unsuccessful transmission. The most common conflict-free access protocol types are FDMA (Frequency Division Multiple Access), TDMA (Time Division Multiple Access), and CDMA (Code Division Multiple Access). On the other hand, the most common contention-based access protocols are Aloha type protocols and Carrier Sensing type protocols. IEEE 802.11 MAC (Medium Access Control) uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) which is a contention based and carrier sensing type multiple access protocol [1].

1.3 Multiple Access Protocols used in IEEE 802.11

There are two types of multiple access protocols used in IEEE 802.11: centralized and distributed. Although there are two different types, three multiple access mechanisms are used in IEEE 802.11 which are Distributed Coordination Function (DCF), Point Coordination Function (PCF) and Hybrid Coordination Function (HCF). DCF is a distributed multiple access protocol where the others, PCF and HCF, are centralized.

One of the MAC mechanisms used in IEEE 802.11 is the PCF which uses a STA as the coordination unit of the network. PCF is based on polling where the chosen STA works as a coordinator and it polls all the STAs to give transmission right to the polled STA. PCF is a centralized multiple access protocol and is not commonly deployed due to difficulties of implementing centralized systems. Most of the IEEE 802.11 MAC relies on Distributed Coordination Function (DCF) which depends on CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance). DCF is responsible for the coordination of transmission attempts of the stations in the network in a distributed manner. In DCF, each station in the network senses the channel all the time and keeps track of the status of the medium, i.e., whether the medium is idle or busy. When the medium is idle, the sensing node waits for a random amount of time; this period is determined by choosing a random number in an interval called the contention window. The node then transmits according to a reservation rule. If the channel is busy, the node stops the timer and starts it again after sensing the channel idle. Before starting the transmission, each node reserves the channel for a certain amount of time by using Request to Send (RTS) message, which a short message, and when another short message which is Clear to Send (CTS) is received by node that wants to transmit, it starts the transmission. In the sense of being clear,

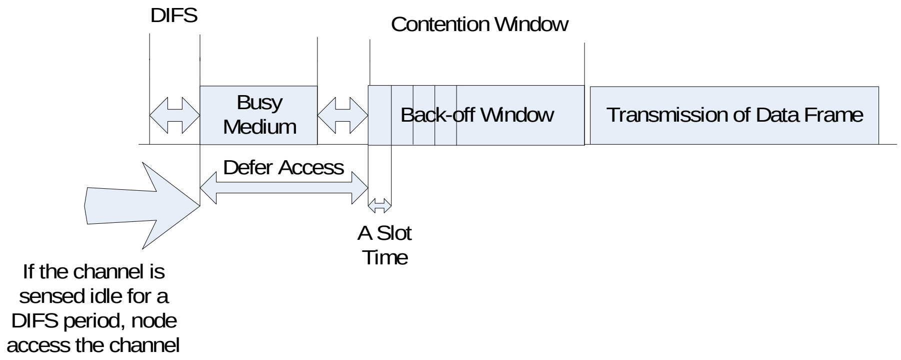


Figure 1.5: DCF Basic Access Method [2]

IEEE 802.11 DCF coordinates the transmission traffic between nodes by using a random back off timer, a carrier sensing mechanism and a reservation protocol to increase the probability of successful transmission. IEEE 802.11 DCF MAC will be explained in Section 3.1 in detail.

Hybrid Coordination Function (HCF) is another MAC used in IEEE 802.11 combining DCF and PCF but in this thesis we only focus on the commonly used DCF.

1.4 Outline

In Chapter 2, we describe the fairness problem with emphasis on air-time fairness in detail in IEEE 802.11 WLANs and related work on fair algorithms. In Chapter 3, we describe our proposed algorithm and give the mathematical background for the proposed approach. In Chapter 4, numerical results are provided to validate the proposed approach in various scenarios. Finally, Chapter 5 concludes this thesis.

Chapter 2

Fairness in IEEE 802.11 Networks

2.1 Problem Definition

One of the important properties of IEEE 802.11 DCF is that DCF maximizes the throughput of the node which obtains the minimum throughput among all the contending nodes. DCF is therefore a max-min fair MAC mechanism. DCF may not guarantee transient channel access fairness because of the randomness involved in channel access but it ensures long term channel access fairness. While DCF maximizes the minimum throughput in the system, it may also decrease the throughput of other nodes since all the nodes in the system are to have the same throughput in DCF when the nodes are saturated; they have an infinite amount of backlog. Equivalently, the slowest communication peer in the network penalizes other nodes in DCF. This phenomenon is called *rate anomaly* [11]. Alternatively, a MAC is called air-time fair if the air-time usages of contending nodes are the same in the long term again for saturated users. Note that a throughput-fair algorithm is not air-time fair and vice-versa. The advantage of an air-time fair algorithm is that slow users cannot penalize other nodes as in DCF. Although DCF is fair in terms of channel access and throughput, DCF does not guarantee air-time fairness since DCF does not take the packet lengths and transmission data rates into consideration. When multiple data rates rate and different packet lengths are considered in the system, nodes that have slower transmission data rates or longer packet lengths invade the channel more than the other nodes in DCF. Although other fairness definitions can be of further interest, we attack the rate anomaly problem in this thesis by modifying DCF so as to achieve air-time fairness only.

2.2 Existing Work and Motivation

2.2.1 Existing Work

Most of the research on fairness of IEEE 802.11 MAC is based on the adjustment of contention window in IEEE 802.11 MAC. Contention Window (CW) of IEEE 802.11 MAC must be specified by maxima; the most common values of maxima are 31 and 1023. The value of contention window does not depend only on the maxima; when a collision is detected, nodes double their contention window in order to be conservative and draw new random numbers to wait. Most of the researchers proposed that limiting the contention window within these values creates the fairness problem, and they propose medium access protocols by using the commercial IEEE 802.11 DCF. The major difference between the proposed methods and commercial IEEE 802.11 DCF is in the definition of contention windows.

The reference [12] suggests that the rate (performance) anomaly problem can be resolved by changing CW_{min} values of IEEE 802.11 DCF for each node. The authors propose that CW_{min} should be chosen to be inversely proportional with transmission data rates. Consider an IEEE 802.11b network where the bit rates are 11Mbps, 5.5Mbps, 2Mbps and 1Mbps, and two different nodes with different bit rates: assume one node has bit rate of 11Mbps and the other one as 1Mbps. The reference [12] proves that choosing CW_{min} for node with rate 11Mbps as 32 slots and for node with 1Mbps as 352 slots resolves the performance anomaly problem. However, it is not clear how to have an all-distributed implementation for this mechanism.

The reference [13] proposes another CW scaling system where each node in the system observes the idle slots and scales their CW accordingly. This method satisfies short-term fairness in the network, high throughput demand, low collision overhead and low delay. In this method, each node counts the empty slots between two transmission attempts and compares that value with theoretical calculations and adjusts the CW by using an AIMD (Additive Increase Multiplicative Decrease) algorithm.

In [14], a method called Time Fair Carrier Sense Multiple Access Protocol (TFCSMA) is proposed and it helps to achieve air-time fairness for the system. The proposed method considers Packet Error Rate (PER), throughput estimation and transmission data rates. By using PER and bit rates, each STA estimates a throughput and it controls its CW by using certain control mechanisms. Hence, air-time fairness for the system is achieved by adjusting CW of the nodes.

[15] proposes a priority based medium access (P-MAC) protocol for fairness and increasing the total throughput. The proposed method adjusts CW of each node, and it is shown that wisely tuning CW parameter leads maximal aggregate throughput for the system. The defined algorithm is based upon knowing the number of stations competing with each other and traffic flow weights. By using traffic flow weights, weighted fairness is achieved and by knowing the number of competing nodes, maximum aggregate throughput is obtained.

In [16], the authors implement optimal CW values in an IEEE 802.11e testbed and they show that optimal CW value changes from node to node. Nodes in the testbed have different bit rates and weights, so optimal value of CW differs. For instance, for the nodes that have same transmission data rates but different weights, optimal CW is smaller for the nodes that have higher weights. The situation is also the same in the case of same weights and different bit rates; for higher bit rates optimal CW is smaller.

The reference [17] is based on the observation that achieving air-time fairness will degrade the aggregate throughput of the system so there should be a balance between these; the new fairness definition they propose is called *proportional fairness*. The authors propose a centralized type of approach in which there is a node that controls the air-time usage of the STAs in the system. Moreover, burstification of packets in each node increases the time fairness in the system without considerable reduction in the aggregate throughput. [17] also points out that adjusting CW will improve the fairness and does not affect the performance of the system significantly.

The reference [18] supports [17] from the main idea perspective. [18] attacks the proportional fairness problem from the AP selection point of view. [18] concentrates on choosing APs intelligently in order to achieve the proportional fairness goal. This approach also improves load balancing in the system.

[19] defines a novel proportional fairness criterion for throughput allocation in multi-rate IEEE 802.11 to achieve fairness in a network in which all the nodes have different traffic demands and channel usages. The researchers also show that by satisfying this performance criterion, optimized throughput allocation will be obtained.

The reference [20] describes another algorithm called TCP Friendly Rate Control (TFRC) in a network in which all the nodes use TCP as a transport layer protocol and air-time fairness can be achieved by adjusting the sending rate in transport layer. The proposed algorithm is a cross-layer approach, because TCP, which is a transport layer, controls the MAC layer. The drawback of the system can be assumed as its cross-layer design, because it does not support UDP traffic or any other traffic definitions other than TCP.

The reference [21] solves performance anomaly problem with a combination of contention window scaling approaches and TCP rate control approach. According to TCP rate control, each window adjusts its CW and air-time fairness for the system is exhibited and aggregate throughput of the system is improved. This protocol has also a drawback stemming from cross-layer design and it again only supports TCP traffic.

2.2.2 Motivation

This thesis focuses on the performance anomaly problem of IEEE 802.11 which is defined by [11]. [11] shows that if there is a multi-rate IEEE 802.11 network, the throughput that is obtained for the two nodes including the one with the fastest transmission data rate and the slowest data rate is same; in other words, throughput of a node in an IEEE 802.11 network is independent from the bit rate of the node. Consequently, nodes with higher transmission data rates are penalized by slower nodes. If the nodes with higher transmission data rates are not penalized, the performance anomaly problem can be reduced. The concept of air-time fairness is an attempt to address the performance anomaly problem.

The authors [22] show that performance of IEEE 802.11 WLANs can be improved by obtaining time-based fairness in the network. They define a property called baseline property which indicates the main problem of IEEE 802.11 DCF. The baseline property suggests that the long-term throughput of a node in a multi-rate network is bounded by the throughput of a node where all the stations in the network have the same transmission data rate and they are equal to its rate. To be more precise, the upper throughput bound of a node is determined by its transmission data rate and it is indicated that IEEE 802.11 DCF is fair in the meaning of throughput, then if these two statements are combined, it can be argued that the throughput of each node in the system is bounded by the slowest communication data peer. When the theoretical bounds are obtained, the performance of the system will improve and they can be obtained by guaranteeing time-based fairness [22]. In the current thesis, we propose an air-time fair mechanism in which air-time fairness can be achieved by running multiple instances of DCF in each node.

2.3 Proposed Method Introduction

We propose a new approach for achieving air-time fairness in IEEE 802.11 which is very simple to implement and requires nothing except for the DCF defined in the standard. The main aim of our algorithm is achieving air-time fairness rather than throughput fairness, but we do not bound the nodes with higher transmission data rates in the system such as in the commercial IEEE 802.11 MAC. In our algorithm, when the nodes have same packet lengths but different transmission data rates, the node with the highest transmission rate gets the highest throughput. We note that we do not guarantee an increase in the aggregate throughput while achieving air-time fairness. What we propose is running multiple instances of the standard DCF at each node and we do not employ a centralized mechanism and we do not change the distributed manner of DCF. In our proposal, each node in the system is responsible for calculating the number of back-off algorithms, say N, that should be run at the particular node. This parameter N, on the other hand, can be calculated by dividing the air-occupancy of the current packet waiting for transmission by a constant which is defined as the maximum possible packet length divided by the worst transmission data rate in the network. Each node in the system then calculates the required number of back-off algorithms by the help of this constant. However, the parameter N need not be an integer and we therefore propose a distributed algorithm that switches between $N_- = \lfloor N \rfloor$ and $N_+ = \lceil N \rceil$ back-off algorithms. We show that the method we propose achieves exact air-time fairness at the expense of an acceptable aggregate throughput reduction. The most important difference of this method from other approaches in the literature is this method does not take into consideration the contention window definitions and its maxima.

Property	Node 1	Node 2
Number of Channel Access	48029	47416
Throughputs in Mbps	0.901	0.890

Table 2.1: Channel Access and Individual Throughputs in a Throughput Fair Network: Nodes have constant packet lengths of 2346 bytes but different transmission data rates. Node 1 has speed of 1Mbps and Node 2 has a speed of 11 Mbps

Property	Node 1	Node 2
Number of Channel Access	26174	283408
Throughputs in Mbps	0.491	5.319

Table 2.2: Channel Access and Individual Throughputs in an Air-Time Fair Network: Nodes have constant packet lengths of 2346 bytes but different transmission data rates. Node 1 has speed of 1Mbps and Node 2 has a speed of 11 Mbps

Property	Throughput Fair	Air-Time Fair
Number of Empty Slots	16784160	21153040
Aggregate Throughput in Mbps	1.791	5.881

Table 2.3: Throughput Fair Algorithm vs Air-Time Fair Algorithm

Chapter 3

DISTRIBUTED AIR-TIME FAIR MAC

3.1 IEEE 802.11 DCF MAC

IEEE 802.11 DCF MAC is a basic MAC protocol and is based on one of the carrier sense mechanisms which is CSMA/CA. IEEE 802.11 DCF MAC is distributed and it automatically coordinates the medium access for all nodes in the system. If the medium is sensed busy, a random back-off timer starts to count down. When the transmission is successful, the receiver sends a positive acknowledgment (ACK) to the sender to help scheduling a retransmission or not [2].

The CSMA/CA protocol is built upon a simple approach called "Carrier Sensing" (CS). The transmission medium is kept track of by all the nodes with this elementary approach. The reason why there is a need for such a mechanism is to reduce the probability of collisions that would occur. In this mechanism, all the nodes sense the channel physically and virtually, then decide what it should do: transmit, schedule a retransmission, defer access to the channel, or start the random back-off mechanism. There are two CS mechanisms called “Physical Carrier Sensing” and “Virtual Carrier Sensing”. Physical CS mechanism is used in IEEE 802.11 Physical (PHY) layer and it shares the information with IEEE 802.11 MAC layer. In Physical CS, the node compares the received signal with a predefined threshold “CW_{th}” and if the received signal is higher than CW_{th}, medium is defined as busy [23]. Physical CS helps nodes to choose channels appropriately, i.e., by choosing different channels that do not overlap with each other or overlap in some aspect with the help of PHY CS, interference between the channels can be reduced [24]. Virtual CS is another CS mechanism used in IEEE 802.11 and it is designed on the IEEE 802.11 MAC layer. Virtual CS is also known as *Network Allocation Vector (NAV)* [2]. NAV contains the time periods of the transmission, so it helps each STA to determine how much time the wireless medium should be considered as busy, i.e., NAV contains the transmission time of the transmitting node so other nodes can plan their transmission schedules based on the time data contained in NAV. NAV information is announced in RTS (Request-to-Send) and CTS (Clear-to-Send) frames, so all the nodes that capture RTS and CTS frames know the busy time period of the wireless medium, to be more precise they sense the channel virtually.

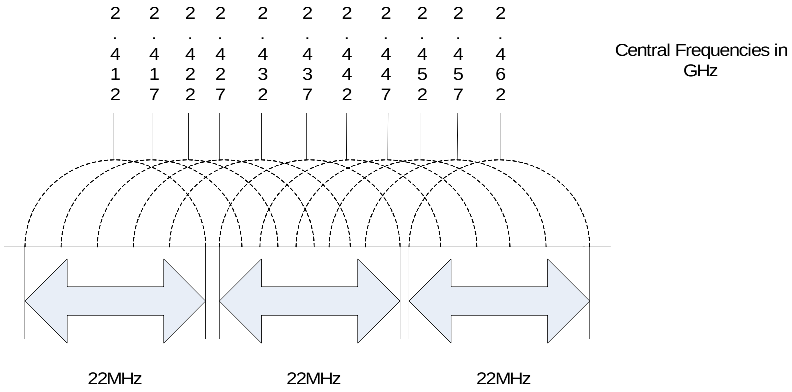


Figure 3.1: IEEE 802.11b Channels used in USA and Canada

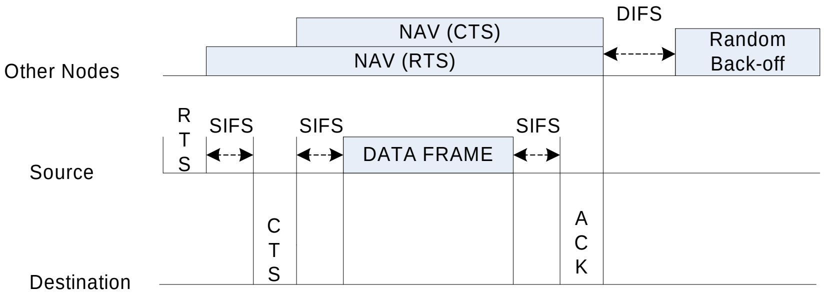


Figure 3.2: RTS/CTS Timing Mechanism [2]

3.1.1 IEEE 802.11 DCF MAC Access with RTS/CTS Mechanism

RTS and CTS frames are smaller frames than the data frames and they are used for channel reservation. RTS is for requesting channel reservation and CTS is a positive or negative response to this request. If a node has a packet to transmit, it sends a frame called RTS to reserve the channel and according to the received frame which is a response to this reservation process and called CTS, node transmits or waits. RTS and CTS frames reduce the probability of collisions in the system and these frames are mostly used where multiple BSSs use the same channel. Consider two BSSs (BSS 1 and BSS 2) whose communication ranges overlap and both use the same channel (Figure 3.3). A node wants to transmit a packet to the node, which is the transmission range of both BSS 1 and BSS 2, in BSS 1; but in BSS 2 there is a ongoing transmission in BSS 2. The receiver node will hear both transmissions, so there will be a collision occurring at the receiver which cannot be detected by both senders. If RTS/CTS mechanism is used in such a scenario, there would not be a collision because nodes will send a RTS frame to the receiver and wait for a CTS frame before starting the transmission. In other words, RTS/CTS mechanism is usually used in networks where nodes cannot hear each other. In this thesis, we focus on 802.11 networks in which RTS/CTS is not employed which is generally the default configuration in most 802.11 cards.

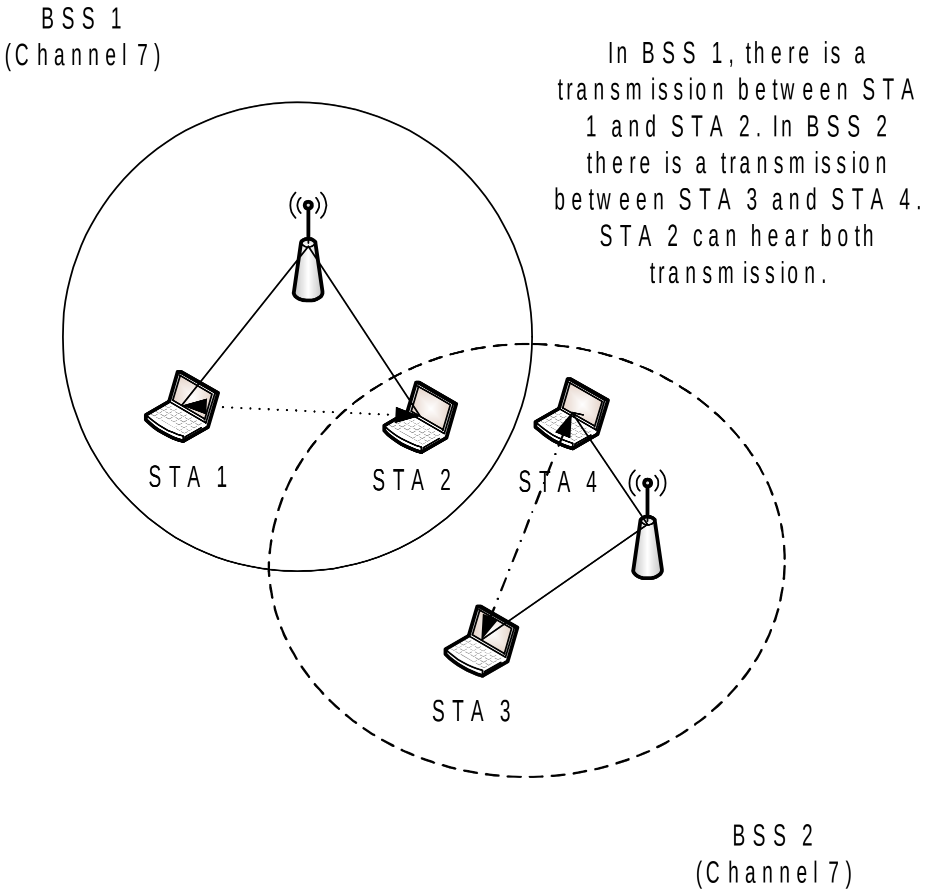


Figure 3.3: An Example Network where RTS/CTS is required

3.1.2 IEEE 802.11 DCF MAC Access without RTS/CTS Mechanism

The time between two consequent frames is called *InterFrame Space (IFS)*. There are five IFS defined in IEEE 802.11 Standard:

- SIFS Short interframe space
- PIFS PCF interframe space

IEEE 802.11 Type	SIFS	DIFS	aSlotTime	CW$_{min}$	CW$_{max}$
IEEE 802.11a	16μs	34μs	9μs	16	1023
IEEE 802.11b	10μs	50μs	20μs	31	1023
IEEE 802.11g	10μs	50μs	20μs	32	1023

Table 3.1: IEEE 802.11 Parameters used in IEEE 802.11 DCF

- DIFS DCF interframe space
- AIFS arbitration interframe space
- EIFS extended interframe space

Durations of IFSs are defined in PHY layer specifications and both are independent from the transmission data rates.

In DCF basic access procedure, the node waits for a DIFS period and accesses the channel if the channel is sensed idle. Otherwise, if the channel is sensed busy, a random back-off number is chosen from the interval [0,Contention Window(CW)-1] uniformly. There are two limits defined for contention window: CW$_{min}$ and CW$_{max}$. CW$_{min}$ is predefined and typical value for CW$_{min}$ is 31; CW$_{max}$ is also predefined and its typical value is 1023. These values limit the contention window, lower bound determines the starting point of contention window and upper bound shows where doubling of contention window should be stopped. If the channel is sensed busy during the back-off state, the node defers channel access and stops the back-off timer (Figure 3.4).Consider a network in which CW$_{min}$ is set to 15 and CW$_{max}$ is set to 31. Assume a node wants to transmit a packet. First of all, the node waits for a DIFS period and assume it senses that channel busy. This node then draws a uniform random variable from the interval [0,15] and assume that the particular instance of this random variable be five. The node then waits 5*aSlotTime where aSlotTime is defined in the PHY layer specifications and for IEEE 802.11b its default value is 20μs. The node then accesses the channel again and assume a further collision occurs in the network. After this collision, the node (almost) doubles its contention window in order to be conservative and CW value becomes 31. Again a uniform random number is chosen from the interval of [0,CW-1], but now this interval is [0,31]. The node repeats the same procedure but now if another collision is detected it would not double its contention window since CW reaches the upper limit CW$_{max}$. This procedure goes on until the node makes a successful transmission. If it transmits its packet successfully, CW value is reset to CW$_{min}$ and the mechanism described above is repeated. Figure 3.5 illustrates a detailed example of this procedure. This mechanism is called *"Random Back-off Algorithm"* and in this thesis we concentrate mainly on enhancing this algorithm to handle the rate anomaly problem observed in IEEE 802.11 networks.

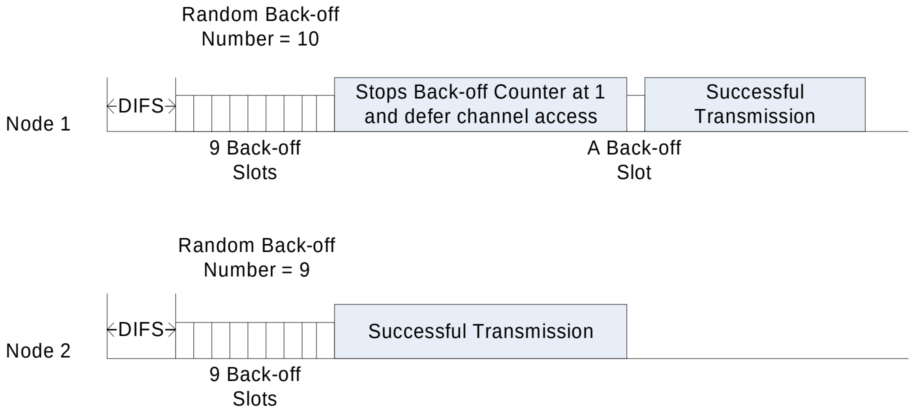


Figure 3.4: Channel Usage of Two Nodes using Random Back-off Mechanism

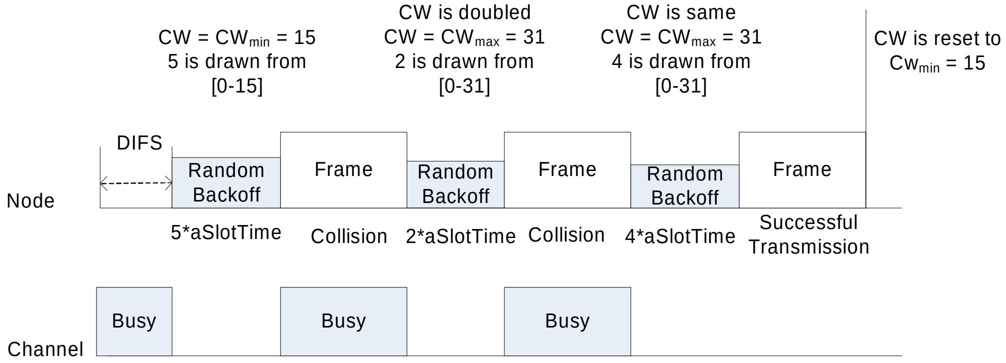


Figure 3.5: Random Back-off Procedure in a Node

3.2 DCF MAC Enhancement: Multiple Random Back-Off Algorithms

As stated in [11], in conventional IEEE 802.11, a node with the slowest transmission data rate has the same throughput as the node with the highest transmission data rate. This is also known as max-min fairness and the conventional IEEE 802.11 DCF MAC ensures this fairness definition (see also Chapter 2). The main contribution of this thesis is the observation that if we can use more random back-off algorithms for nodes with higher transmission data rates or smaller packets, then we would not penalize them as in the conventional 802.11 DCF. In order to be more precise, the random back-off algorithm used in IEEE 802.11 DCF MAC guarantees equal channel access to all nodes and we suppose if a node in the system behaves like more than one node by running multiple instances of the conventional IEEE 802.11 DCF MAC random back-off algorithm, then the corresponding node will access the channel more than all the nodes that only use one random back-off algorithm. The nodes with higher transmission data rates or smaller packets will gain access to the channel more than the others, therefore air-time fairness can be achieved. Our work in this thesis is built on this idea; if nodes use multiple random back-off algorithms, air-time fairness can be achieved and correspondingly the performance anomaly problem can be solved. However, the question of how to find the number of instances of this algorithm to be run on a given node remains to be answered so as to yield air-time fairness.

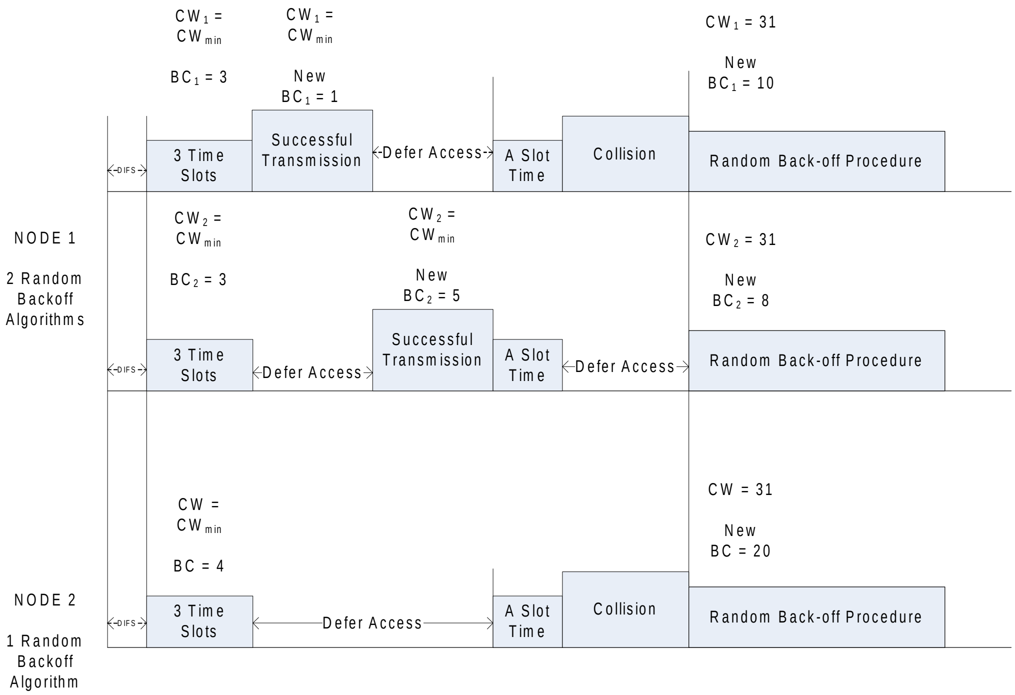
IEEE 802.11 DCF MAC random back-off algorithm is designed on the basis of equal channel access. Each node in the system uses the wireless medium equally in the long term (see also Table 2.1). Hence, the channel access rate for each node is same and the throughput of each node will be independent of its transmission data rate or packet lengths. By using multiple random back-off algorithms, we observe that node which uses multiple algorithms will access the channel more and it can be assumed as rewarded. There is a direct relationship between the number of instances of the random back-off algorithms and the channel access rate. For example, if a node starts using two random back-off algorithms, its channel access rate will be doubled. This fact leads us to come up with various IEEE 802.11 DCF MAC algorithms which are different from each other and we mostly concentrate on one algorithm and it is explained in Section 3.3 and its mathematical proof is given in Section 3.3.1. Before we come up with our final version of the algorithm, we worked on three different approaches and they are described from Section 3.2.1 to Section 3.2.3.

When multiple random back-off algorithms are running in one node, there are two types of collisions detected by the node: internal and external collisions. For both types of collisions, traditional collision definition is valid: collision is the state of two or more transmissions occurring at the same time. An internal collision can be defined as one that occurs between multiple random back-off algorithms in the node. An external collision is the collision that occurs between nodes using the system. Both algorithms that we recommend differ from the standpoint of how they treat internal and external collisions although they all use multiple random back-off algorithms.

3.2.1 Multiple Random Back-Off Algorithm Version 1

In the first version of the multiple random back-off algorithm, each node is allowed to use multiple back-off algorithms and they all detect the collisions both internal and external. In this version, nodes do not consider the internal collision, they only pay attention to the external collisions. When an internal collision occurs, one of the multiple random back-off algorithms in the node transmits and the others which participate in the internal collision wait. After transmission is completed, one of the other algorithms, which participates in the internal collision, transmits and the others wait; this process continues until all the algorithms finish transmitting. In the sense of being clear, if multiple algorithms in the node have the same random back-off number, that node will invade the channel multiple times and the air-time utilization of the node would be determined by the number of algorithms that participate in the internal collision. When an external collision is detected by the node, it doubles all its contention windows of multiple random back-off algorithms and all algorithms choose new uniform random numbers according to the new contention windows. This process is done by using the conventional IEEE 802.11 DCF MAC random back-off mechanism rules. If contention window exceeds CW$_{max}$, it is set to CW$_{max}$ and all the numbers that are drawn uniformly from the interval of [0,CW-1].

When an algorithm transmits the packet successfully, it follows the resetting procedure defined in Section 3.1.2. It resets its CW to CW$_{min}$ and before transmission it waits until a DIFS period, if the medium is sensed busy then a uniform random back-off number is chosen from the interval [0,CW$_{min}$]. After back-off period reaches to 0, then it starts transmitting; if there is a collision it behaves as described above. Figure 3.6 is a good example of this approach.



$CW_{min} = 15$
$CW_{max} = 31$
BC_1 = Back-off Counter of Algorithm 1 of Node 1
BC_2 = Back-off Counter of Algorithm 2 of Node 1
BC = Back-off Counter of Node 2

Figure 3.6: Multiple Random Back-Off Algorithm Version 1 Example

3.2.2 Multiple Random Back-Off Algorithm Version 2

The second version of the algorithm is almost the same as the first version. The only thing that is different than the first version is the internal collision part. All the nodes in the system sense both internal and external collisions and again they give priority to external collisions. When an internal collision occurs in the second version, one of the algorithms running in the node transmits and after transmission all the algorithms that had participated in the internal collision reset their CW to CW$_{min}$ and they follow the procedure defined in Section 3.1.2. When an external collision occurs or an algorithm successfully transmits the packet, the procedures that are followed by the nodes are the same as the states that are described in Section 3.2.1. Figure 3.7 helps in clarifying the proposed approach.

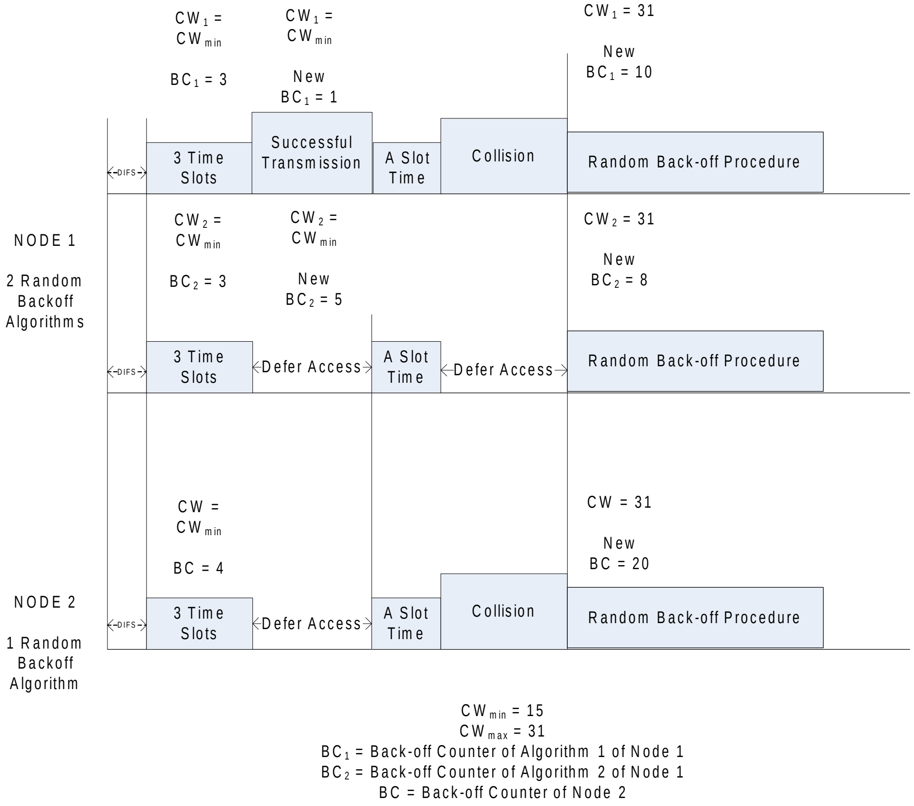


Figure 3.7: Multiple Random Back-Off Algorithm Version 2 Example

3.2.3 Multiple Random Back-Off Algorithm Version 3

In the third version of the algorithms, nodes take into consideration both internal and external collisions. There are no changes in external collision and successful transmission parts; they are all same as in the first and the second version of the algorithms. The only difference is in the internal collision part. When an internal collision occurs, the node assumes the internal collision as an external one. It doubles the contention windows of the algorithms that participated in the internal collision and chooses uniform random variables distributed along [0,CW-1] for these algorithms. Then it starts the random back-off phase described in Section 3.1.2. For instance, there is an internal collision between two algorithms running on the same node and this node has three running random back-off algorithms. The internal collision is detected by the node and it doubles two contention windows of the algorithms in the collision under the scope of the rules of conventional IEEE 802.11 DCF MAC. The third algorithm in the node is not affected by this process. Figure 3.8 presents an example that summarizes this approach.

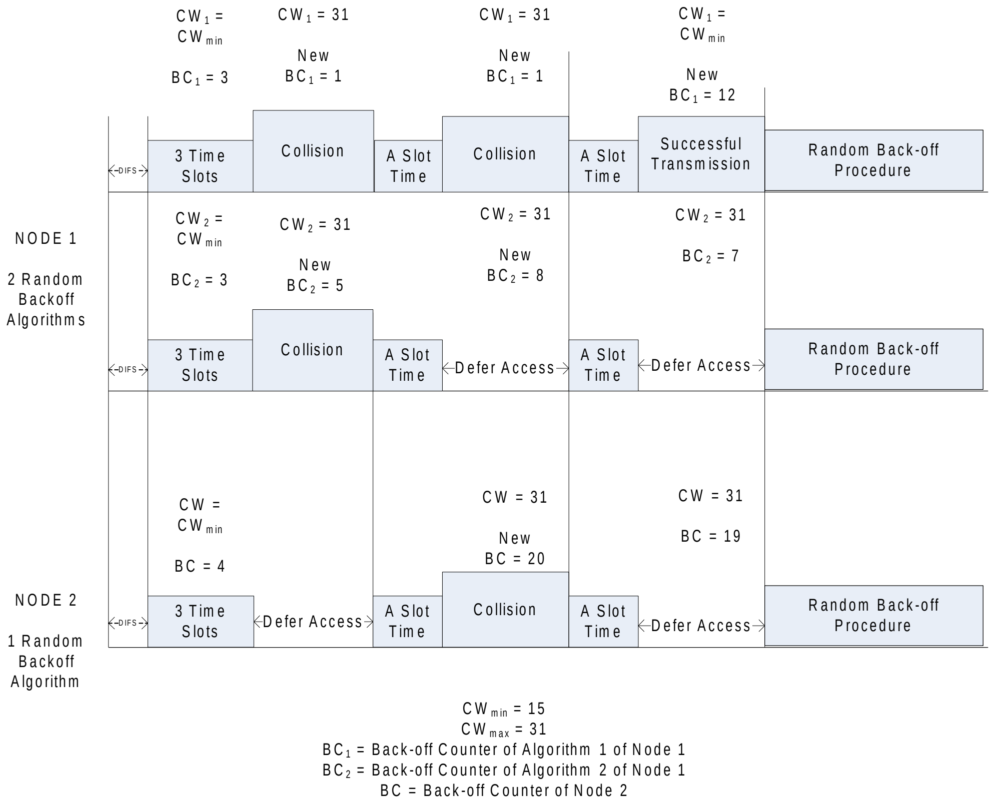


Figure 3.8: Multiple Random Back-Off Algorithm Version 3 Example

There are several drawbacks of each of these three algorithms and these drawbacks led us to our final version which is next described together with the drawbacks of first three approaches in Section 3.3.

	Occupancies							
	Version 1		Version 2		Version 3		Standard	
Packet Ratio	Node 1	Node 2	Node 1	Node 2	Node 1	Node 2	Node 1	Node 2
1	49.996	50.004	50.020	49.980	50.012	49.988	50.142	49.858
2	49.192	50.808	49.821	50.179	49.989	50.011	66.553	33.447
3	48.813	51.187	50.105	49.895	49.993	50.007	75.133	24.867
4	48.762	51.238	50.500	49.500	49.933	50.067	79.905	20.095
5	48.602	51.398	50.765	49.235	50.042	49.958	83.365	16.635
6	48.112	51.888	50.930	49.070	49.967	50.033	85.929	14.071
7	47.490	52.510	50.604	49.396	49.988	50.012	87.397	12.603
8	46.317	53.683	49.792	50.208	49.988	50.012	88.880	11.120
9	44.743	55.257	49.002	50.998	49.950	50.050	89.960	10.040
10	43.030	56.970	47.464	52.536	49.975	50.025	91.051	8.949
11	41.128	58.872	45.889	54.111	49.955	50.045	91.687	8.313
12	39.055	60.945	43.929	56.071	49.811	50.189	92.167	7.833
13	36.901	63.099	42.109	57.891	49.878	50.122	93.061	6.939
14	33.594	66.406	39.326	60.674	49.982	50.018	93.300	6.700
15	31.508	68.492	37.802	62.198	50.064	49.936	93.737	6.263
16	28.550	71.450	35.785	64.215	49.863	50.137	94.109	5.891
17	25.662	74.338	32.116	67.884	49.774	50.226	94.431	5.569
18	22.658	77.342	30.252	69.748	49.963	50.037	94.778	5.222
19	20.918	79.082	27.665	72.335	50.127	49.873	94.858	5.142
20	18.916	81.084	25.587	74.413	50.048	49.952	95.297	4.703

Table 3.2: Channel Occupancy Ratios of a Two-Node Network for both Version 1, Version 2, Version 3 and IEEE 802.11 DCF MAC: Node 1 always runs only one algorithm because it has constant packet length and Node 2 runs 1 to 20 algorithms because it has packet length which is smaller than Node 1

3.3 Proposed Distributed Air-Time Fair MAC

Three algorithms (Versions 1-3) described before increases the channel utilization of the network. They all give better results than the traditional IEEE 802.11 DCF MAC from the air-time point of view (see also Table 3.2). However, when the number of instances of these algorithms increase, the air-time fairness metrics deteriorate since nodes with a large number of algorithms dominate the system. Therefore, air-time fairness may not be achieved and these algorithms fail to exactly solve the rate anomaly problem. The reason why the stability of the system deteriorates is the dependency factors in the internal collision part. In the first two versions of the algorithms, internal collisions are not allowed for improving the channel occupancy of the node but this approaches deviates from air-time fairness. Then, we conclude that internal collisions should be allowed leading to the third version of the algorithm which appears to be the the best among these but it also has an important drawback; it penalizes all the algorithms running inside a node when an external collision occurs. This becomes an important problem when the algorithm counts in the nodes are high. Consequently, we propose the final version of the random back-off algorithm. The rest of this thesis is based on this approach. The proposed algorithm is an improved version of the third algorithm. In the proposed algorithm, both internal and external collisions are considered with the same priority and the procedures that are followed after a collision are the same for both internal and external ones. The major difference from the third one is the external collision part. When an external collision is detected by the nodes, nodes only double the contention windows of the algorithms that participated in the collision by obeying the rules of IEEE 802.11 DCF MAC random back-off mechanism (see also Figure 3.9). For example, let us assume a network with two nodes and let one node use two random back-off mechanisms and the other one use three random back-off mechanisms. Assume that at some point the second algorithm in the first node collides with the third algorithm in the second node. Then, nodes double only the corresponding algorithms' contention windows and other algorithms running are not affected by this process. Proposed algorithm and its mathematical proof is described in Section 3.3.1.

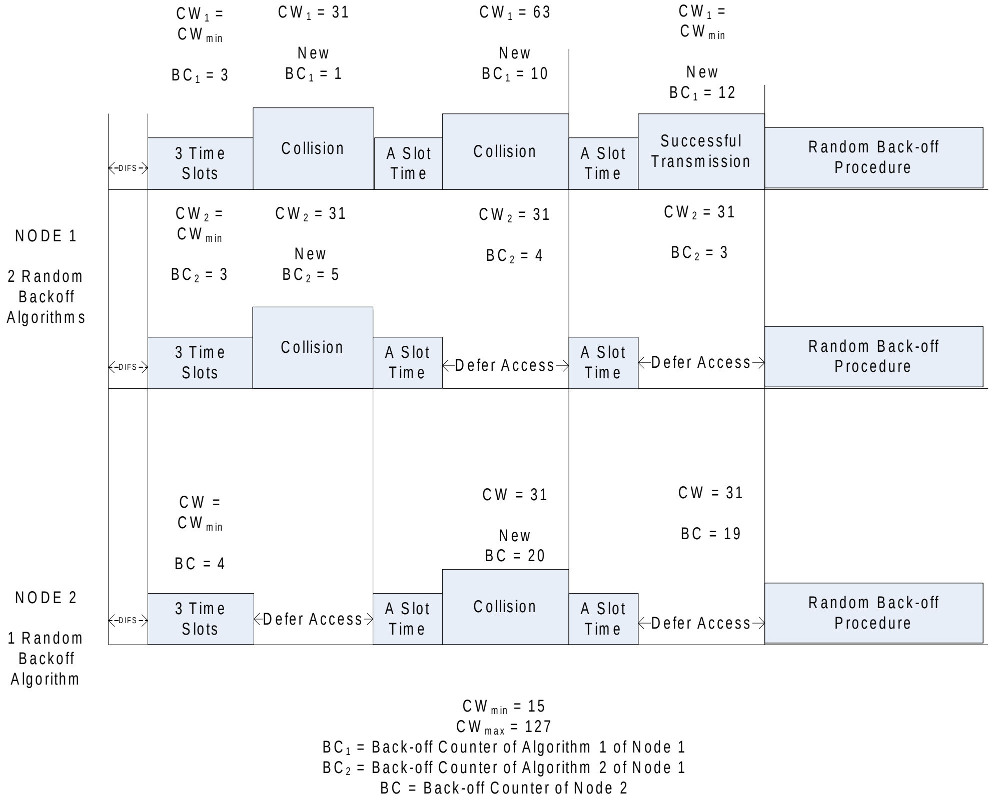
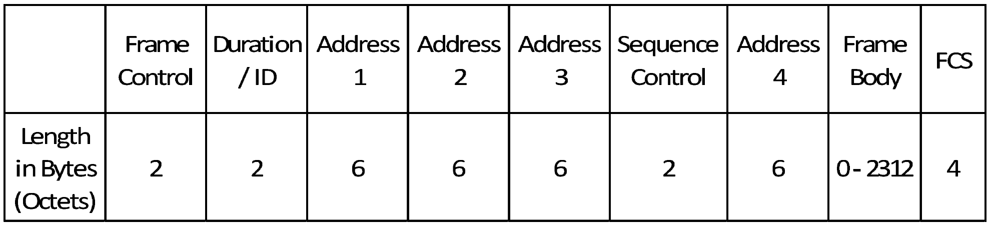


Figure 3.9: Proposed Multiple Random Back-Off Algorithm Example

3.3.1 Proposed Algorithm

Our proposed algorithm has no effect on the start mechanism of random back-off. If the node senses the channel idle for a DIFS period, it transmits its packet. If the transmission is successful, nothing is done; but if there is a collision random back-off mechanism is started and the number of required algorithms are calculated by using our proposed method.



	Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Frame Body	FCS
Length in Bytes (Octets)	2	2	6	6	6	2	6	0 - 2312	4

Figure 3.10: IEEE 802.11 Data Frame

The first significant feature of our proposed algorithm lies in the fact that it can be implemented all in a distributed fashion. We define an upper bound B_u for all nodes that is representative of the maximum air-time that a single packet can use in the transmission medium. The bound B_u is calculated by using the maximum packet length and the smallest communication data rate defined in IEEE 802.11b standard - the reason of choosing IEEE 802.11b is its common deployment and popularity. Maximum packet length that can be used in IEEE 802.11 is 2346 bytes with headers (Figure 3.10) and for IEEE 802.11b the minimum transmission data rate is 1Mbps; by using these values, we obtain

$$B_u = \frac{2346\,bytes \times 8\,bits/byte}{1\,Mbps} = 18.768\,msec. \tag{3.1}$$

All nodes in the system then calculate the actual air-time B_a required for transmitting the data frame with its header. When a node calculates its actual air-time required for data transmission, it decides how many algorithms it should run by dividing the upper bound to B_a that is calculated. For instance, consider a node that has a frame length of 2000 bytes and its transmission data rate is 2Mbps. The node then calculates its air-time by using the following equations:

$$\text{frame length in bytes} \times 8 = \text{frame length in bits}. \tag{3.2}$$

$$B_a = \frac{\text{frame length in bits}}{\text{transmission data rate in Mbps}} \times 1000 = \text{actual air-time in milliseconds.} \tag{3.3}$$

After calculating B_a, the node calculates the number of back-off algorithms denoted by N. This calculation is done by using:

$$N = \frac{18768\, msec}{\text{actual air-time}} = \text{number of algorithms.} \tag{3.4}$$

Using the above expressions, the node obtains the number of algorithms N that is required for air-time fairness satisfaction, i.e., $N = 2.346$. However, note that this number is not necessarily an integer as in this example. In order to cope with this problem, we define $N_- = \lfloor N \rfloor$ and $N_+ = \lceil N \rceil$. Each node is then allowed to alternate between N_- and N_+ algorithms in the manner described below. For this purpose, we first introduce a parameter β which is defined as follows:

$$\beta = \frac{N - N_-}{N_+ - N} \times \frac{N_+}{N_-}. \tag{3.5}$$

The way we select these two parameters B_+ and B_- is based on the following expression:

$$B_+ = \frac{B \times \beta}{\beta + 1} \tag{3.6}$$

$$B_- = B - B_+. \tag{3.7}$$

To summarize, for B_+ successful transmissions, the node uses N_+ back-off algorithms and for B_- successful transmissions, the node uses N_- number of algorithms. The numbers B_+ and B_- may also be non-integers; in such situations B_+ and B_- can be allowed to be expected values of two discrete-valued random variables $\mathbf{B}_+$ and $\mathbf{B}_-$ with fractional means as given in (3.6) and (3.7), respectively. In our simulations, we use an alternative method. For this purpose, we define a limit and use a random number to update the B_+ value to $\lfloor B_+ \rfloor$ or $\lceil B_+ \rceil$, or B$_-$ value to $\lfloor B_- \rfloor$ or $\lceil B_- \rceil$ according to a parameter called limit denoted by L:

$$L = B_+ - \lfloor B_+ \rfloor. \tag{3.8}$$

For this switching mechanism, a number is chosen from the interval [0,1] uniformly when the node sends B_- packets using N_- algorithms or B_+ packets using N_+ algorithms and this number is then compared with the limit to decide on how to change B_- and B_+. As an example, assume $L = 0.4$ and an instance of the uniform random variable is generated. Assume it is 0.5 in the state of B_- and N_-, then B_- will be changed to $\lceil B_- \rceil$ and B_+ will be changed to $\lfloor B_+ \rfloor$. By using this solution, we approximately handle non-integer cases for B_- and B_+.

Let us now assume a two-node scenario for mathematical analysis purposes. The first node is characterized with the parameters N_1, N_{1+}, and N_{1-}, where N_1 is the number of back-off algorithms to be run on node 1. Note that $N_1 = B_u/B_{a1}$ where B_{a1} is the actual air-time calculated for the packet to be transmitted at node 1. For node 1, let B_{1+} and B_{1-} denote the average number of successive successful transmissions for which N_{1+} and N_{1-} back-off algorithms are to be run, respectively. We assume geometrically distributed successful transmission counts $\mathbf{B_1}_+$ and $\mathbf{B_1}_-$ with means B_{1+} and B_{1-}, respectively. The second node is characterized with the parameters N_2, N_{2+}, and N_{2-}, where N_2 is the number of back-off algorithms to be run on node 2. Also note that $N_2 = B_u/B_{a2}$ where B_{a2} is the actual air-time for the packet to be transmitted at node 1. For node 2, let B_{2+} and B_{2-} denote the average number of successive successful transmissions for which N_{2+} and N_{2-} back-off algorithms are to be run, respectively. We assume geometrically distributed successful transmission counts $\mathbf{B_2}_+$ and $\mathbf{B_2}_-$ with means B_{2+} and B_{2-}, respectively. One can then construct a four-state Markov chain with the states (N_{1-}, N_{2-}), (N_{1-}, N_{2+}), (N_{1+}, N_{2-}), and (N_{1+}, N_{2+}). A state (i, j) is representative of i and j back-off algorithms that are run at nodes 1 and 2, respectively. At a given state (i, j), on the average $i/(i+j)$ of successful transmissions belong to node 1 and $j/(i+j)$ transmissions belong to node 2. Based on the steady-state probabilities of this Markov chain, one can show that a successful transmission belongs to node 1 with probability p_1:

$$p_1 = \frac{N_1}{(N_1 + N_2)}.$$

Similarly, a successful transmission belongs to node 2 with probability p_2:

$$p_2 = \frac{N_2}{(N_1 + N_2)}.$$

But the expected air-time used for node 1 per successful transmission is $p_1 B_{a1}$ which is equal to $p_2 B_{a2}$ which is the expected air-time used for node 2 per successful transmission. Therefore, we conclude that the overall expected air-time use for both nodes are exactly the same. At this point, for the two-user case and for geometrically distributed $\mathbf{B_{i+}}$ and $\mathbf{B_{i-}}$ for $i = 1, 2$, our proposed distributed algorithm is shown to achieve exact air-time fairness. Although it is interesting to prove air-time fairness for general number of users and for more general distributions for $\mathbf{B_{i+}}$ and $\mathbf{B_{i-}}$, these extensions are left outside the scope of this thesis which also provides a simulation-based study of such scenarios.

Figure 3.11 gives the calculation and transition steps of this approach.

In the proposed algorithm we have used simple algebraic expressions such as division, multiplication, flooring and ceiling in order to satisfy the air-time fairness issue for the long-term. The major property of our algorithm is its distributed manner, it does not require any central mechanism for synchronization and every node is responsible for itself so there is no need to keep track of the network in each node. Hence it reduces the complexity of the approach, the only complexity of the algorithm is using multiple back-off algorithms; but it is not an important issue for stations which are designed for more complicated tasks.

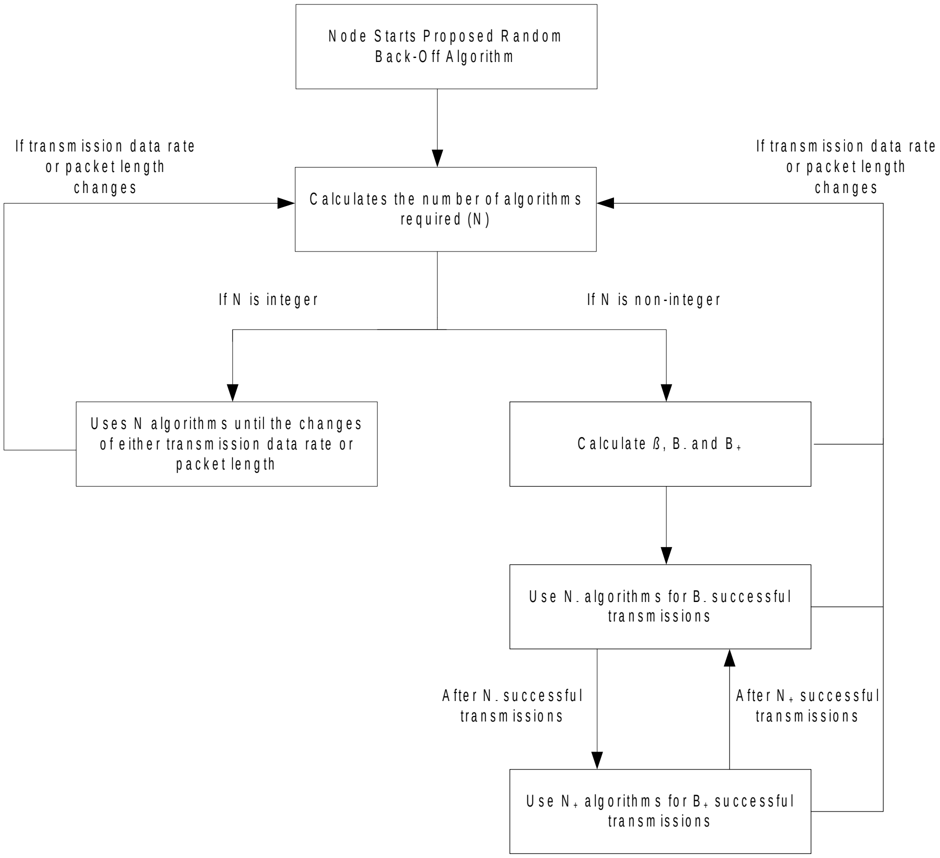


Figure 3.11: Calculation of the Parameters and Transition Steps

Chapter 4

NUMERICAL RESULTS

4.1 Aggregate Throughput and Jain's Fairness Index

In the simulations, we have focused on mainly two parameters of the network: *Aggregate Throughput* and *Jain's Fairness Index*. We adapted Jain's fairness index to our simulations and for some simulations we have used different parameter called *Probability of a Successful Transmission in a Slot* instead of aggregate throughput.

Aggregate throughput is defined as the total number of bits that are successfully transmitted in one second by all the nodes in the system. To explain the definition better, consider a two node network and the network is active for ten seconds. In average, first node transmits 100 bits/sec and second node transmits 250 bits/sec. The aggregate(system) throughput then becomes

$$Aggregate\,Throughput = 100 + 250 = 350\,bps. \tag{4.1}$$

For some simulations, probability of a successful transmission in a slot is calculated by dividing the number of slots in which a successful transmission occurs by the total number of slots when the system is active. As an example, consider a two-node network again. First node makes 15 successful transmissions and each successful transmission lasts 10 slot times. Second node makes 5 successful transmissions and each successful transmission of this node lasts 25 slot times and the system is active for 300 slots. Then the probability of a successful transmission in a slot becomes 0.92.

Jain's fairness index is defined in [25] for throughput. The writers have defined the fairness index as:

$$fairness(throughput) = \frac{(\sum_{i=1}^{n} T_i)^2}{n\sum_{i=1}^{n} T_i^2} \tag{4.2}$$

where n is the total number of nodes in the system and T_i is the throughput of *Node i*. Fairness index becomes *1* if the system is totally fair, i.e., throughputs of each node (T_is) have almost the same value; but if one node dominates the system, fairness index becomes *1/n*, i.e., one of the nodes has a throughput value which is very high then $(\sum_{i=1}^{n} T_i)^2$ converges to $\sum_{i=1}^{n} T_i^2$ so fairness index becomes *1/n*. We have used the same formula (Equation 4.2), but we have changed T_i with O_i. O_i is the occupancy of Node i, in other words O_i is the ratio of air-time usage of Node i to the total system time; then the fairness formula for air-time becomes:

$$fairness(air - time) = \frac{(\sum_{i=1}^{n} O_i)^2}{n\sum_{i=1}^{n} O_i^2}. \tag{4.3}$$

All simulations are run in IEEE 802.11b networks and for all networks we have calculated Jain's fairness index, but for some networks we have calculated aggregate throughput and for the others probability of a successful transmission in a slot is calculated by using the definitions above.

4.2 Varying Packet Lengths

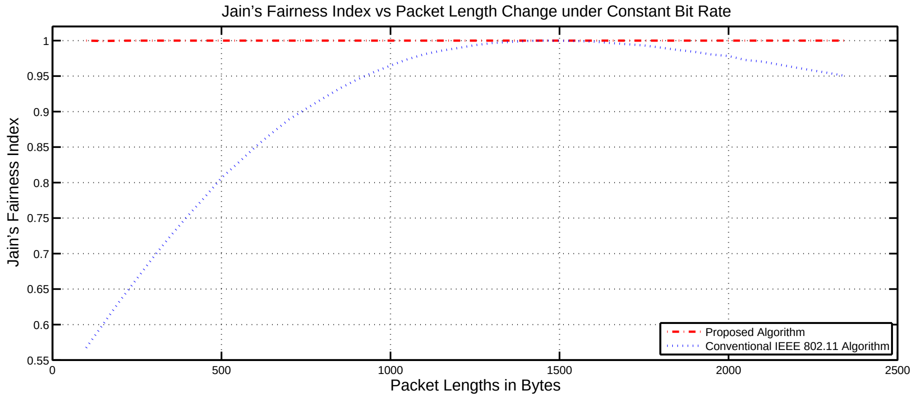


Figure 4.1: Jain's Fairness Index vs Packet Length Changes under 1 Mbps

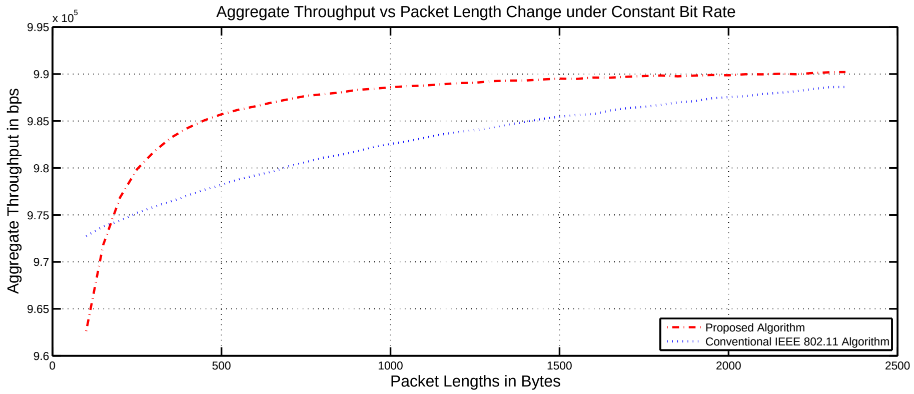


Figure 4.2: Aggregate Throughput vs Packet Length Changes under 1 Mbps

In this simulation, we want to observe the packet length effect for both our proposed algorithm and the conventional IEEE 802.11 DCF MAC for the long term. We have designed a two-node network in which the transmission data rates are time invariant, i.e, the bit rates of the nodes do not change. We have defined two nodes: one of them has a constant packet length of 1472 bytes and a bit rate of 1 Mbps, the other one has also constant bit rate of 1 Mbps but its packet length is varied from 100 bytes to 2300 bytes with constant increase of 50 bytes and last data for packet length is 2346 byte which is the upper bound of an IEEE 802.11 packet. The update parameter (B) is 100 and the simulation duration is 1000 seconds.

According to Figure 4.1 we say that air-time fairness can be achieved when two nodes have the same packet length and it is satisfied when the packet length is 1472 bytes for the conventional algorithm. This is expected because IEEE 802.11 DCF MAC guarantees equal channel access for the long term (see also Chapter 2) and depending on this fact, if the nodes have different packet lengths and same bit rates, the node with longer packets will invade the channel more; so air-time fairness is disrupted. For the proposed algorithm, there is no such disruption, because both of nodes invade the channel equally. From the aggregate throughput perspective, there is not any significant difference; because both of algorithms have almost the same value (Figure 4.2). This shows that while satisfying the air-time fairness, proposed algorithm also preserves the aggregate throughput of the system.

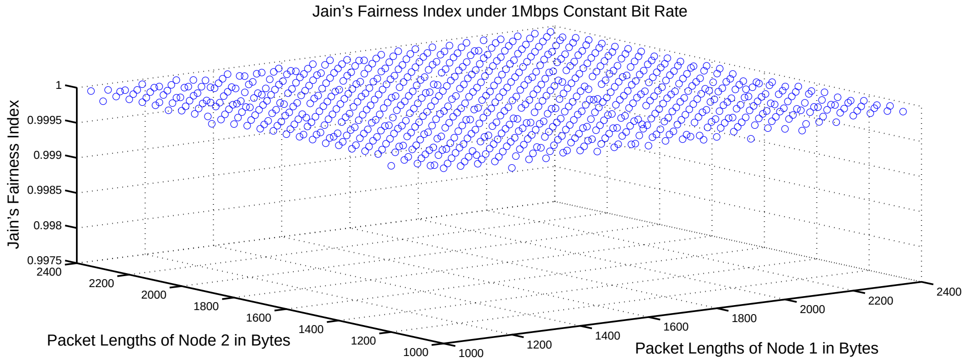


Figure 4.3: Jain's Fairness Index under 1 Mbps for Varying Packet Lengths

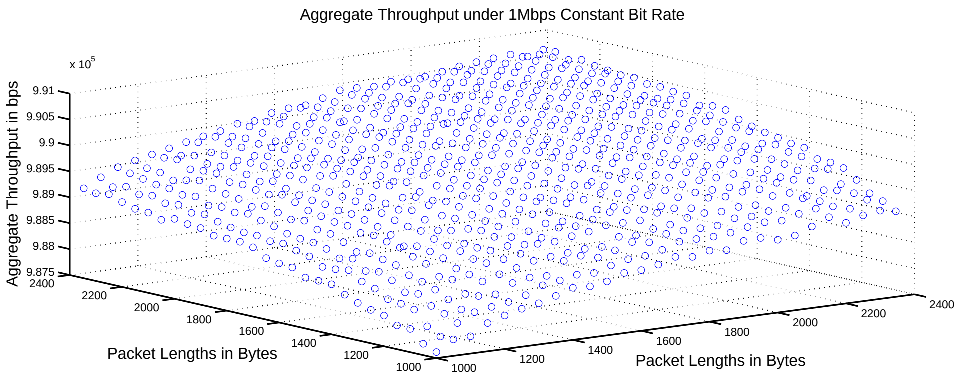


Figure 4.4: Aggregate Throughput under 1 Mbps for Varying Packet Lengths

In Figure 4.3 and Figure 4.4, all the nodes packet lengths vary from 1000 bytes to 2346 bytes and the communication data rate is again constant which is 1 Mbps. The fairness index is in % 0.5 margin of 1 for all data, so it shows that air-time fairness in the proposed algorithm is not affected from the packet length changes. Aggregate throughput is also not affected from the varying packet lengths. This leads us to a conclusion that proposed algorithm is not affected from the packet length changes, it always preserves air-time fairness and there is no drastically change in the aggregate throughput.

4.3 Varying Data Rates

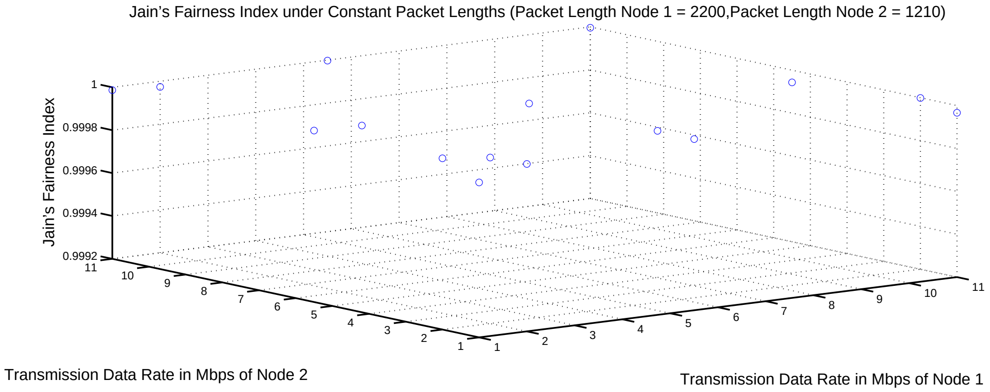


Figure 4.5: Jain's Fairness Index under Constant Packet Lengths (3D-Plot)

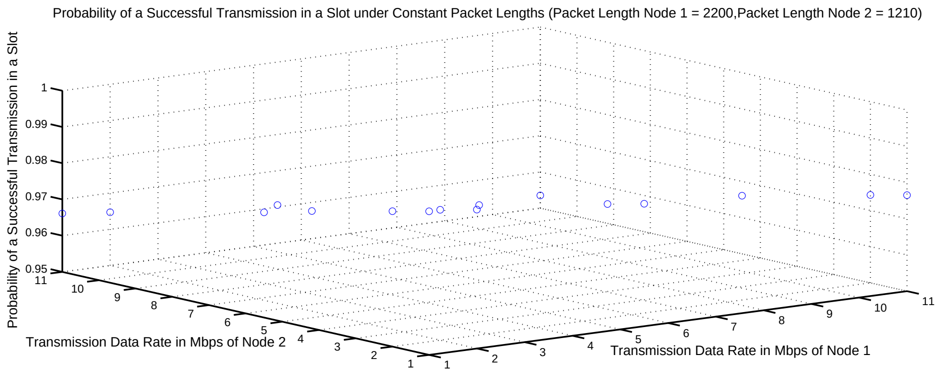


Figure 4.6: Probability of a Successful Transmission in a Slot under Constant Packet Lengths (3D-Plot)

In this simulation, we have designed a two node network and both of the nodes have varying transmission data rate, but they have constant packet lengths. The bit rates are chosen 1, 2, 5.5 and 11 Mbps; and the packet lengths of Node 1 and Node 2 are 2200 and 1210 bytes, respectively. The simulation duration is 1000 seconds and B is 100.

As it is seen from Figure 4.5, in the proposed algorithm, fairness index is in % 0.6 margin of 1 which tells that air-time fairness is achieved. In IEEE 802.11 DCF MAC, the nodes with slowest communication data rate invade channel more because their transmissions last longer than the nodes with highest speed under the same packet length. Therefore, there is a significant improvement in the proposed algorithm. Although the transmission speeds of the nodes change, the fairness index does not change hence air-time fairness is preserved. According to Figure 4.6, changing data rates do not affect the probability of a successful transmission in a slot significantly. The reason of choosing this parameter is to see whether the network is penalized in the means of empty slots, when the speed changes or not, and in Figure 4.6 it is observed that there is no such a penalty.

4.4 Varying Update Parameter (B)

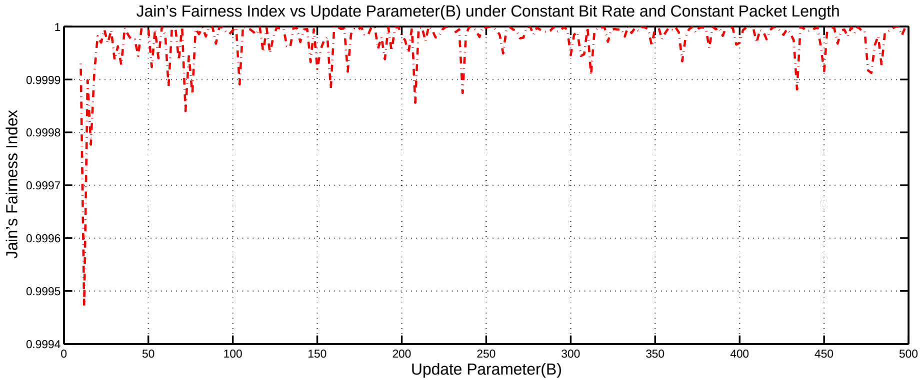


Figure 4.7: Jain's Fairness Index under 1 Mbps Constant Bit Rate and Constant Packet Lengths of 1472 bytes and 899 bytes

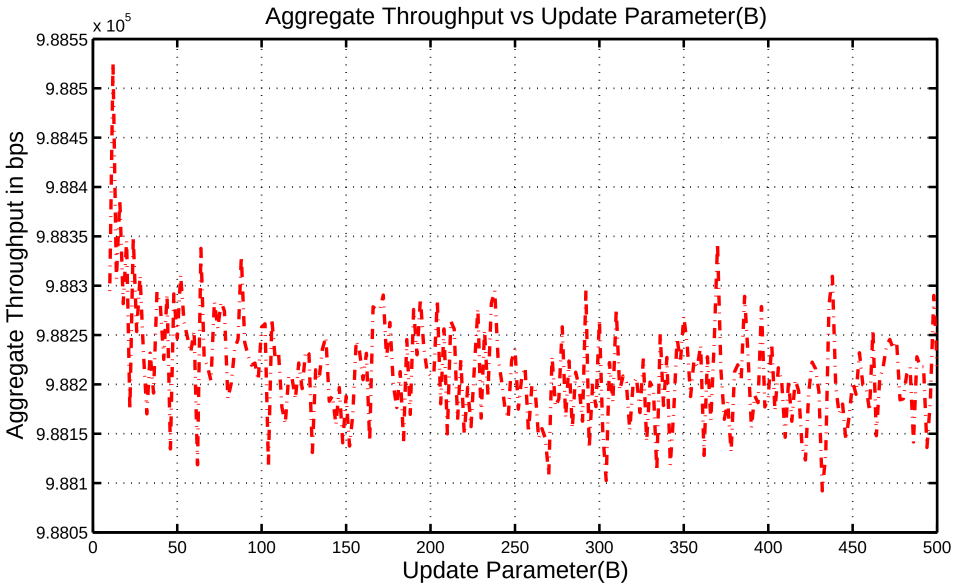


Figure 4.8: Aggregate Throughput under 1 Mbps Constant Bit Rate and Constant Packet Lengths of 1472 bytes and 899 bytes

In this simulation, we have two node network and the nodes have constant bit rates of 1 Mbps and packet lengths of Node 1 and Node 2 are 1472 bytes and 899 bytes, respectively. B is varied from 10 to 500 and the simulation duration is 1000 seconds.

From the observation of Figure 4.7, the fairness index is in % 0.6 margin of 1 again; because in the long term mean of B_- and B_+ converges to the theoretical limit (see also Section 3.3.1). Hence, the air-time fairness is again preserved under varying update parameter (B). The aggregate throughput is not affected significantly. Under varying B, the proposed algorithm works fine.

4.5 Multi-Node

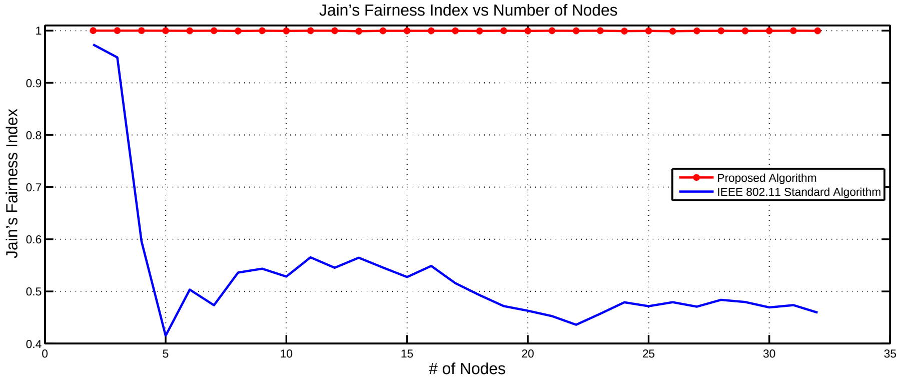


Figure 4.9: Jain's Fairness Index vs Number of Nodes

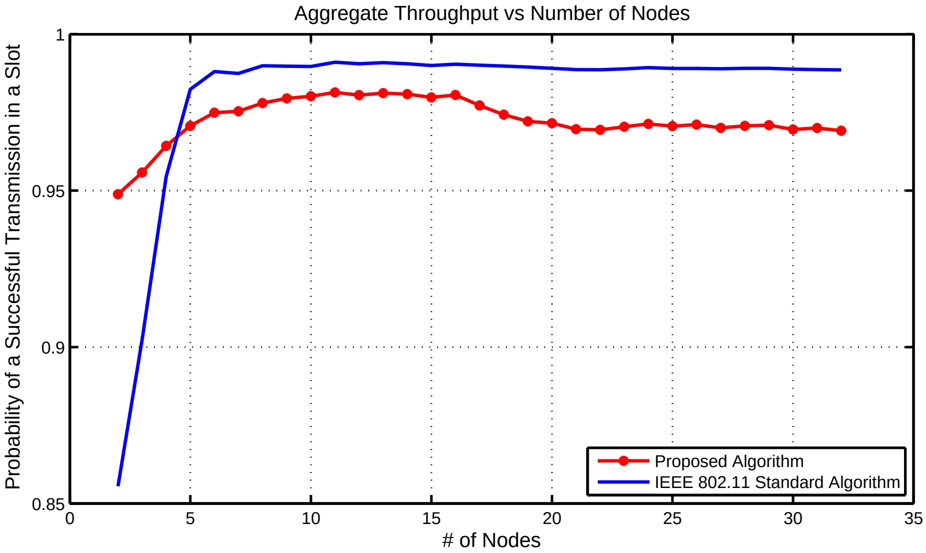


Figure 4.10: Probability of a Successful Transmission in a Slot vs Number of Nodes

In this system, nodes are added randomly, i.e., they have different communication data rates and different packet lengths. B is set to 100 and the duration of the simulation is 1000 seconds. The packet length of each node is chosen from the interval [768,2346] bytes uniformly and the speed is chosen from the standard IEEE 802.11b transmission data rates: 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps. 32 nodes are added sequentially and the list of added nodes are given below:

- Node 1 - Frame Length = 1194 bytes; Data Rate = 11 Mbps
- Node 2 - Frame Length = 1667 bytes; Data Rate = 11 Mbps
- Node 3 - Frame Length = 2148 bytes; Data Rate = 11 Mbps
- Node 4 - Frame Length = 1396 bytes; Data Rate = 2 Mbps
- Node 5 - Frame Length = 2246 bytes; Data Rate = 1 Mbps
- Node 6 - Frame Length = 2055 bytes; Data Rate = 1 Mbps
- Node 7 - Frame Length = 1490 bytes; Data Rate = 5.5 Mbps
- Node 8 - Frame Length = 1909 bytes; Data Rate = 1 Mbps
- Node 9 - Frame Length = 1147 bytes; Data Rate = 2 Mbps
- Node 10 - Frame Length = 2231 bytes; Data Rate = 5.5 Mbps
- Node 11 - Frame Length = 1959 bytes; Data Rate = 1 Mbps
- Node 12 - Frame Length = 2300 bytes; Data Rate = 11 Mbps
- Node 13 - Frame Length = 1983 bytes; Data Rate = 2 Mbps
- Node 14 - Frame Length = 1221 bytes; Data Rate = 5.5 Mbps
- Node 15 - Frame Length = 1905 bytes; Data Rate = 11 Mbps
- Node 16 - Frame Length = 2016 bytes; Data Rate = 2 Mbps

- Node 17 - Frame Length = 970 bytes; Data Rate = 11 Mbps
- Node 18 - Frame Length = 930 bytes; Data Rate = 11 Mbps
- Node 19 - Frame Length = 1177 bytes; Data Rate = 11 Mbps
- Node 20 - Frame Length = 2084 bytes; Data Rate = 11 Mbps
- Node 21 - Frame Length = 1140 bytes; Data Rate = 11 Mbps
- Node 22 - Frame Length = 2310 bytes; Data Rate = 11 Mbps
- Node 23 - Frame Length = 1936 bytes; Data Rate = 2 Mbps
- Node 24 - Frame Length = 1323 bytes; Data Rate = 1 Mbps
- Node 25 - Frame Length = 1712 bytes; Data Rate = 11 Mbps
- Node 26 - Frame Length = 1214 bytes; Data Rate = 2 Mbps
- Node 27 - Frame Length = 1566 bytes; Data Rate = 11 Mbps
- Node 28 - Frame Length = 1708 bytes; Data Rate = 2 Mbps
- Node 29 - Frame Length = 2039 bytes; Data Rate = 5.5 Mbps
- Node 30 - Frame Length = 1266 bytes; Data Rate = 11 Mbps
- Node 31 - Frame Length = 2214 bytes; Data Rate = 5.5 Mbps
- Node 32 - Frame Length = 1554 bytes; Data Rate = 11 Mbps

The reason of choosing random packet lengths and data rates is to combine both Section 4.2 and Section 4.3. For this system, the probability of a successful transmission in a slot is calculated as in the case of varying data rates.

As it is seen on Figure 4.9, whichever node joins the system, air-time fairness is preserved when our proposed algorithm is used; while the probability of a successful transmission in a slot is almost preserved. Conventional IEEE 802.11

DCF MAC fails to satisfy the air-time fairness, because of the reason explained in detail in Chapter 2. Although it is failed to meet demand of air-time fairness, it has higher probability of a successful transmission in a slot. The reason of this is when the node count increases in the proposed algorithm, the number of independent random back off algorithms in the system increases; therefore the system senses more nodes than the actual number of nodes. This is a drawback for the proposed approach.

Chapter 5

CONCLUSIONS

In this thesis, we propose a distributed air-time fair MAC to cope with the performance anomaly problem in IEEE 802.11 networks. The proposed method is based on running multiple instances of the conventional random back-off algorithms at each node where the multiplicity of the algorithms can also change in time according to a proposed scheme so as to achieve air-time fairness. While providing air-time fairness, the aggregate throughput of the system is preserved with slight reductions in aggregate throughput with respect to increasing number of users. Transient response of the proposed method and mathematical analysis of multi-node systems are left for future work.

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