Identification and Mitigation of Throughput Unfairness in WLANs

by

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April 2014

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Md. Sultan Mahmud

Dedication

To my parents.

Acknowledgement

First of all, I would like to thank Allah for giving me the ability to complete this thesis work.

I would like to express my sincere gratitude to my supervisor, Dr. Md. Forkan Uddin. This thesis would not have been completed without his support and guidance. His constant encouragement gave me the confidence to carry out my work.

I would like to thank all my teachers, who imparted the knowledge and directions that have helped me throughout my life. I express my gratitude to my teachers from Bangladesh University of Engineering and Technology. The knowledge I learned from the classes in my M.Sc. level was essential for this thesis.

I would also like to thank my friends for providing support and encouragement. Their suggestions helped me in countless ways.

Last but not the least, I would like to thank my parents. Their optimism and encouragement have allowed me to overcome any obstacle that I face. Their unconditional support made it possible for me to finish this thesis.

ABSTRACT

Co-channel interference exists in IEEE 802.11 based wireless local area networks (WLANs) due to the limited number of non-overlapping channels in the current standards. In this thesis, the impact of co-channel interference is investigated in carrier sense multiple access with collision avoidance (CSMA/CA) based WLANs through simulation. Severe throughput unfairness is found among the users in WLANs due to asymmetric co-channel interference among the users. To mitigate the throughput unfairness problem in WLANs, a centralized algorithm is developed to configure the minimum contention window of the nodes based on an analytical formulation. A heuristic is also developed to configure the minimum contention window of the nodes based on the results of the centralized algorithm and a simple distributed algorithm is proposed to mitigate the throughput unfairness problem. The performance of the proposed algorithms is evaluated by simulation and found to be very effective. It is found that the distributed provides better fairness than the centralized algorithm. However, the total network throughput under the distributed algorithm is little bit less than the centralized algorithm.

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LIST OF ABBRAVIATIONS

ACK	Acknowledgement
AP	Access Point
BEB	Binary Exponential Backoff
BSS	Basic Service Set
CCK	Complementary Code Keying
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CTS	Clear To Send
CST	Carrier Sensing Threshold
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	Distributed Inter Frame Space
DS	Distribution System
DSSS	Direct Sequence Spread Spectrum
ESS	Extended Service Set
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific, and Medical
MAC	Medium Access Control
MC-CDMA	Multi-Carrier Code Division Multiplexing
MIMO	Multiple Input Multiple Output
NIC	Network Interface Card
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open System Interconnection
PCF	Point Coordination Function
QoS	Quality of Service
RSSI	Received signal strength indicator
RTS	Request To Send
SIFS	Short Interframe Space
SINR	Signal to Interference plus Noise Ratio
UNII	Unlicensed National Information Infrastructure
WLAN	Wireless Local Area Network
WS	Work Station

LIST OF SYMBOLS

N_o	:	Noise Power
P_t	:	Transmit Power
η	:	Path loss Exponent
δ	:	Slot Time
γ	:	Minimum Required SINR at Receiver
λ	:	Packets per Second
$\mathcal{N}$	:	Set of Nodes
m	:	Maximum Backoff Stage
T_s	:	Transmission time of one packet
T_c	:	Collision time of one packet
G	:	Channel Gain
p	:	Collision Probability
τ	:	Attempt rate of a node
d_o	:	Far-field cross-over distance
CW_{min}	:	Minimum contention window

CHAPTER 1

INTRODUCTION

The popularity of wireless local area networks (WLANs) has increased significantly in recent years due to many reasons such as mobility, flexibility, ease of installation and also reduces the cost of setting up and maintenance. Institute of Electrical and Electronics Engineers (IEEE) is the founder of WLAN product implemented IEEE standard 802.11 in 1997. Currently, most of the WLANs are based on IEEE 802.11 standard which uses carrier sense multiple accesses with collision avoidance (CSMA/CA) medium access control (MAC) protocol. The mobile users are using public access WLANs in different public hotspots such as cafes, airports, trains and universities. WLAN deals with local area networking where the communication done over the air between the connected devices those are within the range. IEEE 802.11 WLANs use two frequency bands: 2.4 GHz Industrial, Scientific, and Medical (ISM) band and 5 GHz Unlicensed National Information Infrastructure (UNII) band [1], [2]. The IEEE 802.11 b/g use 2.4 GHz frequency band, where only three channels are non-overlapping among the total 14 available channels [2], [3]. Due to large number of access points (APs) deployed in close proximity in one another to provide high speed Internet service, WLANs reuse the same frequency spectrum and co-channel interference exists in WLANs.

1.1 WLAN

A WLAN links two or more devices (laptop, tablet, cellphone) using some wireless distribution methods (typically spread-spectrum or orthogonal frequency division multiplexing (OFDM) radio), and usually providing a connection through an AP to the wider Internet. This gives mobility facility to the users within a local coverage area and still to be connected to the network.

1.1.1 Types of WLAN

WLANs can be roughly divided into two types according to its operation modes: infrastructure mode and ad hoc mode. In infrastructure mode, a special node which is known as an AP is connected with all other mobile stations. Stations among themselves do not communicate directly, instead of all the wireless communications must go through the AP which also performs the wireless to wired bridging function, interacting with the mobile stations as well as the existing wired network. In ad hoc mode, no fixed infrastructure exists. Nodes communicate with each other directly. The network is usually self-configuring without fixed network topology. In this thesis, infrastructure modes WLANs are considered.

Infrastructure Networks: The application of infrastructure mode is at office areas or to provide a hotspot. The WLAN equipment's can be installed instead of a wired system using separate wireless links, and can provide considerable cost savings, especially when used in established offices. A backbone wired network is still required and is connected to a server. The wireless network is then split up into a number of cells, each cell is served by an AP. Each AP may have a range of between 30 and 300 meters dependent upon the environment and the location of the AP.

1.1.2 IEEE 802.11 Wireless LAN Architectures

The architecture of the IEEE 802.11 WLAN is designed to support network where most decision making is distributed to the mobile stations (STAs). The IEEE 802.11 architecture consists of several components and services.

- Station (STA)
- Access Point (AP)
- Wireless Medium
- Basic Service Set (BSS)
- Extended Service Set (ESS)
- Distribution System (DS)

IEEE 802.11 architecture defines nine services. These services can be divided into two groups: STAs services and distribution services. STAs services contain authentication, de-authentication, privacy, and delivery of the data and distribution services consist of association, re-association, disassociation, distribution and integration.

Stations (STA)

A Station is a basic component of a WLAN which is used to connect wireless network medium. Stations are computing device that contain IEEE 802.11 specification MAC and physical (PHY) interface to wireless network. Generally the IEEE 802.11 functions are implemented either software or hardware of network adapter or network interface card (NIC). Laptop, tablet, iPad and cell phone are stations in WLAN.

Access Point (AP)

An AP is a device that provides a point of interconnection of wireless station to the wired network or wireless network at the same time or either. AP performs so many functions but bridging function is the most important function.

Wireless Medium

Wireless medium is used to transfer frame from one station to another station. Wireless medium is shared among the users.

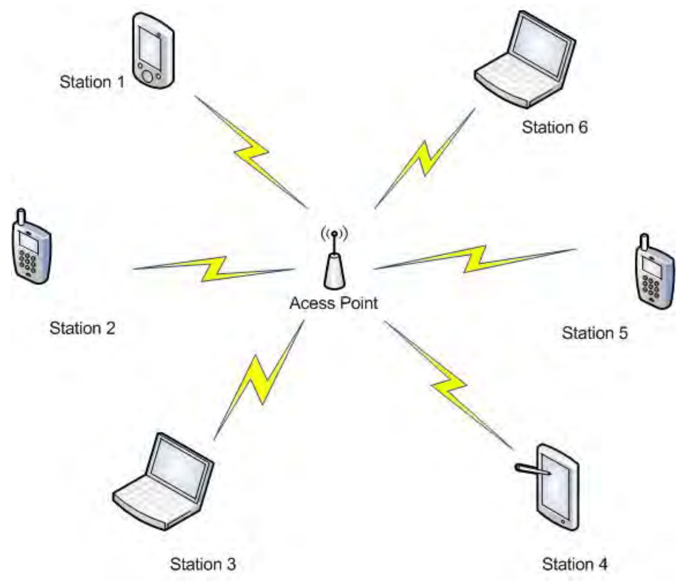

Fig. 1.1 Basic service set.

Basic Service Set (BSS)

The BSS is a collection of stations that able to communicate with each other within a WLAN. It is controlled by an AP [16]. A typical BSS is shown in Fig. 1.1.

Extended Service Set (ESS)

An ESS consists of multiple IEEE 802.11 BSSs forming single subnet work where the APs communicate each other to forward traffic from one BSS to another and provide facility to move mobile stations from one BSS to other i.e., roaming services. A typical configuration of ESS is shown in Fig. 1.2.

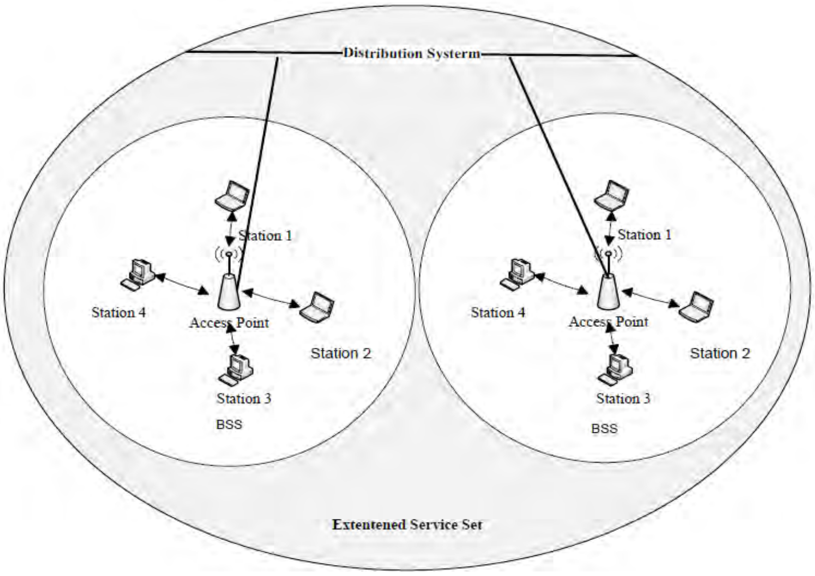

Fig. 1.2 Extended service set.

Distribution System (DS)

A DS is the fixed wired infrastructure used to connect a set of BSSs to create an ESS. The IEEE 802.11 distributions services enable a wireless terminal to roam freely within ESS and also allow an IEEE 802.11 WLAN connect to the wired LAN Infrastructure. A DS is also shown Fig. 1.2.

1.2 IEEE 802.11

The IEEE 802.11 WLAN standard was developed in the 1990's and adopted by IEEE in September 1997 [1]. The IEEE 802.11 standard comes under the IEEE 802.x LAN standards, describing the physical layer, and the MAC sub-layer which belongs to the data link layer in the open systems interconnection (OSI) reference model. The physical layer standards of IEEE 802.11 are described below.

1.2.1 IEEE 802.11 a

IEEE standard 802.11a has been approved in July 1999, included with a new specification. It uses the same data link layer protocol and frame format as the original standard, but an OFDM based air interface (physical layer). It operates in the 5 GHz band with a maximum net data rate of 54 Mbps.

1.2.2 IEEE 802.11b

IEEE 802.11b extends the original IEEE 802.11 direct sequence spread spectrum (DSSS) standard to operate up to 11 Mbps in the 2.4 GHz unlicensed spectrum using complementary code keying (CCK) modulation. The four data rates of 1, 2, 5.5, and 11 Mbps are specified on up to three non-overlapping channels and the lowest two rates are also allowed on up to 14 overlapping channels [17]. The main disadvantage of the 802.11b is the frequency band is common and interference receives from the other networking technology such as Bluetooth, 2.40 GHz cordless phone and so on.

1.2.3 IEEE 802.11 g

IEEE 802.11g standard has been ratified in June 2003. The 802.11g standard provides optional higher bandwidth up to 54 Mbps. IEEE 802.11g used two technology DSSS and OFDM at the 2.4 GHz ISM band.

1.2.4 IEEE 802.11n

IEEE 802.11n is an amendment which improves upon the previous 802.11 standards by adding multiple-input multiple-output (MIMO) antennas. IEEE 802.11n operates on both the 2.4 GHz and the lesser used 5 GHz bands. It operates at a maximum net data rate from 54 Mbps to 600 Mbps [18].

1.2.5 IEEE 802.11 Protocol

The IEEE 802.11 standard defines two channel accessing methods which are the basic distributed coordination function (DCF) and the optional point coordination function (PCF) [23]. The DCF is contention based and PCF is contention free. The DCF can be used in the infrastructure or the ad hoc modes while the PCF can be only used in the infrastructure mode. The IEEE 802.11 DCF protocol is a CSMA/CA MAC protocol. DCF is classified into two categories: basic CSMA/CA and RTS/CTS CSMA/CA. Basic CSMA/CA uses a physical carrier sensing mechanism and RTS/CTS CSMA/CA uses a physical as well as virtual carrier sensing mechanism. In virtual carrier sensing, each node uses request to send/clear to send (RTS/CTS) messages to reserve the channel. This approach is rarely used in practice due to large overhead. On the other hand, in physical carrier sensing each node investigate the status of the channel prior to transmission by comparing the received power in the wireless channel with a carrier sensing threshold (CST) power. Basic CSMA/CA protocol has been widely studied and used in wireless networks because of its distributed nature and ease of implementation. In CSMA/CA protocol, before accessing the medium a node senses the medium. If the medium is free during the distributed inter frame space (DIFS) period then the node transmits its data packet and if the medium is busy then the node set a value which randomly choosing from (0, CW_{min}-1), where CW_{min} is the minimum contention window (CW) of the nodes. The medium is free or busy is determined on the basis of carrier sensing power. The carrier sensing power consists of interference power plus noise power. CST is the minimum power level to which a node compares the received power to decide the status of the medium.

1.3 Co-channel Interference

Co-channel interference is the interference received from all other surrounding WLANs which use the same frequency. In IEEE 802.11 b/g only 14 channels are available. However, only three channels are non-overlapping among the 14 available channels [3]. Due to limited numbers of non-overlapping channels, WLANs reuse the same frequency spectrum. So co-channel interference exists in IEEE 802.11 b/g. Throughput is an important performance metric in any wireless network. Throughput performance of WLANs significantly degrades due to co-channel interference [5], [29].

1.4 Motivation

WLANs suffer from two types of interference: intra-WLAN interference and inter-WLAN interference. Intra-WLAN interference is the interference received from the stations (STAs) within the same WLAN. On the other hand, inter-WLANs interference is the interference received from STAs of all the other surrounding co-channel WLANs which is known as co-channel interference. Interference plays an important role in CSMA/CA MAC protocol because of carrier sensing mechanism. In CSMA/CA, a node keeps silent/idle when the medium is busy due to interference. The intra-WLANs interference is equal for all users in a WLAN. However, co-channel interference, i.e., the inter-WLAN interference is not same for all the users in a WLAN due to different positions of the nodes. Thus, the carrier sensing times of the users in a WLAN are not equal. As a result, there are throughput variations among the users. Throughput fairness is another important performance metric in WLANs. Hence, throughput fairness among the users may severely degrade due to co-channel interference. Thus, it is very important to mitigate the throughput unfairness problem in WLANs.

In CSMA/CA based WLANs, throughputs of the users significantly depend on the contention window (CW) parameter of the users. By configuring the CW parameters of the users, throughputs of the users can be adjusted. Thus, throughput unfairness problem can be mitigated by an effective configuration of the CW parameters of the nodes. However, how to configure the CW of the nodes to mitigate the throughput unfairness problem due to the co-channel interference is not known. So, it is important to study how can configure the CW of the users to provide throughput fairness among the users.

Further, it is also very important to configure the CW of the users in a distributed manner such that algorithm operation and maintenance is simpler and low overhead is required to implement.

1.5 Objectives

In this thesis, a single data rate WLAN is considered to study the impact of co-channel interference. The physical interference model based on signal to interference plus noise ratio (SINR) is considered for the study since it is a more realistic interference model for wireless interference [6]. All the users use the basic CSMA/CA MAC protocol. The CST for all the users is assumed to be the same. The main contributions in this thesis are:

- The impact of transmission power and CST on throughput performance is investigated through simulation.
- The throughput unfairness problem due to asymmetric co-channel interference among the users in WLANs is identified.
- A centralized algorithm based on analytical formulation is proposed to configure the minimum CW parameter of each user in each WLAN to mitigate the throughput unfairness problem.
- Due to complexity of the centralized algorithm, a heuristic is developed based on the results of the centralized algorithm and a distributed algorithm is proposed to configure the minimum CW parameter of each user in each WLAN to mitigate the throughput unfairness problem.
- The performance of the proposed algorithms is evaluated by extensive simulation. It is found that the algorithms are very effective to mitigate the throughput unfairness problem in WLANS

1.6 Outline of the Thesis

The rest of the dissertation is arranged in the following manner:

In Chapter 2, background and recently reported related work on the impact of co-channel interference on throughput performance in WLANs are discussed. Impact of transmission power, CST and the minimum CW on the throughput performance is also described in this chapter. Chapter 3 consists of brief description on network topology, interference and propagation model and the basic CSMA/CA MAC protocol. Chapter 4 consists of impact of physical (PHY) layer and MAC layer parameters such as transmitter power, CST and the minimum CW on the throughput performance in WLANs. The optimal values of transmission power and CST are also determined in this chapter. Throughput unfairness problem due to co-channel interference is studied in Chapter 5. In Chapter 6, a centralized algorithm is proposed based on analytical formulation to mitigate the throughput unfairness problem in WLANs and the performance of this algorithm is also evaluated. In Chapter 7, a heuristic is developed and a distributed algorithm is proposed to mitigate the throughput unfairness problem in WLANs. The performance of the heuristic algorithm is also evaluated in this chapter. Chapter 8 concludes the thesis and discusses the scopes of future work.

CHAPTER 2

BACKGROUND AND RELATED WORK

In this chapter, the number of channel in IEEE 802.11 based WLANs, AP placement and hidden terminal and exposed terminal problems in WLANs are discussed. Related work to this thesis work is also reviewed.

2.1 Background

In this section, different frequency bands of IEEE 802.11 different physical standards, number of available channels and allocation of channel in WLAN are discussed. The main problems in CSMA/CA based WLANs are also discussed.

2.1.1 Channel in WLAN

IEEE 802.11 is a set of standards for implementing WLAN communication in the 2.4 GHz and 5 GHz frequency bands [2], [27]. The graphical representation of 2.4 GHz frequency band is shown in Fig 2.1, where the separation between two adjacent channels is 5 MHz.

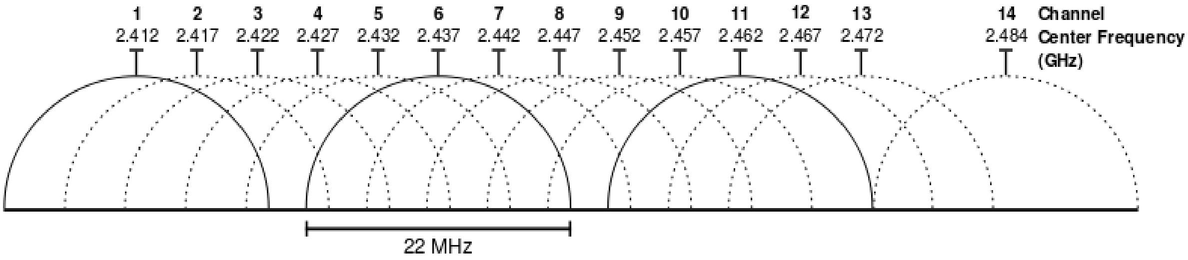

Fig. 2.1 Graphical representation of WLANs channels in the 2.4 GHz band.

IEEE 802.11b/g use 2.4 GHz ISM frequency band. IEEE 802.11b/g equipment may occasionally suffer interference from microwave ovens, cordless telephones and Bluetooth devices due to this frequency band [2], [3], [17]. Only three channels are non-overlapping among the total 14 available channels [2], [3]. The three non-overlapping channels are 1, 6, 11 and their center frequencies are 2412, 2437 and 2462 MHz, respectively [2]-[5]. The total bandwidth of each channel is 22 MHz. IEEE 802.11a uses the 5 GHz UNII band. Most of the countries of the world offer at least 23 non-overlapping channels rather than the 2.4 GHz ISM frequency band. The IEEE 802.11n devices uses 20 MHz/40 MHz channel, there three non-overlapping channels are available. When large numbers of APs are deployed then the channels are need to be reused, since the numbers of non-overlapping channels are limited.

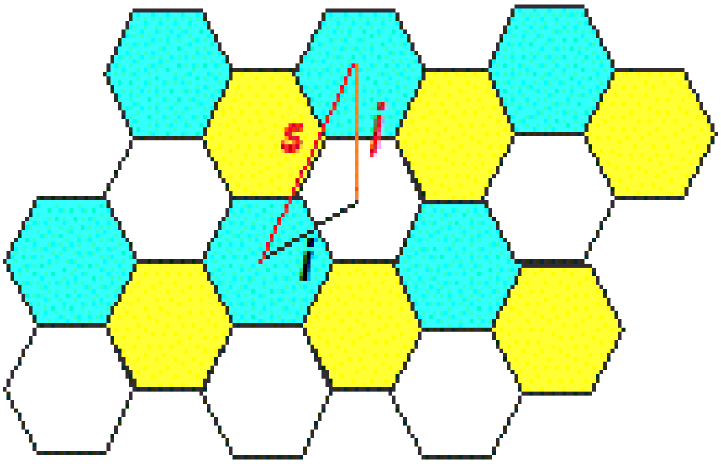

Fig. 2.2 Frequency reuse plan for Q=*3*, with hexagonal WLANs *(i=1, j=1*).

In wireless networks, frequencies allocated to the service can be reused in a regular pattern of areas, e.g., in cellular networks. This phenomenon is called frequency reuse. The nearest distance between the center of two cells or WLANs using the same frequency is called frequency reused distance and can be determined by the following equation [15],

$$S = \sqrt{3Q}\,\mathrm{R} \tag{2.1}$$

where, S is the frequency reuse distance, R is the radius of the cell or WLAN and Q is the number of cluster size. The cluster size Q is given as

$$Q=\sqrt{i^2+i.j+j^2} \tag{2.2}$$

where, i and j are integer value and Q = 1, 3, 5,...,. The values of i and j determine the relative location of the co-channel WLANs or cells.

2.1.2 AP Placement

When an IEEE 802.11 infrastructure mode WLAN is deployed it is ensured that all relevant locations in the target area are covered by the AP. In a simple scenario, this could be meant that the received SINR at any point in the target area must be exceeded a specified receiver's SINR threshold to support specified data rate. The coverage area of an AP is depends on the electrical characteristics of the obstacles in an indoor environment. When a large number of APs are deployed in a geographical area it should be considered that by reducing the number of deployed APs, the overall cost of the indoor environment system and its operation expenses can be minimized. In this thesis, fixed AP placement is considered.

2.1.3 Problems in WLAN

The performances of WLANs are affected by the hidden terminal and exposed terminal problems. Before discussing about the hidden terminal and exposed terminal problems, transmission range and carrier sensing range should be discussed.

Transmission Range: Transmission range is the range within which the transmitted packet can be successfully transmitted. The transmission range depends on transmitted power and radio propagation which increases with transmits power.

Carrier Sensing Range ***(R_{cs})***: Carrier sensing range is the range within which a node can sense the medium is free or busy. R_{cs} depends mainly on the transmit power and the CST of the nodes [25].

Hidden node

A node is said to be hidden if the node is out of the carrier sensing range of a transmitting node but in the range of receiving node [18], [31]. In Fig.2.3, node A and C cannot carrier sense each other. If node A sends packet to node B, node C cannot sense node A. If node C wants to send packet to node B, node C senses the medium is free and it starts to transmit as a result collision occurs at B. Hence, node A is "hidden" for C. Hidden terminal problem is higher at lower transmits power. Due to the hidden terminals problem throughput in WLAN decreases significantly. The hidden terminal problem can be reduced by increasing the transmit power or by decreasing CST.

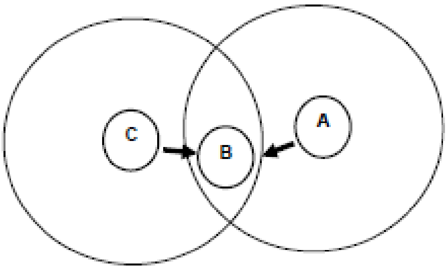

Fig. 2.3 Hidden terminal problem.

Exposed node

For a given transmitter-receiver pair, an exposed terminal is a node which can sense carrier and not transmit packets due to transmitting of a node for other transmitter-receiver pair but the transmission of that transmitter-receiver pair can be successful [28]. In Fig. 2.4, if node B sends packet to node C, then node A sense medium is busy. As a result, node A cannot send to D even there is no problem of transmission of packet. The node D is exposed node for node A. Exposed terminal problem is higher at higher transmits power. Due to the exposed terminals problem throughput in WLAN decreases significantly. The exposed terminal problem can be reduced by reducing the transmit power or by increasing the CST.

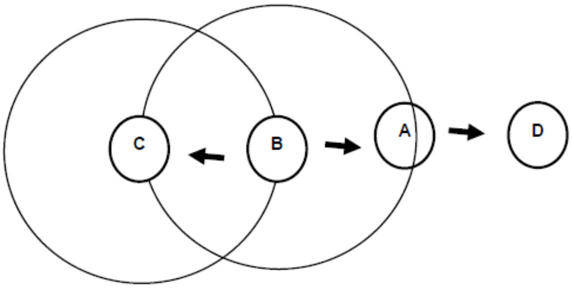

Fig. 2.4 Exposed terminal problem.

There is an inherent tradeoff between the number of hidden terminals and exposed terminals. If the transmit power increases, hidden terminal problem reduces but exposed terminal problem increases [30]. So transmit power should be chosen in such a way that the combined effect of hidden terminal and exposed terminal problems are lower.

2.2 Related Work

Co-channel interference occurs between two or more APs if they use the same frequency channels. The performance of a WLAN is severely affected by co-channel interference [27], [29], [33], [34]. Co-channel interference causes packet errors, retransmissions and limits the overall performance of IEEE 802.11 systems [5]. Co-channel interference related with transmits power, CST and the minimum CW. The impact of transmit power, CST and the minimum CW on throughput performance in WLANs is discussed in the following based on the existing literature.

2.2.1 Impact of Transmit Power in WLANs

Many researchers have worked on the impact of transmit power in WLANs. In [5], Prabhat Kumar et al. provide an algorithm for minimizing the co-channel interference which is based on transmission power adjustment of APs by using the concept of cognitive radio. The power adjustment only can be done at the AP and not at the work station (WS), where the WSs have a fixed power level. The idea behind the algorithm is to have an acceptable power level transmitted to the active WSs. The adjustment of the power levels are done based on the estimated distance of the WS from associated AP, until the maximum power is reached. The algorithm requires received signal strength indicator (RSSI) information to be sent by mobile WS to the AP at some convenient time interval according the expected mobility of WS in the service set. The AP gets updated about the distance of the WS with the help of the RSSI information received. Based on the current distance of WS from the AP, the algorithm will make some decision on the transmission power level required. This process would be repeated for every WS in the service set. In [7] , [13], it is investigated that if the transmit power is high then co-channel interference is high and a power and rate control (PRC) algorithm is proposed to reduce co-channel interference, which uses a lower transmit power leads to less interference, and enable more concurrent transmissions to achieve better throughput.

2.2.2 Impact of Carrier Sensing Threshold in WLANs

A number of studies have been carried out on the impact of CST on the performance of WLANs. The spatial reuse of a network depends on physical carrier sensing [8], [10]. Before attempting for transmission, a node senses the medium and defers its transmission if the channel is sensed busy. Carrier sense reduces the likelihood of collision by preventing nodes in the vicinity of each other from transmitting simultaneously, while allowing nodes that are separated by a safe margin (termed as the carrier sense range, R_{cs}) to engage in concurrent transmissions. The latter effect is referred to as spatial reuse. In wireless networks, the choice of the carrier sense range depends on CST. If the transmit power of all the nodes is the same, a large value of CST implies a small value of R_{cs} (i.e., better degree of spatial), but the interference to be tolerated by the transmission may be also high. On the other hand, a small value of CST implies a larger value of R_{cs}, (i.e., reduce spatial reuse) but the resulting SINR will be comparatively higher. The impact of CST and spatial reuse is studied in [9], [10], [19]-[21]. In [19], it is investigated that the MAC layer overhead has a great impact on the choice of the CST and the data rate. The network throughput depends on spatial reuse. The level of spatial reuse is controlled by varying the CST. The impact of CST on the network capacity has been investigated in [7]-[10]. For a particular transmission rate, Zhai et al. [10] determined the optimal CST that maximizes spatial reuse for several regular topologies. Based on the SINR requirement to sustain a predetermined transmission rate, Vasan et al. [4] proposed an algorithm that dynamically adjusts the CST to maximize spatial reuse, in order to allow more flows to co-exist in IEEE 802.11 based hotspot wireless networks. By default, each transmission rate is associated with a CST such that a node is expected to transmit successfully at the rate using the CST. For a particular data rate the product of transmits power and CST is constant i.e., lower the transmit power, higher the CST and vice versa. A combination of a low transmits power and a high CST leads to a large number of concurrent transmissions, with each transmission sustaining a small data rate. On the other hand, a combination of a high transmits power and a low CST leads to a small number of concurrent transmissions, with each transmission sustaining a large data rate. CST is a tunable parameter that controls spatial reuse and transmission quality [14]. A larger value of CST allows better spatial reuse at the expense of increased interference (and hence the likelihood of frames is corrupted because of accumulative interference).

2.2.3 Impact of Joint Transmit Power and CST in WLANs

The network capacity of a WLAN depend on the achievable channel capacity at each individual wireless link, the level of spatial reuse and the total number of concurrent transmissions that can be accommodated in the network. For a particular data rate, the relation between the transmit power and CST in determining the network capacity is analyzed [9]. Wireless medium is shared, and the sharing range is determined by the transmit power and CST each wireless node uses. One can increase the level of spatial reuse by either reducing the transmit power or increasing the CST. In [7], it is investigated that the number of concurrent transmission depends on CST and the network capacity is a function of transmit power and CST. The maximum network capacity can be achieved by tuning one parameter while fixing the other at an appropriate value. The authors also argued that tuning the transmit power offers more advantages than tuning the CST, because of the number of sufficient power levels are available for tuning. The transmit power is so determined that the transmitter can sustain the highest possible data rate, while keeping the adverse interference effect on the other neighboring concurrent transmissions minimal. In [12], the authors investigated that the capacity of a network is degraded due to inter-BSS co-channel interference and provides a solution to eliminate it by using multi-carrier code division multiplexing (MC-CDMA) which produced two streams.

2.2.4 Impact of Contention Window Size in WLAN

IEEE 802.11 standard devices are basically CW based to share the medium among the multiple users. The binary exponential back-off (BEB) mechanism is designed to deal with MAC. In [24], [26], it is investigated that in single WLAN the use of a small value of minimum CW reduces the back-off period between the frame transmissions and increases throughput especially if the number of stations in the WLAN is low. On the other hand, if the number of stations in a network is large but the value of the minimum CW is small then collision increases significantly and throughput of the network decreases. In [16], the authors studied the IEEE 802.11b and IEEE 802.11g networks and found that the transmission probability or attempt probability of a node increase with reducing the value of the minimum CW. In [11], Bianchi provides the expression of the optimal value of the minimum CW in case of single WLAN to obtain the optimal throughput. The optimal value of the minimum CW is given as,

$$CW_B = N_c\sqrt{2T_c} \tag{2.3}$$

where, N_c is the number of contending nodes of the WLAN and T_c is the collision time in mini-slots.

2.3 Summary

In this chapter, the literature related on the thesis has been reviewed. It is found that by tuning the transmit power and CST, the co-channel interference can be reduced but cannot be mitigated completely. So far the research on co-channel interference of WLANs has been focused on to improve the throughput performance. To the best of our knowledge, the throughput unfairness problem due to co-channel interference is not addressed. In this thesis, the throughput unfairness problem in WLANs due to co-channel interference is investigated and solutions to overcome the throughput unfairness problem are provided.

CHAPTER 3

SYSTEM MODEL

In this chapter, network topology, propagation and interference model and basic CSMA/CA protocol are described.

3.1 Network Topology

Consider a WLAN which has six co-channel WLANs, similar as Fig. 4.1. Hexagonal structure is considered for the co-channel WLANs with cluster size of 3. Each co-channel WLAN consists of an AP and a set of users. All the seven WLANs use the same channel. The AP of a WLAN is located at the center of the WLAN to provide maximum coverage. The users in the WLANs are randomly distributed and their positions are known. The total number of users in the WLANs is N. Denote the set of all the users by $\mathcal{N}$. Each node has an omni-directional antenna and cannot transmit and receive at the same time. The transmission power of all the users is fixed and equal. Only uplink is considered in our model which means that only users access their APs. Also consider that the users are in saturation, i.e., they always have packets to send to their APs. A single rate system is assumed where all the nodes use the same modulation and coding scheme. All the nodes use a basic CSMA/CA MAC protocol. The CST for all the nodes is assumed to be the same.

3.2 Propagation and Interference Model

The wireless signal is radiated in the space and the signal strength is reduced with increasing distance. The channel gain between two nodes is assumed to be time-invariant. The channel gain between nodes n_1 and n_2, $G_{n1,n2}$ is given by $(\frac{d}{d_0})^{-\eta}$, where d is the distance between the nodes, d_0 is the far-field cross-over distance and η is the path loss exponent of medium. In WLANs the users suffer from interference. The throughput of a wireless network is affected by interference model. To achieve optimal throughput it is very important to choose an appropriate interference model for WLANs. In this thesis, a physical interference model is considered for wireless interference. Let the minimum required SINR at the receiver for successful packet decoding is γ for the given modulation and coding scheme. A packet sent by transmitter n_1 will be successfully received by the receiver n_2 if the received SINR is not less than the minimum required SINR during the reception of the packet [6] , i.e., a packet transmission from node n_1 to n_2 will be successful if

$$\frac{G_{n1,n2}\, P_t}{N_0 + \sum_{n' \in \mathcal{N} \setminus n_1} G_{n',n2} P_t Y_{n'}} \geq \gamma \qquad (3.1)$$

where P_t is the transmit power, N_0 is the noise power and $Y_{n'}$ is a binary variable taking value 1 if node n' transmits and 0 otherwise.

3.3 Basic CSMA/CA MAC Protocol

The users in the WLANs access the channel using a distributed coordination function (DCF). Every node senses the medium for a time equal to DIFS before initiating a transmission of a packet. A node senses medium as busy if the received power (interference power plus noise power) is higher than the CST i.e., if

Interference Power + Noise Power≥ Carrier Sensing Threshold (CST).

If the medium is sensed idle by a node in DIFS period it transmits its data packet. Otherwise, the node sets a value of CW randomly choosing from a uniform distribution (0, CW_{min}-1), where CW_{min} is the minimum CW of the nodes. Hence, after the DIFS time, the time is divided into mini-slots and each node senses the channel in each mini-slot if they do not transmit. If a node senses the channel as busy in a mini-slot, the node does not reduce its CW i.e., it freezing and resumed when the channel is detected as idle again for a DIFS interval, then node reduces its CW by one. This is called back-off process. Each node continues the back-off process until their CWs become zero [1], [11], [16]. A node transmits its data packet when its CW becomes zero. Since all the nodes randomly chose the values of CWs, more than one node might have the same CW. In that case, they will start transmission at the same time and the success or failure of a transmission will depend on the used interference model. The packet sizes of all the nodes are assumed to be equal. If a packet transmission is successful, the receiver will send an acknowledgement (ACK) packet after a short inter frame space (SIFS) time. If a node receives an ACK packet which has already transmitted a data packet, it will attempt to send the next data packet according to the procedure mentioned above. If a data packet transmission fails, the packet will be retransmitted. During retransmission, the value of CW is randomly chosen from a uniform distribution (0, $2^m CW_{min}$-1), where m is the number of retransmission attempts to send the packet. For example, a node will choose CW from a uniform distribution (0, $2CW_{min}$-1) after the first failure. This is called binary exponential backoff (BEB) mechanism. When a data packet transmission is successful and an ACK packet is received by the sender, for the next data packet, CW will be reset by randomly choosing from a uniform distribution (0, $\mathrm{CW}_{\mathrm{min}}$-1). If a packet is not successful for five retries, the data packet is dropped. The operation of basic CSMA/CA MAC protocol is shown in Fig. 3.1.

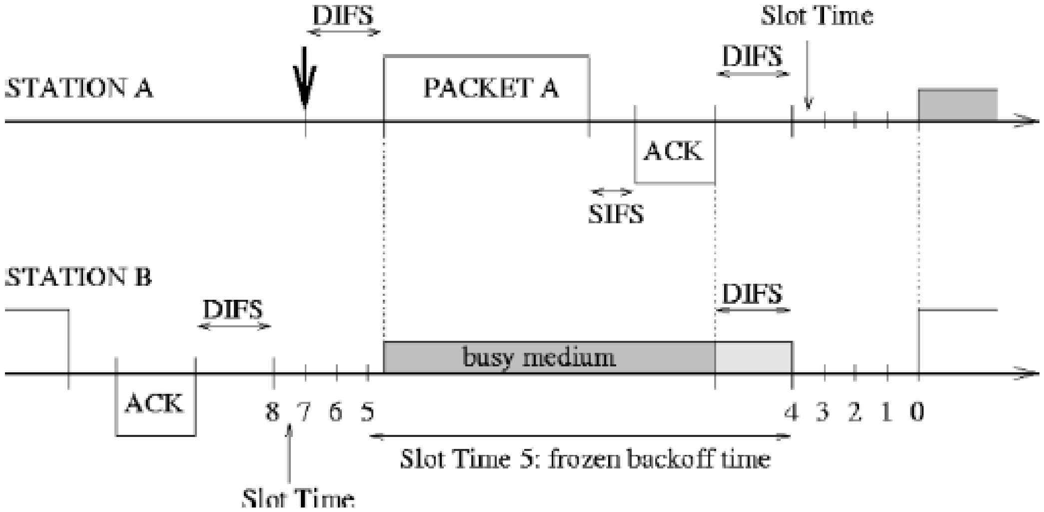

Fig 3.1 Basic CSMA/CA.

CHAPTER 4

IMPACT OF MAC LAYER AND PHY LAYER PARAMETERS ON THROUGHPUT

In this chapter, the impact of transmit power, CST and CW on throughput performance in WLANs are studied through simulation. Networks and algorithm parameters, simulator setup and simulation results are also described in this chapter.

4.1 Networks and Algorithm Parameters

A WLAN and its six co-channel WLANs is considered in a network. In this thesis, two WLAN scenarios have been taken which are shown in Fig. 4.1 and Fig. 4.2. The radius of each WLAN is 100 m. The AP of each WLAN is set at the center of the WLAN and labeled by a circle. The users are randomly distributed in 800 × 800 m^2 area. In network scenario-1, among all the users in the area, only 55 users belong to 7 co-channel WLANs including 11 users of the centre WLAN. In network scenario-2, the total numbers of users 53 belong to 7 co-channel WLANs. IEEE 802.11b standard is considered for the WLANs. The physical layer parameters and CSMA/CA MAC parameters are given in Table 4.1 and Table 4.2, respectively.

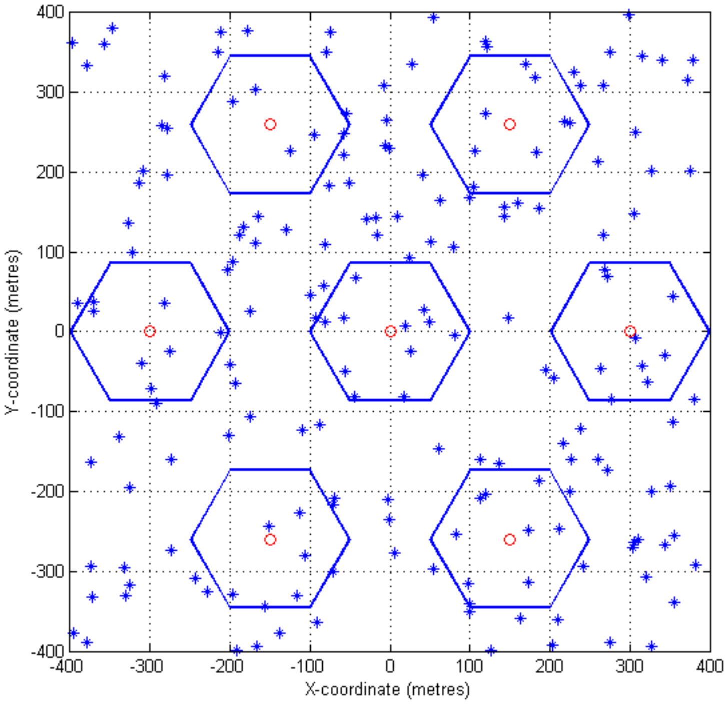

Fig. 4.1 The positions of the nodes in WLANs of network 1.

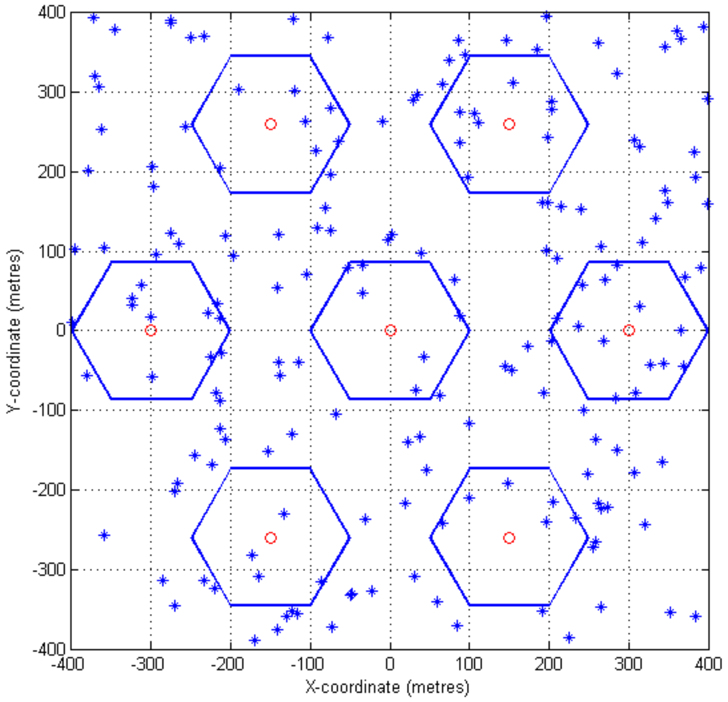

Fig. 4.2 The positions of the nodes in WLANs of network 2.

Table 4.1 Physical Layer Parameters.

Parameter	Value
SINR threshold (dB)	6.4
Noise power (dBm)	-100
Path-loss exponent	3.5
Far-field crossover distance (m)	1
Data rate (Mbps)	2

Table 4.2 MAC Layer Parameters.

Parameter	Value
SIFS (μs)	10
DIFS (μs)	50
a slot time (μs)	20
Data packet size (byte)	1058
ACK packet size (byte)	14
PHY+MAC header (byte)	24

4.2 Simulator Setup

The WLANs are simulated with a custom simulator written in C++. The commonly available network simulators are not used because they cannot provide the flexibility of tuning the network parameters. The average rates of the sources are set to equal values and their traffic is assumed to be Poisson. The source rate of the users is kept sufficiently large to make their queues saturated. To determine the total throughput for a given network scenario, the network is simulated for 500 s and the total throughput is calculated as $1058 \times 8 \times N_{pkt} / 500$ bps, where N_{pkt} is the total number of packets received by the APs at the end of the simulation. For a network scenario, the average throughput over five simulation runs has been considered as a total throughput.

In this thesis, two networks are simulated to investigate the impact of CST, transmit power and CW on throughput performance.

4.3 Impact of Transmit Power and CST on Throughput Performance

To determine the optimal configuration of transmission power and CST for the WLAN scenarios in Fig. 4.1 and Fig. 4.2 are simulated by varying the transmit power of the users at different CST power levels. The minimum transmission power select in such a way that all the nodes can be connected to the network. In this thesis, the transmit power is varied from -25 dBm to -11 dBm. At first, the impact of transmit power and CST is investigated at default CW. So the minimum CW of all the nodes are set to 31 which is the default minimum CW of the nodes for both networks. The total throughput of the WLANs with respect to the transmit power at different CSTs is shown in Fig. 4.3 and Fig. 4.4 for the network 1 and network 2, respectively. For a given CST, the throughput performance is poor at a low transmit power due to severe hidden terminal problem. The numbers of hidden terminals problem reduce with increasing transmit power as a result throughput increase. Furthermore, the total throughput starts to reduce from its optimal value (at optimal transmit power) with increasing transmit power for decreasing the spatial reuse due to co-channel interference. It is found that the optimal value of transmit power increases with increasing the CST power, which is clear transmit power versus throughput curves in Fig.4.3 and Fig 4.4. Since at higher transmit power co-channel interference is more as compared to lower transmit power, which makes optimal spatial reuse occur at higher CST. It is also found that the total network throughput is not so good at low CST even when the transmit power is optimized. However, the total optimal throughput at different CST power levels -96, -94 and -92 dBm with the corresponding optimal transmit power are very close.

The optimal values of throughput at default CW and their corresponding transmission power at different CST are shown in Table 4.3 and Table 4.4 for the network 1 and network 2, respectively. The optimal value of transmit power and CST for the both networks are shown in Table 4.5. The noise power is considered to be -100 dBm in this thesis. Therefore, CST power level should be roughly 4 to 8 dB higher than the noise power to get better throughput performance with the optimal transmit power.

For the system in Fig 4.1 and 4.2, if the transmitting distance between two transmitting nodes is higher than 200 m, they are not hidden terminals problem. To avoid the hidden terminals problem completely, the carrier sensing range is assumed to be 200 m, the transmit power levels are found to be -23.39, -19.27, -16.32 and -13.81 dBm for CST of -98, -96, -94 and -92 dBm, respectively for network 1 and network 2. The simulation results have shown that the throughputs obtained by these transmit power levels are very close to the optimal throughput. Thus, one can obtain a very close throughput to the optimal throughput by setting the transmit power to a value such that the hidden terminal problem is avoided completely.

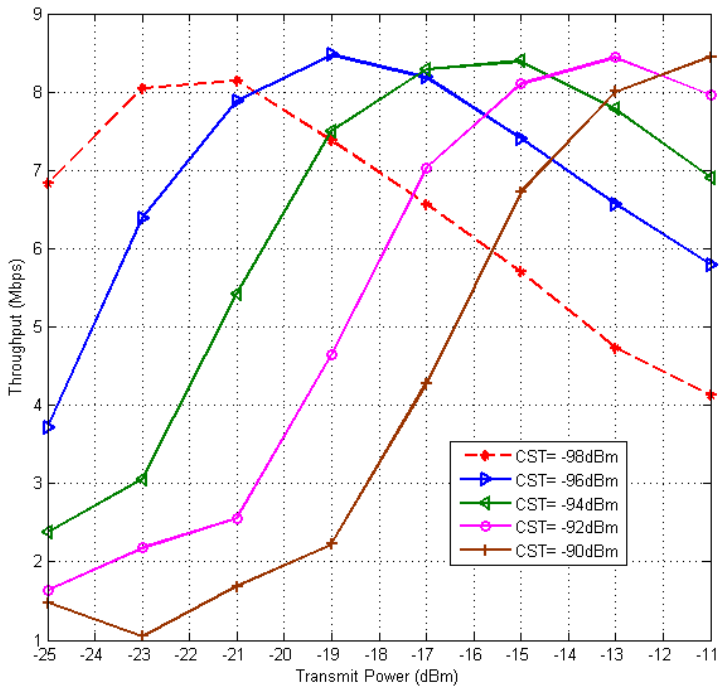

Fig 4.3 The total throughput of network 1 with respect to transmit power at default CW.

Table 4.3 The optimal value of throughput for different CSTs and the corresponding transmit power for the network 1 at default CW.

CST (dBm)	The optimal transmit power (dBm)	The optimal throughput (Mbps)
-98	-21	8.141
-96	-19	8.470
-94	-15	8.389
-92	-13	8.439
-90	-11	8.445

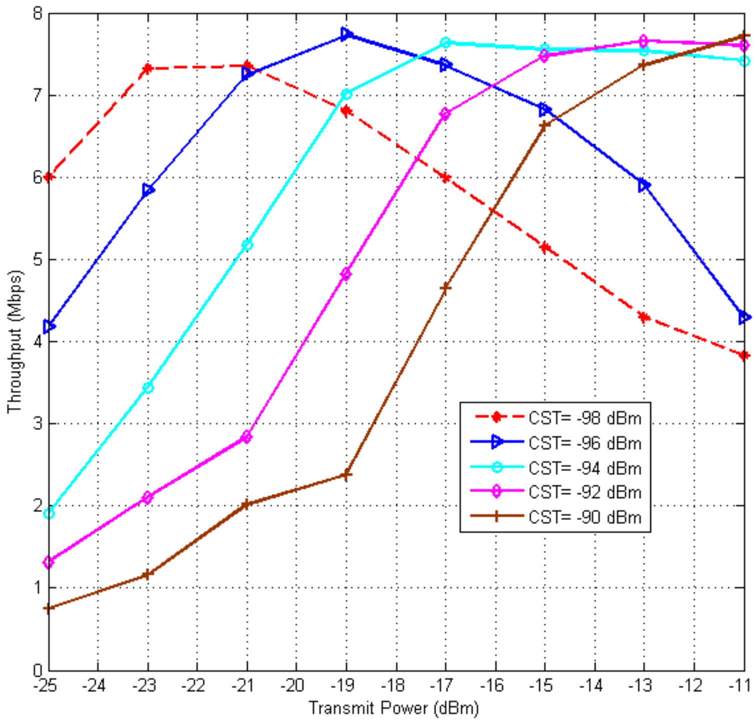

Fig 4.4 The total throughput of network 2 with respect to transmit power at default CW.

Table 4.4 The optimal value of throughput for different CSTs and the corresponding transmit power for the network 2 at default CW.

CST (dBm)	The optimal transmit power (dBm)	The optimal throughput (Mbps)
-98	-23	7.349
-96	-19	7.728
-94	-17	7.632
-92	-15	7.654
-90	-13	7.716

Table 4.5 The optimal CST and transmission power for the network 1 and network 2 at default CW.

Network	The optimal CST (dBm)	The optimal transmit power (dBm)
1	-96	-19
2	-96	-19

4.4 Impact of Contention Window on Throughput Performance

The same procedure described in 4.3 has been followed to investigate the throughput of a WLAN significantly depends on CW. In [11], G. Bianchi analyzes throughput performance in single WLAN. The author provides the expression of the optimal value of the minimum CW as $N_c\sqrt{2T_c}$ to achieve the maximum throughput, where N_c is the number of contending nodes in the WLAN and T_c is the collision time in mini-slots. For the WLAN system, the collision time is found to be 219 mini-slots using the following equation.

$$T_c = \frac{8(L_d+PHY+MAC)}{C\delta} + \frac{DIFS}{\delta} \tag{4.1}$$

where L_d is the data packet size and PHY and MAC are the physical and MAC layer headers, respectively, and δ is the duration of a mini-slot. The Bianchi optimal CW of the nodes is calculated for each WLAN of the system shown in Fig. 4.1 and Fig. 4.2.

Using Bianchi optimal CW, the total throughput of the system is determined by varying the transmit power from -25 dBm to -11 dBm for CST power level -98, -96, -94, -92 and -90 dBm. The throughput performance at Bianchi optimal CW is shown in Fig. 4.5 and Fig. 4.6 for the network 1 and network 2, respectively. The optimal value of throughput at Bianchi optimal CW and their corresponding transmit power at different CSTs are shown in Table 4.6 and Table 4.7. The optimal value of transmit power and CST for both networks are shown in Table 4.8. The results show that the insights on the impact of transmit power and the CST remains almost same even when the Bianchi optimal CW is used. The simulation results also show that the throughput at default CW is lower as compared to Bianchi optimal CW because the smaller CW increases the collision probability. The comparison between the optimal throughput performance at default CW and Bianchi optimal CW is shown in Table 4.9.

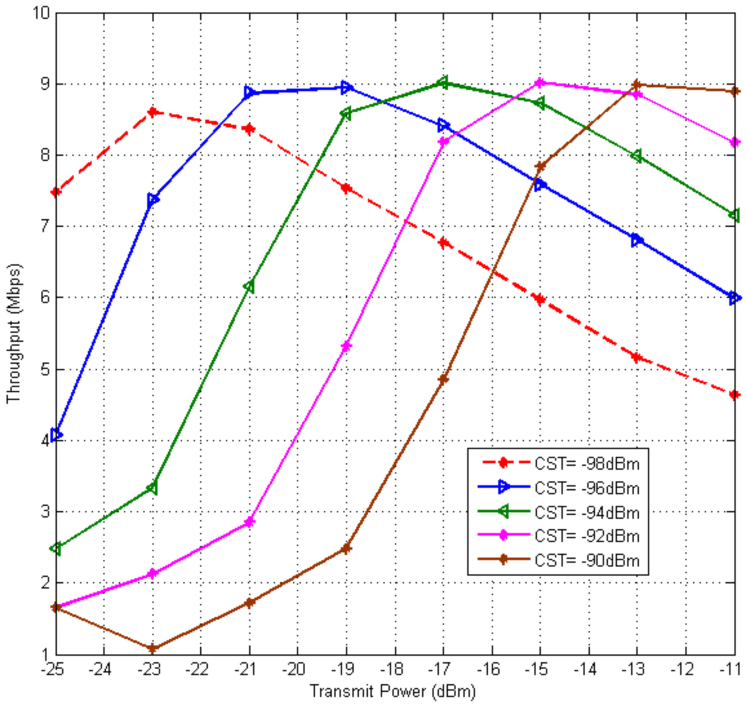

Fig 4.5 The total throughput of network 1 with respect to transmit power at Bianchi optimal CW.

Table 4.6 The optimal value of throughput for different CSTs and the corresponding transmit power for the network 1 at Bianchi optimal CW.

CST (dBm)	The optimal transmit power (dBm)	The optimal throughput (Mbps)
-98	-23	8.602
-96	-19	8.944
-94	-17	9.011
-92	-15	9.013
-90	-13	8.977

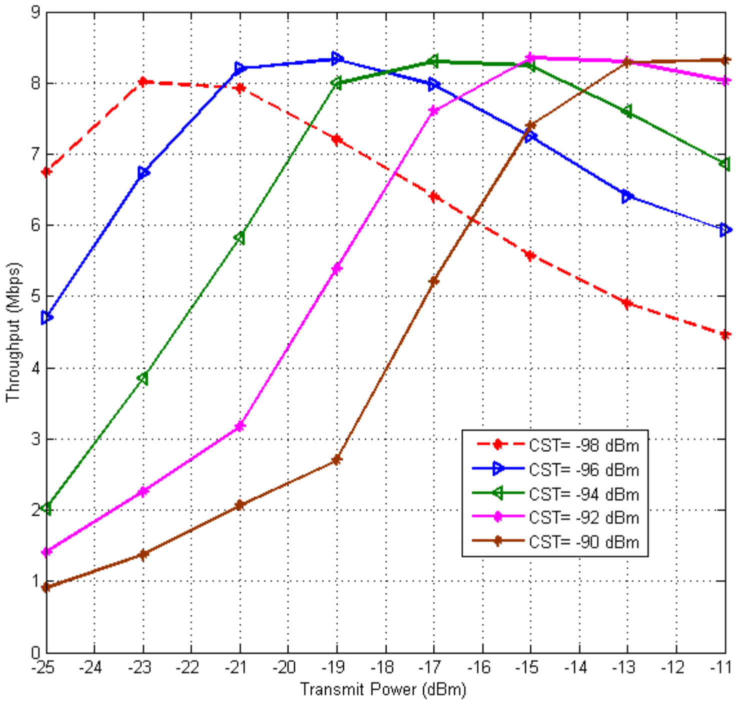

Fig 4.6 The total throughput of network 2 with respect to transmit power at Bianchi optimal CW.

Table 4.7 The optimal value of throughput for different CSTs and the corresponding transmit power for the network 2 at Bianchi optimal CW.

CST (dBm)	The optimal transmit power (dBm)	The optimal throughput (Mbps)
-98	-23	8.012
-96	-19	8.330
-94	-17	8.300
-92	-15	8.350
-90	-13	8.312

Table 4.8 The optimal CST and transmission power for the network 1 and network 2 at Bianchi optimal CW.

Network	The optimal CST (dBm)	The optimal transmit power (dBm)
1	-92	-15
2	-92	-15

Table 4.9 Comparison between the optimal throughput performance at default CW and Bianchi optimal CW.

Network	The optimal throughput(Mbps) at default CW	The optimal throughput(Mbps) at Bianchi optimal CW
1	8.470	9.013
2	7.728	8.350

4.5 Summary

In this chapter, the impact of transmission power, CST and the minimum CW on the throughput performance in WLANs has been studied. It is found that the throughput is not good at a low transmit power or at a high transmit power. Roughly the optimal transmit power is 8 to 12 dB higher than the minimum power required to connect the network and the optimal CST value is 4 to 8 dB higher than the noise power. The simulation results also show that throughput improves significantly if the minimum CW set to the Bianchi optimal CW instead of the default CW.

CHAPTER 5

UNFAIRNESS PROBLEM

In this chapter, the throughput unfairness problem is investigated at the default CW as well as the Bianchi optimal CW with the optimal transmission power and CST.

5.1 Unfairness Problem due to Co-channel Interference

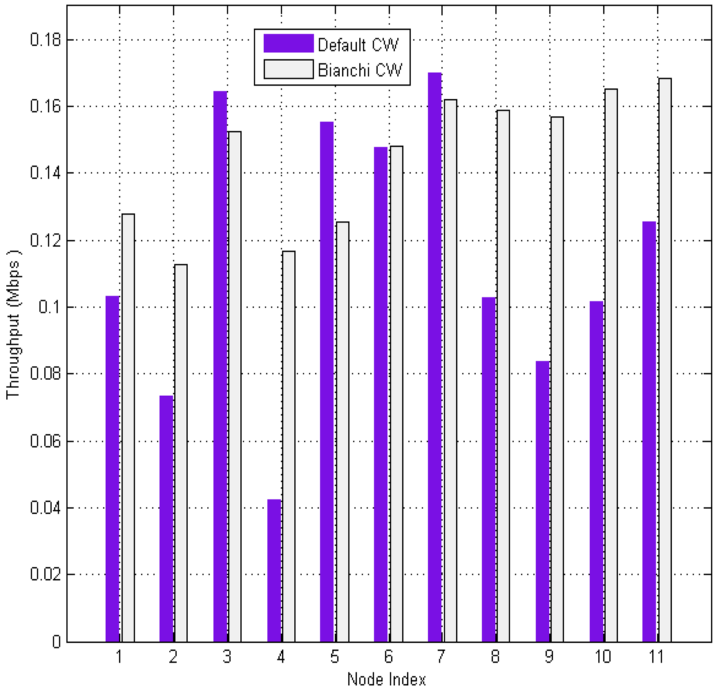

Fig. 5.1 Throughput of each user of the center WLAN of network 1.

In Chapter 4, the simulation results show that at default CW the optimal transmit power and CST power are -19 dBm and -96 dBm, respectively. On the other hand, at Bianchi optimal CW the optimal transmits power and CST are -15 dBm and -92 dBm, respectively. Now, the throughput unfairness problem to be investigated at default CW as well as Bianchi optimal CW with optimal transmit power and CST.

The throughput of each user of the center WLAN of network 1 is determined at the default CW and Bianchi optimal CW. The throughputs of the users of the centre WLAN at default CW and Bianchi optimal CW are shown in Fig. 5.1, where node index is labeled in x- axis. At default CW, the minimum and the maximum throughputs of the users are found to be 0.043 Mbps and 0.174 Mbps, respectively. Thus, the throughput unfairness among the users is very significantly at default CW configuration of the nodes. On the other hand, the maximum and the minimum throughputs of the users are found to be 0.173 Mbps and 0.114 Mbps, respectively, at the Bianchi optimal CW. Though configuring the WLANs with Bianchi optimal CW can reduce the throughput unfairness problem among the users but the unfairness problem is still significant. It is also observed that the throughputs of the users near to AP are higher due to low co-channel interference.

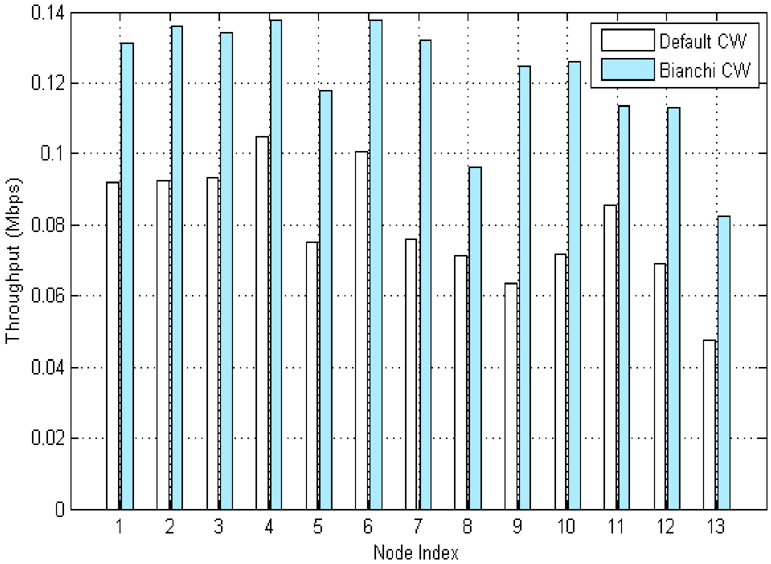

Fig. 5.2 Throughput of each user of the right hand side WLAN of the center WLAN of network scenario-2.

The throughput of each user of the network scenario-2 is also determined at the default CW and Bianchi optimal CW. The throughputs of users of the right hand side WLAN of the center WLAN are shown in Fig. 5.2. The maximum and the minimum throughputs of the users of the right hand side WLAN of the centre WLAN are found to be 0.105 Mbps and 0.047 Mbps, respectively, at the default value of the minimum CW. At Bianchi optimal CW, the maximum and minimum throughputs of the users are found to be 0.138 Mbps and 0.082 Mbps, respectively. Thus, for the both networks scenario the conclusions remain the same.

5.2 Summary

In this chapter, the throughput unfairness problem in WLANs due to asymmetric co-channel interference among the users has been investigated. It is found that the throughput unfairness among the users is very significant at the default value of the minimum CW. Though the unfairness problem reduces for using Bianchi optimal CW, the unfairness problem is still significant.

CHAPTER 6

CENTRALIZED ALGORITH TO MITIGATE THE THROUGHPUT UNFAIRNESS PROBLEM

In this chapter, a centralized algorithm is proposed based on an analytical formulation to solve the throughput unfairness problem. The effectiveness of the algorithm is evaluated through simulation.

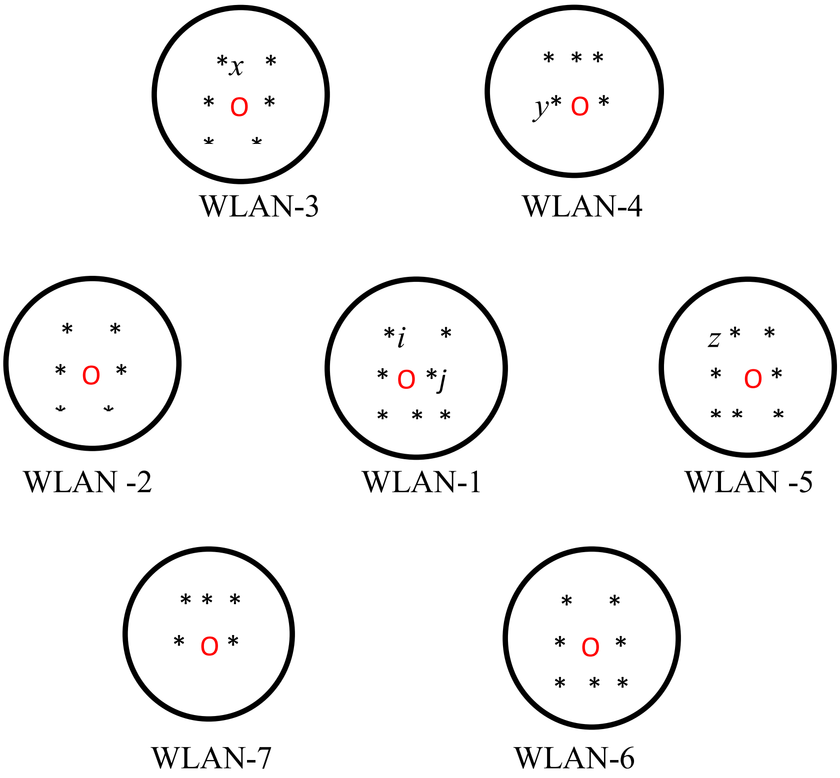

Fig.6.1 Co-channel WLANs arrangement.

6.1 Centralized Algorithm

Consider a WLAN network topology composed of several co-channel WLANs shown in Fig. 6.1, where the users are distributed randomly under different WLANs. Each co-channel WLAN has an AP, which indicate by 'O' symbol and '*' indicate the nodes or users. Assuming that node *i* belongs to one of the WLAN.

Each node in a CSMA/CA based wireless network passes time mainly in four states: idle, carrier sense, successful transmission and collision. In the following, the expressions of fraction of times in different states of node i are derived by relating the fraction of times of different states, and the algorithm to configure the minimum CW of the nodes is described.

6.1.1 Fraction of Times in Different States:

The carrier sensing time is divided into three parts: carrier sensing for transmission of one node only, carrier sensing for transmissions of two nodes simultaneously, and carrier sensing for transmission of three nodes simultaneously. The carrier sensing time for transmission of more than three nodes at the same time is very less and it is neglected in the analysis.

Let $\pi_i^{idle}, \pi_i^{cs}, \pi_i^{cs-2}, \pi_i^{cs-3}, \pi_i^{s}$ and π_i^{c} be the fraction of times that the node *i* passes times in idle state, carrier sensing state for transmission of single node, carrier sensing state for transmission of two nodes, carrier sensing state for transmission of three nodes, successful state , and collision state, respectively.

The max-min throughput fairness to be provided among the users. Let λ packet/s be the max-min throughput of each user. The fraction of successful time can be written as

$$\pi_i^s = T_s\lambda \tag{6.1}$$

where T_s is the transmission time of one packet. Again,

$$T_s = k\delta \tag{6.2}$$

where *k* is the number of slots for transmission of DATA and acknowledgement (ACK) of a packet. And δ is the slot time.

i.e., $k = \frac{(DATA+SIFS+ACK)Time}{Slot\ Time}$

Using (6.2) in (6.1), we obtain,

$$\pi_i^s = k\delta\lambda \tag{6.3}$$

The total fraction of time in successful and collision states can be written as

$$\pi_i^s + \pi_i^c = \frac{\lambda T_s}{1-p_i} = \frac{k\lambda\delta}{1-p_i} \tag{6.4}$$

where p_i is the collision probability of a transmission of node *i*. The fraction of time in idle state can be written as

$$\pi_i^{idle} = \frac{CW_{min}^i}{2}\,\delta\lambda(1+2p_i+2^2p_i^2 + \ldots\ldots\ldots\ldots + 2^m p_i^m)$$

$$= \frac{CW_{min}^i}{2}\,\delta\lambda\left[\frac{1-(2p_i)^{m+1}}{1-2p_i}\right] \tag{6.5}$$

where CW_{min}^i is the minimum CW of node *i* and *m* is the maximum backoff stage. Assuming that the nodes access the medium independently when they are in idle state, the fraction of times in the carrier sensing states can be written as

$$\pi_i^{cs} = \sum_{n\in\mathcal{N}_i^{cs}} \frac{k\lambda\delta}{1-p_n} \tag{6.6}$$

$$\pi_i^{cs-2} = \sum_{(x,y)n\in\mathcal{N}_i^{cs-2}} \frac{k\lambda\delta}{(1-p_x)} \cdot \frac{k\lambda\delta}{(1-p_y)} \tag{6.7}$$

$$\pi_i^{cs-3} = \sum_{(x,y,z)n\in\mathcal{N}_i^{cs-3}} \frac{k\lambda\delta}{(1-p_x)} \cdot \frac{k\lambda\delta}{(1-p_y)} \cdot \frac{k\lambda\delta}{(1-p_z)} \tag{6.8}$$

where $\mathcal{N}_i^{cs}$ is the set of nodes such that node *i* senses carrier if one of the nodes in $\mathcal{N}_i^{cs}$ transmits, $\mathcal{N}_i^{cs-2}$ is the set of pair of nodes such that node *i* senses carrier if one of the pair of nodes in $\mathcal{N}_i^{cs-2}$ transmit simultaneously, and $\mathcal{N}_i^{cs-3}$ is the set of triplet of nodes such that node *i* senses carrier if one of the triplet of nodes in $\mathcal{N}_i^{cs-3}$ transmit simultaneously. Note that $\mathcal{N}_i^{cs-2}$ does not include any node in $\mathcal{N}_i^{cs}$ and $\mathcal{N}_i^{cs-3}$ does not include any node or pair of nodes in $\mathcal{N}_i^{cs}$ and $\mathcal{N}_i^{cs-2}$. p_x, p_y, p_z are the collision probability of nodes *x, y, z*, respectively. Assuming that each node shares the medium equally in a WLAN, $\frac{k\lambda\delta}{(1-p_x)}$ is approximated as $\frac{1}{\mathcal{N}_x}$, where $\mathcal{N}_x$ is the number of contending nodes in the WLAN of node *x*. Thus, (6.7) and (6.8) can be approximated as

$$\pi_i^{cs-2} \approx \sum_{(x,y)n\epsilon\mathcal{N}_i^{cs-2}} \frac{1}{\mathcal{N}_x} . \frac{k\lambda\delta}{(1-p_y)} \tag{6.9}$$

$$\pi_i^{cs-3} \approx \sum_{(x,y,z)n\epsilon\mathcal{N}_i^{cs-3}} \frac{1}{\mathcal{N}_x} . \frac{1}{\mathcal{N}_y} . \frac{k\lambda\delta}{(1-p_z)} \tag{6.10}$$

6.1.2 Relation Among the Fraction of Times

The fraction of times at different states of node *i* satisfy the following equation,

$$\pi_i^{idle} + \pi_i^{cs} + \pi_i^{cs-2} + \pi_i^{cs-3} + \pi_i^{s} + \pi_i^{c} = 1 \tag{6.11}$$

Thus, combing the fraction of times of all the states of node *i*, then equation (6.11) becomes,

$$\frac{CW_{min}^{i}}{2}\,\delta\lambda\left[\frac{1-(2p_i)^{m+1}}{1-2p_i}\right] + \sum_{n\epsilon\mathcal{N}_i^{cs}} \frac{k\lambda\delta}{1-p_n} + \sum_{(x,y)n\epsilon\mathcal{N}_i^{cs-2}} \frac{1}{\mathcal{N}_x} . \frac{k\lambda\delta}{(1-p_y)} +$$

$$\sum_{(x,y,z)n\epsilon\mathcal{N}_i^{cs-3}} \frac{1}{\mathcal{N}_x} . \frac{1}{\mathcal{N}_y} . \frac{k\lambda\delta}{(1-p_z)} + \frac{k\lambda\delta}{1-p_i} = 1 \tag{6.12}$$

The set $\mathcal{N}_i^{cs}$ includes all the nodes of self WLAN of node *i* and some nodes from the co-channel WLANs of node *i*. Denote by $\mathcal{N}_i^{cs-s}$, $\mathcal{N}_i^{cs-o}$ the sets of nodes from self WLAN and co-channel WLANs, respectively, such that $\mathcal{N}_i^{cs-s} \cup \mathcal{N}_i^{cs-o} = \mathcal{N}_i^{cs}$. Assuming that there is no hidden terminal in the system, i.e., a node senses carrier if one of the nodes from the same WLAN transmits and $(2p_i)^{m+1} = 0$, (6.12) can be written as

$$\frac{CW_{min}^{i}}{2}\,\delta\lambda\left[\frac{1}{1-2p_i}\right] + \sum_{n\epsilon\mathcal{N}_i^{cs-o}} \frac{k\lambda\delta}{1-p_n} + \sum_{(x,y)n\epsilon\mathcal{N}_i^{cs-2}} \frac{1}{\mathcal{N}_x} . \frac{k\lambda\delta}{(1-p_y)} +$$

$$\sum_{(x,y,z)n\epsilon\mathcal{N}_i^{cs-3}} \frac{1}{\mathcal{N}_x} . \frac{1}{\mathcal{N}_y} . \frac{k\lambda\delta}{(1-p_z)} + \sum_{n\epsilon\mathcal{N}_i} \frac{k\lambda\delta}{1-p_n} = 1 \tag{6.13}$$

where $\mathcal{N}_i$ is the set of nodes in the WLAN of node i , i.e., $\mathcal{N}_i = \mathcal{N}_i^{cs-s} \cup i$.

6.1.3 Algorithm:

An arbitrary node j is assumed in the same WLAN of node i which does not sense carrier for transmission of the nodes in co-channel WLANs. Thus, for node j (6.13) can be written as

$$\frac{CW_{min}^{j}}{2}\,\delta\lambda\left[\frac{1}{1-2p_j}\right]+\sum\nolimits_{n\epsilon\mathcal{N}_j}\frac{k\lambda\delta}{1-p_n}=1 \tag{6.14}$$

From (6.13) and (6.14) we obtain,

$$\frac{CW_{min}^{i}}{2}\left[\frac{1}{1-2p_i}\right]+\sum\nolimits_{n\epsilon\mathcal{N}_i^{cs-o}}\frac{k}{1-p_n}+\sum\nolimits_{(x,y)n\epsilon\mathcal{N}_i^{cs-2}}\frac{1}{\mathcal{N}_x}.\frac{k}{(1-p_y)}+$$

$$\sum\nolimits_{(x,y,z)n\epsilon\mathcal{N}_i^{cs-3}}\frac{1}{\mathcal{N}_x}.\frac{1}{\mathcal{N}_y}.\frac{k}{(1-p_z)}+\sum\nolimits_{n\epsilon\mathcal{N}_i}\frac{k}{1-p_n}=\frac{CW_{min}^{j}}{2}\left[\frac{1}{1-2p_j}\right]+\sum\nolimits_{n\epsilon\mathcal{N}_j}\frac{k}{1-p_n} \tag{6.15}$$

Since $\mathcal{N}_i = \mathcal{N}_j$, so the equation (6.13) becomes

$$\frac{CW_{min}^{i}}{2}\left[\frac{1}{1-2p_i}\right]+\sum\nolimits_{n\epsilon\mathcal{N}_i^{cs-o}}\frac{k}{1-p_n}+\sum\nolimits_{(x,y)n\epsilon\mathcal{N}_i^{cs-2}}\frac{1}{\mathcal{N}_x}.\frac{k}{(1-p_y)}+$$

$$\sum\nolimits_{(x,y,z)n\epsilon\mathcal{N}_i^{cs-3}}\frac{1}{\mathcal{N}_x}.\frac{1}{\mathcal{N}_y}.\frac{k}{(1-p_z)}=\frac{CW_{min}^{j}}{2}\left[\frac{1}{1-2p_j}\right] \tag{6.16}$$

Since the users of the co-channel WLANs are located far in distance from the AP (receiver) of the WLAN of node i, the collision probability for a transmission by node i can be written as

$$p_i = 1-\prod\nolimits_{n\epsilon\mathcal{N}_i^{cs-s}}(1-\tau_n)=1-\frac{\prod_{n\epsilon\mathcal{N}_i}(1-\tau_n)}{1-\tau_i}=1-\frac{D}{1-\tau_i} \tag{6.17}$$

where τ_i is the attempt rate of node i in each mini-slot of idle state and $D = \prod_{n\epsilon\mathcal{N}_i}(1-\tau_n)$. The variable τ_i can be approximated as [11]

$$\tau_i \approx \frac{2}{CW_{min}^{i}} \tag{6.18}$$

Using (6.18), the collision probability of a node of a co-channel WLAN is approximated as follows using the Bianchi optimal attempt rate [11].

$$p_n = 1 - (1-\tau)^{N_n-1} = 1 - \left(1 - \frac{2}{CW_{min}}\right)^{N_n-1} = 1 - (1 - \frac{2}{N_n\sqrt(2T_c)})^{N_n-1} \, . \qquad (6.19)$$

Using (6.17), (6.18), and (6.19) in (6.16), we get a relation between CW_{min}^{i} and CW_{min}^{j} in term of D.

Hence, the other parameters in (6.16) become constant for a given WLAN scenario. In [32], the authors investigated the impact of co-channel interference on the optimal CW in WLANs and found that the optimal value of the minimum CW is 10 to 20% higher than the Bianchi optimal CW due to co-channel interference. However, the throughput difference between the Bianchi optimal CW and the optimal CW is less than 0.5%. Thus, for simplification, Bianchi optimal CW is considered for CW_{min}^{j} , i.e., $CW_{min}^{j} = N_j\sqrt{2T_c}$ and then determine the value of CW_{min}^{i} for all *i* in the WLANs under a suitable value of D.

6.2 Effectiveness of the Proposed Centralized Algorithm

In this section, the centralized algorithm to be implemented with optimal transmit power and CST for the network 1 and network 2 are shown in Fig. 4.1 and 4.2. In Chapter 4 found that the optimal value of the transmit power and CST are -15 dBm and -92 dBm for the network 1 and network 2. Now, the minimum CW of the nodes for the WLAN scenarios shown in Fig. 4.1 and Fig. 4.2 is configured according to the centralized algorithm which already has been described in this chapter. The value of $k = 215$ is used in computation of the minimum CW of the nodes.

Since, $k = \frac{(L_d+SIFS+ACK)}{\delta}$.

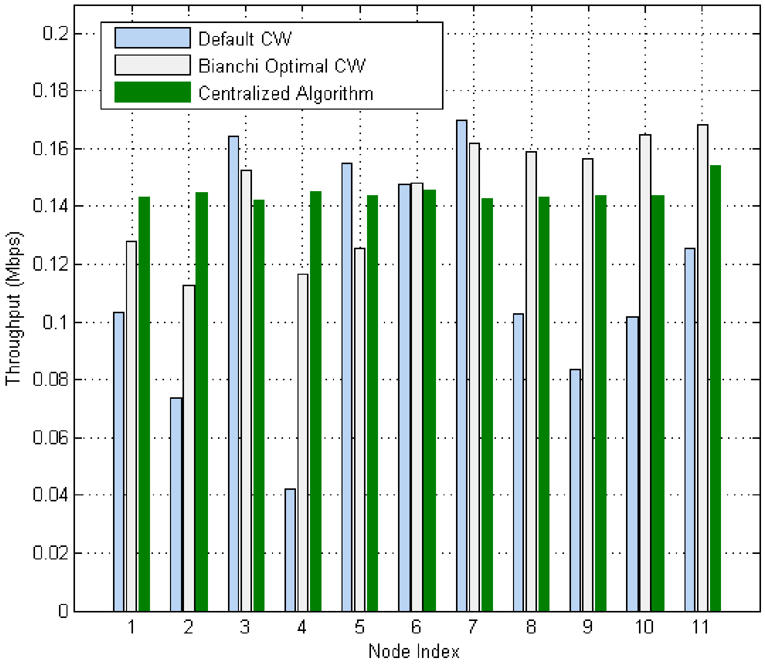

Fig. 6.2 Throughput of each user of the center WLAN of network 1.

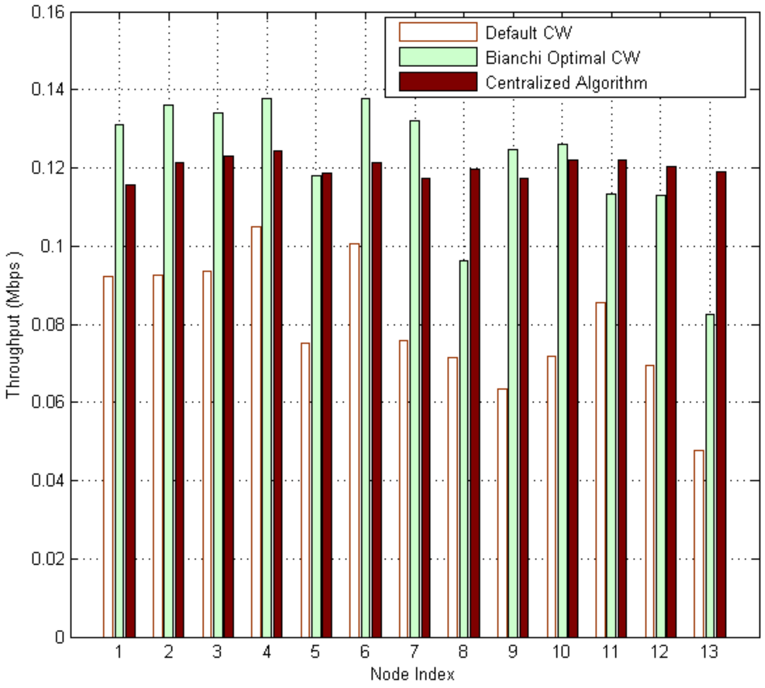

Fig. 6.3 Throughput of each user of the right hand side WLAN of the center WLAN of network scenario-2.

The throughput of each users of the center WLAN of network 1 under three types of configurations of CW of the nodes are shown in Fig. 6.2. The simulation results show that the maximum throughput of the user is 0.152 Mbps and minimum throughput of the user is 0.142 Mbps when the CW of the nodes are configured according to the centralized algorithm. Thus, the centralized algorithm is very effective to solve the throughput unfairness problem in WLANs due to co-channel interference.

There is a trade-off between the total throughput and fairness in wireless networks. If one wants to provide max-min fair throughput among the users then the total throughput degrades significantly. But the centralized algorithm provides fairness among the users without losing the total throughput significantly. To verify this, the total throughput of the WLANs is determined under Bianchi optimal and proposed centralized algorithm configurations of WLANs. The total throughput has been found to be 9.013 Mbps at Bianchi optimal CW while the total throughput at centralized algorithm is 9.011 Mbps for network 1. Thus, the throughput lost is not significant to provide the max-min throughput fairness among the users with the centralized algorithm.

The throughput of each user of the right hand side WLAN of the center WLAN for another WLAN scenario shown in Fig. 4.2 is determined under the three types of configuration of CW of the nodes. The throughput of the users of the right hand side WLAN of the center WLAN is shown in Fig. 6.3. The maximum and the minimum throughputs of the users of right hand side WLAN are found to be 0.122 Mbps and 0.118 Mbps when the centralized algorithm is used. The total throughputs under Bianchi optimal CW and the centralized algorithm are 8.350 Mbps and 8.340 Mbps, respectively. Thus, the results demonstrate that the centralized algorithm is very effective to provide throughput fairness among the users without losing total throughput considerably.

6.3 Summary

In this chapter, a centralized algorithm has been proposed based on an analytical formulation to mitigate the throughput unfairness problem in WLANs. The performance of the algorithm is evaluated through simulation by configuring the CW parameters of the nodes under the centralized algorithm. It is found that the algorithm is very effective to mitigate the throughput unfairness problem among the users.

CHAPTER 7
DISTRIDUTED ALGORITH TO MITIGTE THE THROUGHPUT UNFAIRNESS PROBLEM

In previous Chapter 6, a centralized algorithm has been proposed based on analytical formulation. The centralized algorithm is not practical due to the complexity of the algorithm. Huge amount of overheads need to be transmitted to implement the centralized algorithm. As results, in this chapter, a heuristic is developed based on the results of the centralized algorithm and a distributed algorithm is proposed to mitigate the throughput unfairness problem. The performance of the distributed algorithm is evaluated by simulation.

7.1 Development of Heuristic

From the results of Chapter 6, it is clear that the minimum CW of a node need to be increased (decreased) if its throughput is higher (lower) than the max-min throughput. As a result, it is conjectured that a good approximation for the minimum CW of node *i* would be of the type:

$$CW_{\min}^{i} = CW_B \frac{\lambda_i}{\lambda_{avg}^{i}} \tag{7.1}$$

where CW_B is the Bianchi optimal CW of the WLAN of node i, λ_{avg}^{i} is the average throughput of the nodes in the WLAN of node *i* and λ_i is the throughput of user *i*. The conjecture can be validated by comparing the heuristic values of CW_{min}*'s* determined using equation (7.1) for the throughputs given by Bianchi optimal setting of the minimum CWs of the nodes (i.e., by using the throughputs obtained by simulation for configuring the CW of the nodes to Bianchi optimal CW) with the values of CW_{min}*'s* obtained by our centralized algorithm. The heuristic values and the values of the centralized algorithm of CW_{min}*'s* are shown in Fig. 7.1 for two WLANs of the network scenario-1 of Fig. 4.1 (the x-axis represents the node index), where the node indexes 1 to 11 are for the center WLAN and the node indexes 12 to 18 are for the WLAN located at the left side of the center WLAN. Although some variations are found between the heuristic values and the values of the centralized algorithm for the center WLAN, the trends of increment or decrement of the values of the CWs are similar. For the WLAN left side to the center WLAN, these variations are negligible. The similar results for the other WLANs of the network scenario-1 have been plotted and found negligible variations between the heuristic values and the values of the centralized algorithm. These results are surprisingly good. In the following, a simple distributed algorithm is described based on this heuristic.

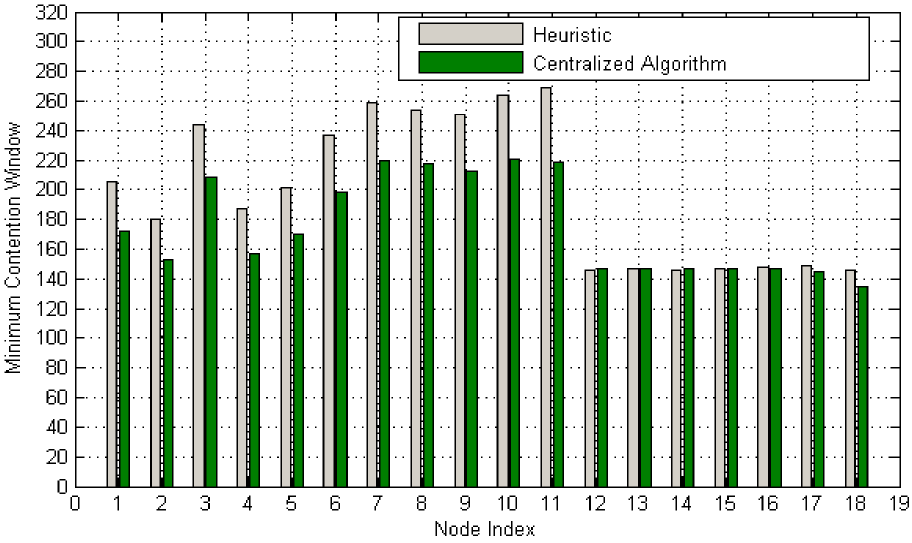

Fig. 7.1 Heuristic and centralized contention windows for two WLANs of the network scenario-1.

7.2 Distributed Algorithm

In this algorithm, each node updates the value of its minimum CW at a time interval Δt. For the time interval t to $t + \Delta t$, let the minimum CW and the throughput of node i are $CW_{\min}^{i}(t)$ and $\lambda_i(t)$, respectively. Let the average throughput of the nodes of the WLAN of node i is $\lambda_{avg}^{i}(t)$ for the time interval t to $t + \Delta t$. At the starting of time $t + \Delta t$, the AP of node *i* calculates the value of $\lambda^i_{avg}(t)$ from the received data during the time interval *t* to $t + \Delta t$ and then broadcast to the nodes of the WLAN. Each node *i* then compute the value of $CW^i_{\min}(t+\Delta t)$ in a distributed manner using the following relation:

$$CW^i_{min}(t + \Delta t) = CW^i_{min}(t)\frac{\lambda_i(t)}{\lambda^i_{avg}(t)} \tag{7.2}$$

Note that the values of $\lambda_i(t)$ and $CW^i_{min}(t)$ are known to node *i*. At time t= 0, it is assumed that λ_i (t) =$\lambda^i_{avg}(t)$ and $CW^i_{min}(t) = CW_B$ for each node *i*.

7.3 Effectiveness of the Proposed Distributed Algorithm

The network in Fig. 4.1 is simulated using the distributed algorithm with Δt =100 s at P_t= -15 dBm and CST= -92 dBm and throughputs of the nodes of the different WLANs are determined at different time interval. In Fig.7.2 shows the throughput of nodes of the center WLAN at different time. Clearly, the distributed algorithm tries to provide equal throughput to the nodes. The long run average throughputs of the nodes are computed at the end of simulation. The throughputs of nodes of the center WLAN is shown in Fig.7.4 under three types of configuration. The maximum and the minimum throughput of the users of the center WLAN are found to be 0.145 Mbps and 0.144 Mbps, respectively for the distributed algorithm. The total throughputs are found that 9.004 Mbps and 9.013 Mbps under distributed algorithm and Bianchi optimal CW, respectively. Thus, the total throughput loss is negligible to provide max-min throughput fairness among the users with the distributed algorithm.

The similar simulation is performed for the other network scenario shown in Fig 4.2. In Fig. 7.3, shows the throughput of the nodes of the right hand WLAN of the centre WLAN at different time. From the figure, it is also clear that the distributed algorithm tries to provide equal throughput to the nodes. The maximum and the minimum throughput of the users of the right hand side WLAN of the centre WLAN are found to be 0.122 Mbps and 0.120 Mbps, respectively for the distributed algorithm. The total throughputs are found that 8.337 Mbps and 8.350 Mbps under distributed algorithm and Bianchi optimal CW, respectively. So the distributed algorithm is also very effective to solve the throughput unfairness problem.

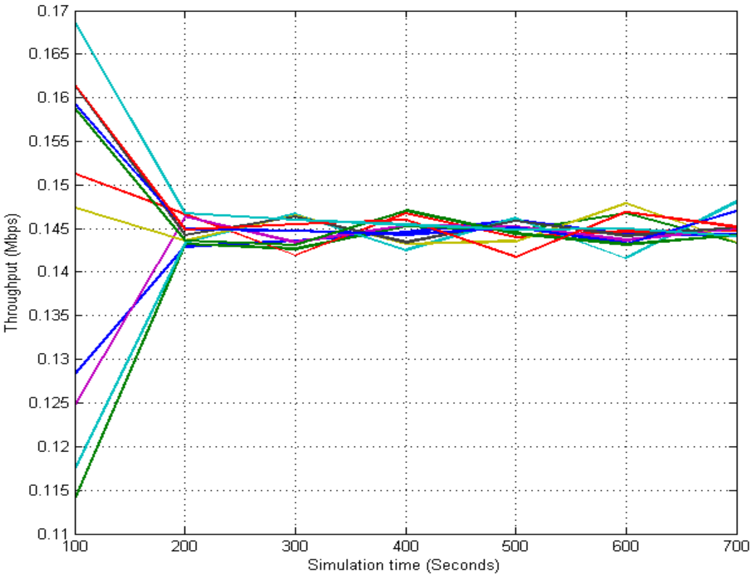

Fig. 7.2 Variation of throughput of each users of the center WLAN (WLAN scenario-1).

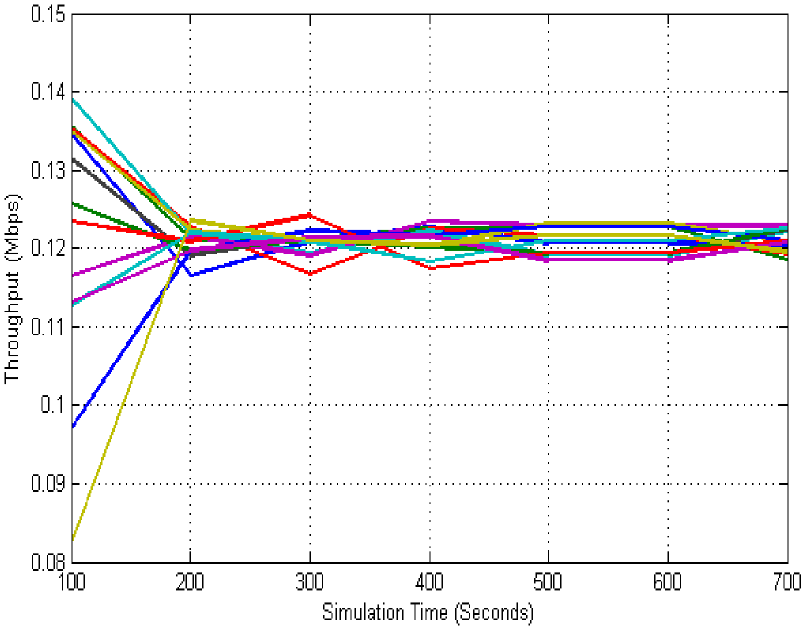

Fig. 7. 3 Variation of throughput of each users of the right hand WLAN of the center WLAN (WLAN scenario-2).

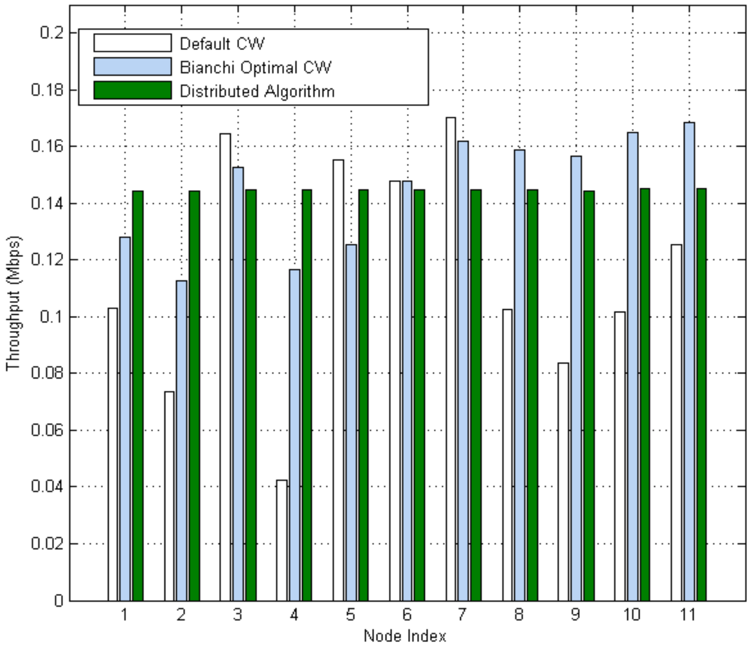

Fig.7.4 Throughput of each user under different algorithms of the center WLAN of network scenario-1.

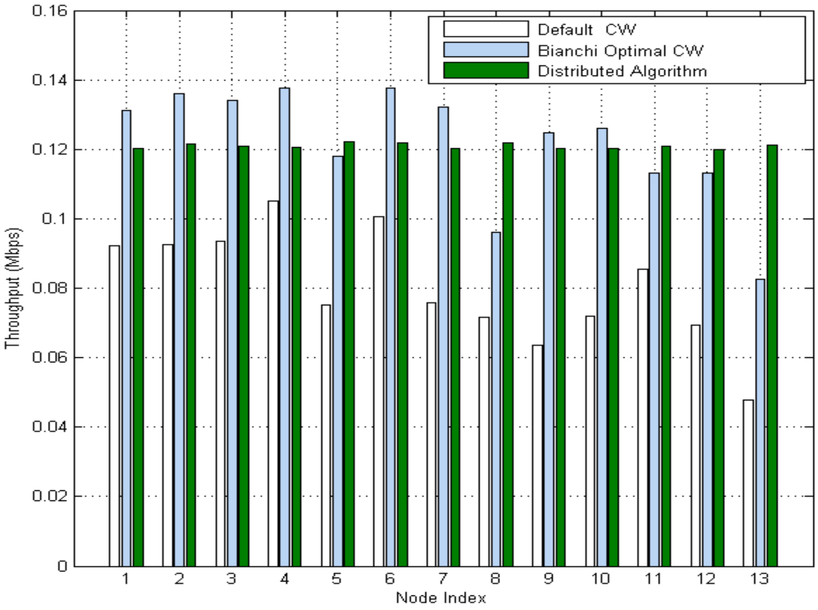

Fig.7.5 Throughput of each user under different algorithms of right hand side WLAN of the center WLAN of network scenario-2.

Table.7.1: Comparison of the of total throughput of the different algorithms.

Network	λ_B (Mbps)	λ_c (Mbps)	λ_D (Mbps)	$\frac{\lambda_B - \lambda_C}{\lambda_B} \times 100$	$\frac{\lambda_B - \lambda_D}{\lambda_B} \times 100$
1	9.013	9.011	9.004	0.022%	0.099%
2	8.350	8.340	8.337	0.119%	0.155%

The total throughputs of the different algorithms are compared in Table.7.1, where λ_B is the total Bianchi optimal throughput, λ_C is the total throughput for the centralized algorithm and λ_D is the total throughput for the distributed algorithm. The results show that the decrement in total throughput under distribted algorithm is less than 1%. The comparison of the throughputs of the centralized and distributed algorithms are shown in Fig.7.6 and Fig.7.7. The results show that the distributed algorithm provides more fairness than the centralized algorithm. However, the total throughput under distributed algorithm is little bit less than that of the centralized algorithm.

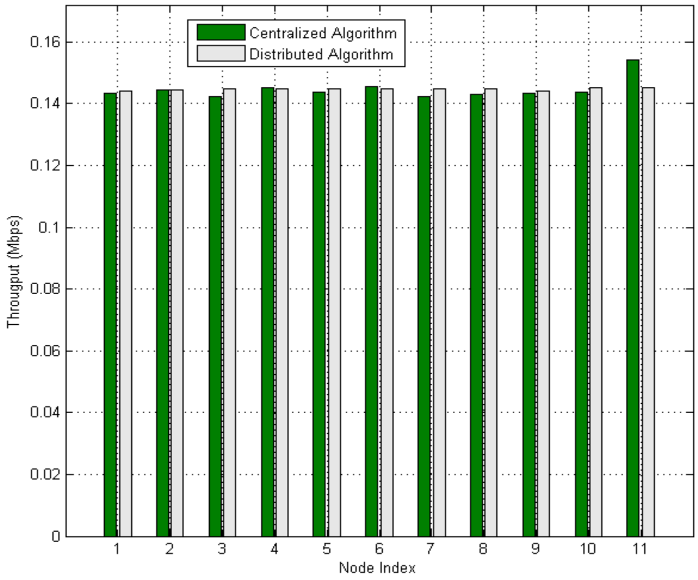

Fig. 7.6 Comparison of throughput of the users under different algorithms of the center WLAN of network scenario-1.

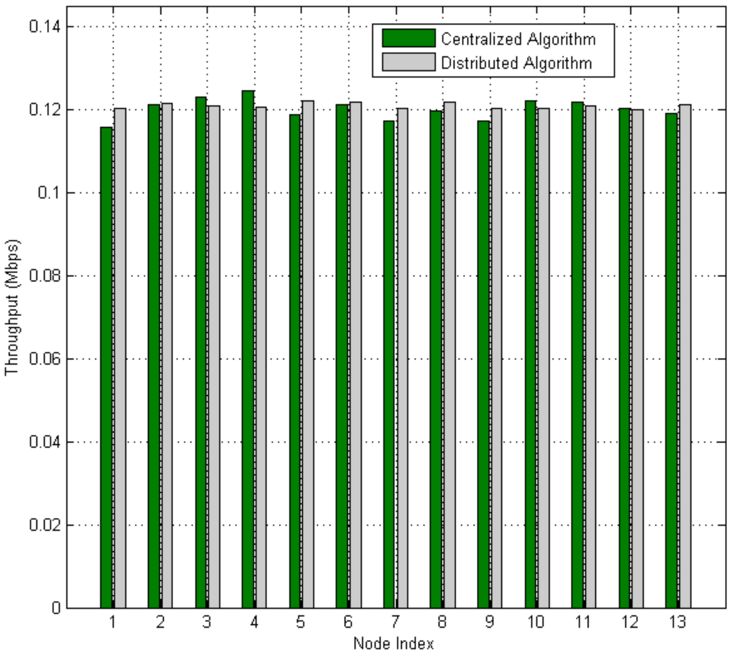

Fig. 7.7 Comparison of throughput of the users under different algorithms of the right hand side WLAN of the center WLAN of network scenario-2.

7.4 Summary

In this chapter, a simple distributed algorithm has been proposed to mitigate the throughput unfairness problem. The simulation results show that the distributed algorithm is very effective to solve the unfairness problem among the users.

CHAPTER 8

CONCULUSION

8.1 Conclusion of the Work

In this thesis, the impact of co-channel interference on throughput performance in WLANs has been studied. Basic CSMA/CA MAC protocol and physical interference model have been considered for the study. From the simulation result, it investigated that throughput unfairness among the users is severe due to asymmetric co-channel interference. To mitigate the throughput unfairness problem, a centralized algorithm has been proposed based on an analytical formulation. Also a heuristic has been developed based on the results of the centralized algorithm. A simple distributed algorithm has been proposed based on the developed heuristic to solve the unfairness problem by configuring the minimum CW of the users. The performance of the both algorithms is evaluated by simulation and found to be very effective.

8.2 Scope for the Future Work

There are several future research scopes related to this thesis. A study on the impact of co-channel interference on high speed WLANs such as IEEE 802.11n need to be carried out. Further, the unfairness problem and the impact of co-channel interference in a multi-rate system need to be investigated. The impact of the adjacent channel interference on throughput performance in WLANs can also be focused to carry out future research.

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