Channel Band Adaptation in Wireless Networks

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To my parents for their love, support and encouragement

To my wife and son for suffering a lot, while i was pursuing my dreams

and

To Dr. Nazar Abbas for being a wonderful advisor

Declaration

I, hereby declare that, this dissertation constituted of my own work and to the best of my knowledge, it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST-SEECS or at any other educational institute, except where due acknowledgement has been made in the dissertation. Any contribution made to the research by others, with whom I have worked at NUST-SEECS or elsewhere, is explicitly acknowledged in the dissertation. I also declare that the intellectual content of this dissertation is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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My Lord, Increase me in knowledge. "Al-Quran Surah Ta-ha (20:114)".

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Abstract

During the last fifteen years, 802.11 Wireless Local Area Networks (WLANs) have emerged as one of the most accepted method of computer networking. Majority of current WLANs such as 802.11 b/g/n operate in 2.4 GHz unlicensed Industrial, scientific and Medical (ISM) frequency spectrum and share the available spectrum resource with large number of electronic appliances including bluetooth, cordless phones, microwave ovens and many others. This wide spread use of ISM band has resulted into its saturation and WLANs operating in this spectrum block are now facing a serious threat of spectrum scarcity. The situation becomes even worse due to inefficient frequency management protocols deployed in conventional WLANs. The primary source of this spectral inefficiency is rooted in static width channelization used in majority of WLANs. Modern wireless networks fine tune several communication parameters such as transmission rate, modulation and central frequency in response to ambient conditions like Signal to Interference and Noise Ratio (SINR), Bit Error Rate (BER) and Signal Strength (SS) values. However, the width of communication channel remains static throughout the course of transmission, disregarding any change in communication conditions. This static behavior may potentially cause under-utilization of spectrum resource and hence results in sub-optimal network performance. Moreover, spectrum sharing protocols in WLANs are context unaware and use standard operating procedures for communication without considering the perspective of communication.

This research work aims to present a detailed theoretical analysis and rigorous experimentation in order to investigate the use of adaptable width channelization in WLANs. The elementary concept of proposed mechanism is to assign spectrum resource to any transmitting node based on its current bandwidth requirements and ambient conditions such as SINR. The proposed mechanism assigns channels with high level of granularity and maximizes spectrum utilization by efficiently managing the width of communication channel. This high percentage of spectrum utilization in turns, substantially increases the overall network capacity. For accurate quantification of performance benefits achievable through adaptable width channelization, we have implemented the proposed mechanism on real testbed of configurable software defined radios. Using this testbed, the impact of adaptable width

channelization on exhaustive list of essential network performance measuring parameters has been evaluated. These parameters include spectrum utilization, throughput, interference, delay spread, Bit Error Rate (BER), transmission range, power consumption, transmission delay, mitigation of Medium Access Control (MAC) layer performance anomaly, channel access fairness and implementation of Quality of Service (QoS).

It is observed that, use of adaptable channelization technique can tackle many performance limiting factors in current WLANs. For instance, if required throughput is low, switching to a narrower channel width simultaneously increases range and decreases power consumption, while both of these are conflicting quantities in traditional WLANs. Similarly SS values at relatively longer distances improve significantly at narrower channel widths while simultaneously decreasing BER. The achieved results depict considerable increase in network wide throughput and decrease in interference among communicating nodes. Moreover, the use of adaptable channelization can also minimize the effect of MAC layer performance anomaly. This anomaly arises when two nodes with variable transmission rates have equal channel access probability. Additionally, using communication channels of adaptable width, we can also implement QoS in WLANs. This can be achieved by providing variable width channels to nodes based on their QoS class.

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Chapter 1

Introduction

The advent of wireless/mobile communication systems has revolutionized the way people communicate by joining together the communications and mobility. Wireless communication is now characterized by remarkable achievements made in significantly short span of time. The evolution of wireless access technologies is about to reach its fifth generation. While looking past, these technologies have followed different evolutionary paths aimed at unified target: performance and efficiency in highly mobile environments. The first generation targeted the transmission of voice through a wireless medium while the aim of second generation was to introduce enhancement in capacity and coverage. The quest in third generation was to transmit data at higher speeds to achieve a true experience of mobile broadband. The fourth generation is aimed to provide a wide range of telecommunication services. These include advanced mobile services supported by mobile and fixed networks which are increasingly packet based along with a support for low to high mobility applications and wide range of data rates. The primary target for development of these applications is to create an environment in accordance with service demands in multiuser environment.

The remarkable achievements made in wireless technologies have shifted the whole paradigm of computer networking. Majority of enterprises now prefer wireless networks over its wired counterpart due to cost effectiveness, mobility and minimal infrastructure requirements. According to a market survey, approximately two billion Wi-Fi[1] supported devices were sold worldwide in year 2014 [55]. This huge number is increasing rapidly with the swift evolution of mobile operating systems such as iOS and Andriod. These operating systems are rich in media centric applications which assert stringent bounds on network performance. In order to meet the challenge of performance requirements, several modifications to IEEE 802.11 physical and MAC specifications have been proposed. These amendments have led to the advent of high speed WLANs such as 802.11/n [2] and 802.11/ac [3] supporting several Mbps of raw transmission rates. However, this high data rate support still needs substantial improvement to meet the challenge of ever increasing demand for higher network capacity.

Few years ago, Wi-Fi networks were deployed for few users per Access Point (AP) scenarios. The emergence of small hand held devices such as smart phones, Personal Digital Assistant (PDA) devices and tablets has substantially increased the number and diversity of users connected simultaneously to same AP. Moreover, the concept of bring your own device [6] on public and enterprise networks has completely changed the concept of wireless communication. A large number of users at public places such as shopping malls, airports, train stations and stadiums use public hot-spots for communication. This large and diverse user base has exhaustively tested the efficiency of networking protocols used in WLANs. Delivering sustained connectivity and user experience to this highly diverse user base is a challenging task. The dense and diverse population of Wi-Fi devices has compelled network design engineers to optimize parameters such as capacity, coverage and spectrum utilization,

[1]Throughout this thesis the terms Wi-Fi and Wireless Local Area Networks (WLANs) are used interchangeably and essentially means the same type of wireless networks defined by IEEE 802.11 standard [1]

which were more or less irrelevant some years ago. In today's and future wireless networks, the most desired goal will probably be increased network capacity, minimal interference among communicating nodes and optimal spectrum utilization.

The rapid advancements in consumer electronics and deployment of large scale enterprise wireless networks necessitates the use of resource agile protocols that can optimally use available network assets. The simplified design of conventional Wi-Fi networks as of 802.11/g [1] and its static channelization is not flexible enough to cope with the above described complex communication scenarios [15][35]. The scarcity of unlicensed ISM wireless spectrum, used by Wi-Fi networks and further sharing of this spectrum with other electronic appliances make a strong case to effectively utilize the frequency resource. However, static width channels [1] used for the communication of Wi-Fi networks have led to the waste of this precious resource [34][35][54].

Majority of current wireless networking protocols adjust several communication parameters according to ambient conditions. However, Wi-Fi networks keep width of the transmission channel static, throughout the communication irrespective of environmental conditions. Some of the current Wi-Fi standards such as 802.11/n and 802.11/ac adds channel width flexibility through channel bonding [58]. However, channel bonding increases/decreases channel widths quite steeply with a factor of 20 MHz and does not serve the purpose of effective spectrum utilization. Moreover, channel bonding also increases interference among nodes due to overlapping of carrier frequencies in multiple channels [19]. Additionally the high per unit area density of wireless clients require more number of APs in close vicinity to provide sustainable wireless connectivity. The benefit of deploying more number of APs per unit area is manifold. These include more number of collision domains resulting in less average channel access time, higher SS values, higher network capacity and better network coverage. However, by increasing number of APs in a small area also increases channel interference due to overlapping of transmission frequencies.

The use of static channelization in Wi-Fi networks causes under-utilization of spectrum resources in several cases. To explain this claim, let us consider a network of three APs in close vicinity that are in interference range of each other. Different number of users are associated with these APs resulting in different throughput requirements of each AP. Assume that, throughput requirements are 10 Mbps, 20 Mbps and 30 Mbps for AP 1, 2 and 3 respectively. According to normal static channel assignment scheme, all of these APs communicate over same channel widths. It is a well known fact that throughput is directly proportional to channel width [59]. In this case, AP 1 is under-utilizing its spectrum share while AP 3 is starving. This phenomenon substantially decreases the efficiency of a wireless network. Therefore, considering the above explained facts, it is highly desired that physical layer protocols of spectrum utilization in Wi-Fi networks should be re-evaluated and new protocols and standards must be implemented to ensure maximum utilization of available frequency resource.

This dissertation intends to propose novel techniques that can significantly improve the utilization of radio spectrum resource by implementing adaptable width channelization in WLANs. This improved spectrum utilization in turns, improves network capacity and decreases interference among nodes. Proposed techniques have been evaluated on exhaustive list of essential network performance parameters. We propose dynamic spectrum sharing algorithms that assign channels of different widths based on environmental conditions and/or throughput requirements of an AP. The effect of proposed algorithms on parameters such as network capacity, throughput, spectrum utilization, interference management, BER, delay spread, transmission range and power consumption has been evaluated through detailed analytical measurements and experimentation that has been conducted on real test-bed.

1.1 Thesis Statement

"The use of adaptable width channelization in 802.11 WLANs can substantially increase the spectrum utilization and overall network capacity while simultaneously reducing channel interference. Secondly, adaptable channelization can also be used to minimize the effect of MAC layer performance anomaly. This anomaly arises when both slow and fast transmitting nodes have equal channel access probability. In addition, adaptable width channelization can also be used as an effective method for QoS implementation."

1.2 Motivation

The use of wireless networks for communication is increasing exponentially due to its convenience and cost effectiveness. Deployment of wireless networks worldwide on a large scale has inspired the researchers to enhance the efficiency of these networks by fine tuning the fundamental performance matrices. These matrices include modulations, channel coding, access mechanisms, data compression and many others. However, rapid increase of wireless communication is adversely affected by the lack of physical resources, wireless spectrum and electrical energy. Majority of today's wireless networking protocols fine tune several communication parameters according to ambient conditions. However, Wi-Fi networks keep width of the transmission channel static throughout the communication irrespective of environmental conditions. This static channelization is a potential cause of spectrum under-utilization in several cases. Therefore, it is highly required that physical layer protocols of spectrum utilization in Wi-Fi networks should be re-evaluated and new protocols and standards must be implemented to ensure maximum utilization of available frequency spectrum.

The width of communication channel affects a number of network parameters including but not limited to throughput, interference, transmission range and power consumption. This substantial impact of channel width inspired us to explore implementation of adaptable channel width assignment in WLANs. The motivation behind this research work is to effectively manage the available wireless spectrum with high level of granularity thus optimally maximizing its utilization. This optimality of spectrum use can be achieved by implementing adaptable width channels pertaining to ambient conditions. During the course of this analysis, we discovered that adaptable width channel assignment has a capability of QoS implementation and mitigation of MAC layer performance anomaly. The above given preeminent advantages of adaptable width channelization in delivering solutions to various performance limiting factors motivated us to conduct a thorough study of these techniques.

1.3 Thesis Contribution

This dissertation aims at achieving three objectives. The first goal is the exploration of performance benefits of deploying adaptable width channelization in WLANs. The second objective is to mitigate the effect of MAC layer performance anomaly of contention based channel access mechanism deployed in conventional multi-rate WLANs. The third objective aims at implementation of QoS in WLANs by employing adaptable width channelization,

To achieve objective one, we first theoretically model the throughput and channel interference of adaptable width channels in 802.11/g WLANs. This theoretical analysis is based on SINR model proposed in [59]. To augment the accuracy of proposed model, it has been rigorously tested through empirical analysis by implementing adaptable width channels on commercially available configurable software defined radio devices. This empirical evaluation is made on an exhaustive list of parameters that define the overall efficiency of wireless networks. These parameters include throughput, network capacity, spectrum utilization, interference management, BER, delay spread, transmission range and power consumption.

To achieve second objective, we have statistically modeled a network comprising of nodes that transmit on variable data rates. This statistical model is extended to mitigate the effect of MAC layer performance anomaly by using SINR model on proposed adaptable width channel assignment. The fundamental idea of mitigating the performance anomaly involves the diversion of surplus spectrum from one cell[2] to another cell. This diversion of spectrum resource is based on the difference of transmission rates of nodes in both the cells. To clarify this approach, let us assume that a node in one cell is transmitting below a threshold transmission rate. This transmission rate is achievable by using a channel of specific width. Then the leftover spectrum will be assigned to a node transmitting at higher transmission rate in another cell.

[2] A Wi-Fi cell is constituted of an area in which all wireless nodes are serviced through a single access point

To achieve objective three, we have modeled a network comprising of a set of nodes which are running throughput sensitive applications such as multimedia streaming and Voice over IP (VoIP). The idea is to implement QoS to this set of nodes by intelligently managing the spectrum resources that guarantee a minimum transmission rate/throughput to these nodes while simultaneously maintaining the fair channel access to all nodes. The proposed analytical model is verified by a set of experiments on test-bed of configurable software defined radio devices. These experiments have been conducted to investigate the effect of dynamic width channels on QoS defining parameters such as throughput, admission control, bandwidth reservation, delay and delay variations.

1.4 Thesis Organization

The remaining part of this dissertation is organized as follows,

Chapter 2 provides the details of radio frequency channelization in current 802.11 WLANs and inefficiencies associated with static width channelization. We have implemented various 802.11 network configuration using off-the-shelf hardware and explored the inefficiencies resulted due to fixed width channels. The explored parameters include transmission rate, interference, BER, transmission range and power consumption.

Chapter 3 presents the literature review of various solution techniques proposed to minimize the effect of performance limitations caused by static width channelization in WLANs. The principal focus in this chapter is to, thoroughly explore the use of flexible channel assignment and channel bonding techniques proposed in literature with their advantages and drawbacks.

Chapter 4 comprehensively describes the proposed channel width adaptation mechanism in WLANs. It gives details of performance benefits that can be achieved by employing channels of adaptable width in different network scenarios. This chapter also presents analytical model and empirical results for extensive list of parameters that define performance of a WLAN. These parameters include spectrum utilization, throughput, network capacity, co-channel interference, BER, delay spread, transmission range and power consumption. A detailed discussion on empirical results is also given in this chapter.

Chapter 5 briefly discusses the MAC layer channel access mechanism and explains how long term fairness causes performance anomaly in WLANs? It also provides proposed method for mitigation of MAC layer performance anomaly of 802.11 networks using adaptable width channelization. In this chapter, we have evaluated the performance of proposed anomaly mitigation technique analytically and empirically in terms of channel occupancy time, average network wide throughput of slow and fast nodes and channel access fairness.

Chapter 6 presents a brief overview of QoS provisioning techniques reported in literature and our proposed mechanism of QoS provisioning in WLANs using adaptable width channelization. In this chapter analytical and experimental evaluation of proposed mechanism in terms of normalized throughput, channel access delay, BER, admission control and channels access fairness among high and low priority nodes has been presented.

Chapter 7 enlists the key conclusions and future directions of this research work.

Chapter 2

Characteristic Properties of Channel Width in 802.11 WLANs

802.11 and 802.11x refers to a family of physical and medium access control (MAC) layer specifications ratified by Institute of Electrical and Electronics Engineers (IEEE). 802.11 specifies an over-the-air interface between a wireless client and an AP in an infrastructure mode and between two wireless clients in an ad-hoc mode. The acceptance of 802.11 WLANs as one of the dominant communication mechanism is made possible by its rapid evolution starting from early conception of idea in 1997. The major advancement seen through this evolution is enhancement of data rate from maximum of 2 Mbps in 802.11-1997(Legacy) to 433.3 Mbps in 802.11/ac proposed in 2013. A large number of modifications in communication factors such as modulations, channel coding, access mechanisms and error correction techniques have also been proposed in recent 802.11 standards. However, the wide spread use of bandwidth hungry applications such as video conferencing, high definition video streaming and online gaming still requires a huge increase in network capacity. Therefore, it is required that available network resources must be used optimally to achieve ever increasing requirement for higher throughput.

In this chapter, we have given a brief comparison of various 802.11 WLAN standards and their transmission properties. Moreover, an explanation of current frequency channelization and associated inefficiencies that lead to sub-optimal network performance are also presented.

The inefficacy of said channelization has been explored in terms of various network performance measuring parameters. We have conducted a series of experiments using off the shelf hardware to analyze performance limitations of current static width channelization deployed in conventional 802.11 networks and analyzed the achieved results. This analysis will help us in building the case for use of adaptable width channelization in WLANs for effective use of scarce network resources in an efficient way.

2.1 802.11 WLAN Standards

A large number of 802.11 standards have been reported and subsequently been ratified by IEEE. The prominent specifications adopted by major manufacturers of WLAN equipment include 802.11 in 1997, 802.11/b in 1999, 802.11/a also in 1999, 802.11/g in 2003, 802.11/n in 2009 and 802.11/ac in 2013. The comparison of various 802.11 networks in terms of operational frequency, channel bandwidth, supported physical layer data rates, frequency modulation techniques and transmission range is given in table 2.1. It is relevant to mention here that, all the experiments in this research study have been conducted on networks complying 802.11/g physical and MAC layer specification ratified in 2003 and further enhanced in 2007 [1]. Hence, in this dissertation the term 802.11 network denotes 802.11/g network unless specified otherwise.

2.2 Frequency Spectrum and Channelization in 802.11 Networks

Current Wi-Fi networks operate on two unlicensed spectrum blocks for their communications. These blocks consist of 2.4 GHz and 5 GHz frequency ranges. This dissertation is targeted to 2.4 GHz spectrum block used by majority of 802.11 WLANs like 802.11 b/g/n. Hence, in this thesis the term spectrum block means 2.4 GHz frequency spectrum. However, we are self-assured that the proposed model is also applicable to 5 GHz frequency range with very few modifications. The 2.4 GHz unlicensed frequency spectrum block is com-

Table 2.1: Comparison of 802.11 WLAN Standards

802.11 Standard	Release Date	Frequency (GHz)	Channel Bandwidth (MHz)	Supported Data Rates (Mbps)	Modulation	MIMO Support	Approximate Range (Meters)	
							Indoor	Outdoor
802.11 (Legacy)	Jun-97	2.4	22	1, 2	DSSS, FHSS	No	20	100
802.11a	Sep-99	5	22	6, 9, 12, 18, 24, 36, 48, 54	OFDM	No	35	120
		3.7					-	-
802.11b	Sep-99	2.4	22	1, 2, 5.5, 11	DSSS	No	35	140
802.11g	Jun-03	2.4	22	6, 9, 12, 18, 24, 36, 48, 54	OFDM	No	35	140
802.11n	Oct-09	2.4	20	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2	MIMO-OFDM	Yes 4 MIMO Streams	70	250
		5	40	15, 30, 45, 60, 90, 120, 135, 150			70	250
802.11ac	Dec-13	5	20	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2, 86.7, 96.3	MIMO-OFDM	Yes 8 MIMO Streams	35	-
			40	15, 30, 45, 60, 90, 120, 135, 150, 180, 200			35	-
			80	32.5, 65, 97.5, 130, 195, 260, 292.5, 325, 390, 433.3			35	-
			160	65, 130, 195, 260, 390, 520, 585, 650, 780, 866.7			35	-

monly known as industrial, scientific and medical (ISM) band. The total available spectrum width in this frequency block is 84 MHz between 2.400 GHz and 2.484 GHz. The total available spectrum in traditional Wi-Fi networks like 802.11/g is divided into 14 channels of 22 MHz [1]. Each frequency channel is separated from its neighboring channel(s) with a guard band of 5 MHz. This guard band provides a cushion for minimization of Co-Channel Interference (CCI). The close packing of 22 MHz channels and guard bands of 5 MHz in limited 84 MHz spectrum block results in overlap of carrier frequencies in multiple channels. Therefore, signals on adjacent channels interfere with each other. Figure 2.1 explains the division of wireless spectrum into overlapping and non overlapping channels and their central frequencies. Across the globe, the available 14 channels are used dissimilarly. For example,

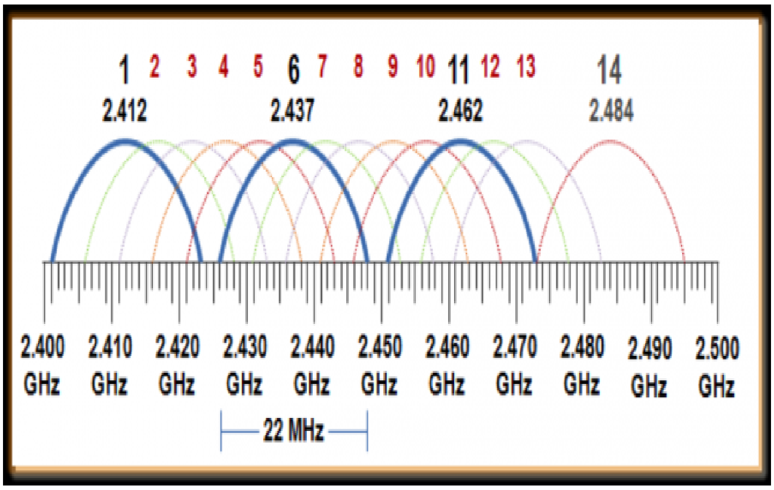


Figure 2.1: 802.11 Channels and their Central Frequencies

in United States, 11 channels are used due to channel interference problems. On the other hand, all 14 channels are used in Japan. In this dissertation, we have discussed the use of 11 channels. 3 out of these channels (1, 6 and 11) are non-overlapping with each other and have minimum CCI. Remaining 8 channels have overlapping sub-carrier frequencies and thus have high values of CCI. Wireless nodes communicate with APs by using one of the non overlapping channels. If more than one and up-to three APs are deployed in close vicinity, that are in interference range of each other, then each AP is configured to use different non overlapping channel. If number of APs are more than 3, then these non-overlapping channels are reused. This reusing of channels also increases interference, if APs are in interference range of each other.

2.3 Properties of Static Width Channels

In this section, we have explain some of the fundamental properties of static width channels in 802.11 WLANs. These properties include data rate, throughput, medium (spectrum) utilization, interference, power consumption and transmission range. The description of these properties will help us in identification of various performance bottlenecks caused by the use of static width channelization.

2.3.1 Data Rate

802.11/g WLANs operate in 2.4 GHz frequency band and use Orthogonal Frequency Division Multiplexing (OFDM) based transmission scheme. The maximum achievable physical layer data rate is 54 Mbps, exclusive of Forward Error Correction (FEC) codes. 802.11/g WLANs support multiple data rates of 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps and 54 Mbps. These data rates are selected automatically by 802.11 hardware based on ambient conditions and bit error/packet drop rates. Each 802.11/g node calculates the Packet Drop Ratio (PDR) and SS values over a specific amount of time and adjusts its transmission rate accordingly. The higher PDR and lower SS values result in lower transmission rate and vice versa. The rate adaptive algorithm uses Adaptive Modulation and Coding (AMC) to adjust a specific transmission rate. In AMC, modulation determines the number of bits per symbol where as coding specifies the amount of FEC bits per data symbol. Figure 2.2 presented in [27] shows the Modulations and Coding Schemes (MCS) of WLANs at different values of Signal to Noise Ratio (SNR). All the 802.11 networks operating in same frequency spectrum are backward compatible to support legacy hardware. This backward compatibility is obligatory for ratification of standard by IEEE. Moreover it also avoids the mandatory depletion of legacy hardware. However, the backward compatibility may cause poor performance of high data rate WLANs. For instance, if 802.11/g and 802.11/b clients are operating in same network, the over all capacity of the network degrades substantially. Since

Protocol	Channel	1	2	3	4	5	6	7	8	9	10
802.11b	20MHz	None	None	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1	MCS 1
802.11a/g	20MHz	None	MCS 0	MCS 0	MCS 1	MCS 2	MCS 2	MCS 2	MCS 2	MCS 3	MCS 3
802.11n	20MHz	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1	MCS 1	MCS 2	MCS 2
802.11n	40MHz	None	None	None	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1
802.11ac	20MHz	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1	MCS 1	MCS 2	MCS 2
802.11ac	40MHz	None	None	None	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1
802.11ac	80MHz	None	None	None	None	None	None	None	MCS 0	MCS 0	MCS 0
802.11ac	160MHz	None	None	None	None	None	None	None	None	None	None
	SNR in dB	11	12	13	14	15	16	17	18	19	20
802.11b	20MHz	MCS 2	MCS 2	MCS 2	MCS 2	MCS 2	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3
802.11a/g	20MHz	MCS 4	MCS 4	MCS 4	MCS 4	MCS 5	MCS 5	MCS 5	MCS 6	MCS 6	MCS 7
802.11n	20MHz	MCS 3	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4	MCS 5	MCS 5	MCS 6
802.11n	40MHz	MCS 1	MCS 2	MCS 2	MCS 3	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4
802.11ac	20MHz	MCS 3	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4	MCS 5	MCS 5	MCS 6
802.11ac	40MHz	MCS 1	MCS 2	MCS 2	MCS 3	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4
802.11ac	80MHz	MCS 1	MCS 1	MCS 1	MCS 1	MCS 2	MCS 2	MCS 3	MCS 3	MCS 3	MCS 3
802.11ac	160MHz	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1	MCS 1	MCS 2	MCS 2	MCS 3

Modulation Key
None = Grey
BPSK = Red
QPSK = Orange
16-QAM = Yellow
64-QAM = Blue
256-QAM = Green

802.11 Type Key
802.11b
802.11ag
802.11n
802.11ac

Figure 2.2: 802.11 MCS at Different SNR Values

a client having 802.11/b radio can achieve maximum data rate of 11 Mbps, which causes longer time to transmit a data frame as compared to a client with 802.11/g radio. In order solve the problem of this low network capacity, 802.11/g networks use protection mechanism [62], that restricts the transmission of 802.11/b clients. In this mechanism the transmission flow of 802.11/g is given high priority as compared to 802.11/b flow. However, this restricted access to transmission medium causes further degradation of individual performance of 802.11/b clients.

2.3.2 Throughput

The support for several transmission rate through adaptive MCS results in variable throughputs of wireless clients. The effective throughput of any client is a function of several communication factors among which transmission rate, packet drop ratio, channel width, MAC layer delay, channel occupancy time, number of contending nodes and distance between sender and receiver are of notable importance. The typical achieved throughput values for 802.11 a/b/g/n under ideal channel conditions and controlled environment have been shown in Figure 2.3. These values have been collected for multiple senders/receivers communicating through an AP in lab environment with almost no interference from other devices. The results given in Figure 2.3 shows that channel width has a direct relation with

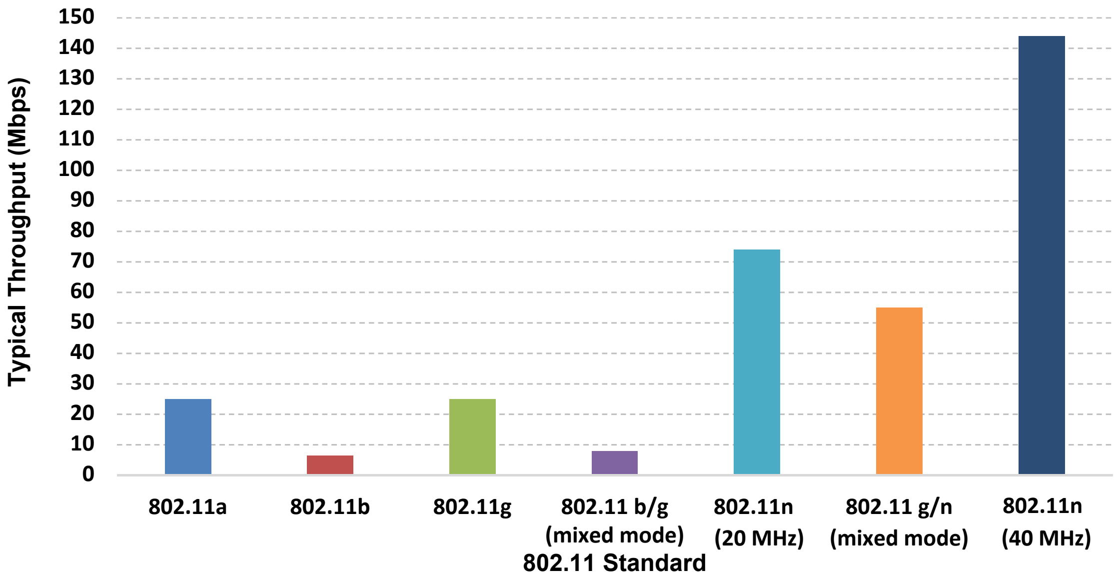


Figure 2.3: Typical Throughput Values for Different 802.11 Networks

achieved throughput. The 802.11/n node operating at 40 MHz channel width has almost twice the throughput as compared to a channel width of 20 MHz with same MCS. As described earlier it is an obligatory requirement for 802.11 standards to support legacy specifications. This support significantly decreases the achievable throughput of high data rate WLANs like 802.11/n. This inference is visible in case of 802.11 b/g mixed mode results. This analysis is also applicable for co-existence of 802.11 g/n nodes in the same network.

Since current WLAN settlements use channels of fixed widths (20, 40, 80 and 160 MHz), it enforces a stringent bound on achievable throughput of a node irrespective of its throughput requirement and communication perspective. This inflexibility may result in sub-optimal performance in several practical scenarios. One of the key contribution of this research is to add elasticity in width of transmission channel pertaining to the node's requirement and environmental conditions. This adaptability in turns, helps us in achieving optimal network wide throughput/capacity.

2.3.3 Medium Utilization

The capacity of any wireless communication system is directly proportional to available channel bandwidth[1]. The spectrum scarcity of overcrowded 2.4GHz ISM band available to WLANs require full capitalization of this resource. This necessity increases the importance of measuring percentage spectrum utilization at various traffic loads. The spectrum occupancy measurements are also essential for wireless network planning and deployment.

We have evaluated the percentage spectrum utilization under various traffic loads. The obtained results are presented in Figure 2.4. From these results, it is evident that 802.11/b networks achieve fairly good spectrum utilization at throughput of 6 Mbps. This high spectrum utilization is a result of modulating a signal through Direct Sequence Spread Spectrum (DSSS). The addition of pseudo noise code (used to cancel the ambient noise effect) in DSSS, spreads the signal on larger bandwidth than it actually required for message transmission. This spreading of signal makes it appear that spectrum utilization is high. On the other hand 802.11/g networks achieve very low spectrum utilization as compared to 802.11/b. Since 802.11/g hardware uses OFDM that modulate signal on orthogonal sub-carriers at very low symbol rate without addition of pseudo noise code, therefore spectrum

[1] It is important to mention that bandwidth and channel bandwidth are two distinct measures. In this dissertation, the channel bandwidth denotes the frequency spectrum of a particular channel measured in MHz while bandwidth denotes the amount of data that can be transmitted in a unit time and is calculated in Mbps

utilization values are low. Similarly the Multiple Input Multiple Output (MIMO) uses multiple antennas for transmitting a signal by using large number of sub-carrier frequencies (with OFDM modulation) thus results in higher values for spectrum utilization. The static

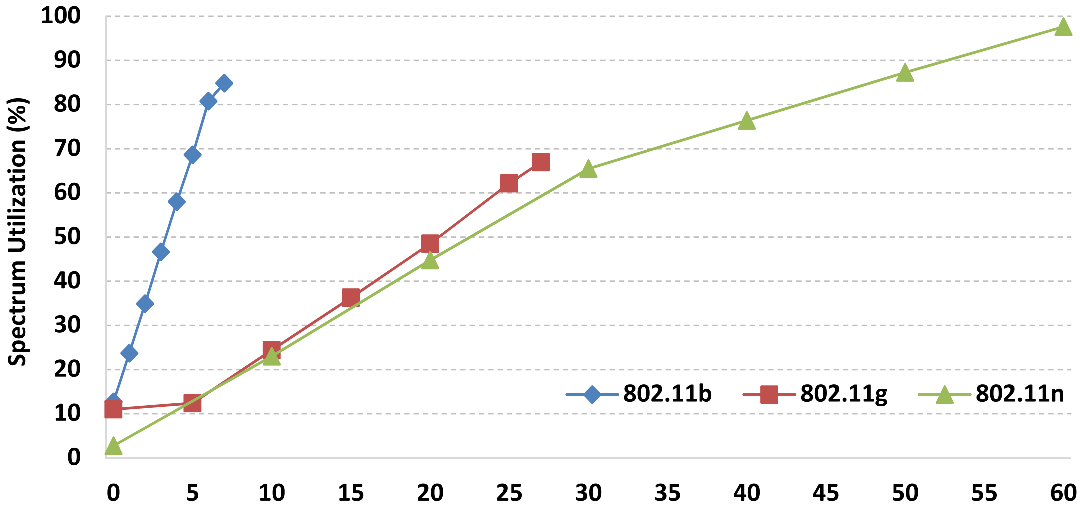


Figure 2.4: Spectrum Utilization of Different 802.11 Networks

width of channels restricts the number of sub-carriers in a transmission channel. This restriction degrades the spectrum utilization. Since at lower transmission rates many of the subcarrier frequencies contain significantly lower number of symbols which results in decreased spectrum utilization. In this study, we have emphasized that if a node is transmitting at lower data rate, it should use narrower width channel to increase the spectrum usage.

2.3.4 Interference

The quality of a communication link is highly influenced by overlapping of radio frequencies among multiple nodes operating in close vicinity. This overlapping causes difficulty in channel access at transmitting nodes and signal detection and decoding at receiving nodes and is largely classified as interference. Radio frequency interference works on the basis of SNR.

SNR can be defined as the ratio of power level containing the meaningful information of a primary modulated signal to the intensity of the background noise. SNR model of wireless communication states that, it would be impossible to generate the meaningful information from the primary modulated signal if power level of the ambient noise or noise produced by an external source is sufficiently higher than the power level of the primary signal.

The populous disposition of 2.4 GHz ISM band has greatly increased the problem of interference in 802.11 WLANs. On a network scale, interference can affect the totality or a set of nodes in a specific region of network. In 802.11 WLANs interference can be categorized in two abstract classes namely external and internal interference.

External Interference

WLANs share ISM frequency spectrum block with large number of electronic appliances such as microwave ovens, cordless phones and children toy remotes. Operation of these appliances near or inside of WLAN can potentially cause external interference. Most of the time, sources causing external interference use high power for their transmission resulting in severe degradation of link quality of WLANs. Additionally, these devices have abrupt transmissions, absenting any signal/transmission detection mechanism. This non-availability of transmission detection from other sources may cause data frames to collide and drop at both receivers. Secondly, since WLANs employ physical layer carrier sensing function for channel access, the unsolicited transmission by external source may force WLAN nodes to wait for long period of time to begin their transmission. This reduced channel access further degrades the performance of WLAN. Since external sources are not part of the network and

Table 2.2: Overlapping Degree of Channels with different Channel Distances

Channel Distance	0	1	2	3	4	5	6	7-10
Overlapping Degree	1	0.7272	0.2714	0.0375	0.0054	0.0008	0.0002	0

are beyond measures of control (except relocation of nodes), this study focuses more on mitigating the effect of interference caused by internal sources.

Internal Interference

Owing to the shared nature of transmission medium in WLANs, two or more transmissions from different nodes may fully or partially overlap in time. The received signals of multiple transmissions will interfere with each other and thus become indistinguishable leading to packet drops. This overlapping of transmission is termed as collision. In order to avoid interference and collisions among contending nodes, WLANs employ carrier sensing function based on "listen before you talk" mechanism. However, close packing and partial overlapping of sub-carrier frequencies in a communication channel may result in a special type of interference called CCI. The amount of CCI is governed by the number and degree of overlapping sub-carriers in adjacent channels. We have calculated this partial overlapping degree at different channel distances on the basis of overlapping sub-carrier frequencies and presented the result in Table 2.2. Another source of internal interference is Inter Symbol Interference (ISI). ISI takes place when two symbols interfere with each other. The cause of ISI is the overlapping of transmission signals generated from same source in time domain due to signal delay spread. 802.11 WLANs employ several interference cancellation techniques at physical layer. These include pseudo noise addition in case of DSSS and frequency shifting in Frequency Hopping Spread Spectrum (FHSS). More advanced techniques of interference avoidance have been deployed in 802.11 n/ac WLANs like use of MIMO-OFDM transmission systems. However, static width channelization in WLANs can offer very less flexibility in terms of interference avoidance. Since each channel has specific set of sub-carrier frequencies with constant degree of overlapping, CCI cannot be mitigated to a notable extent.

2.3.5 Bit Error Rate

The ratio between number of erroneous bits to total number of bits received is defined as Bit Error Rate (BER). In 802.11 networks there are two major sources of bit errors that includes poor link quality and collisions. The quality of a communication link is characterized by Signal to Noise Ratio (SNR). A higher value of SNR depict a better link quality and lower bit error rates. Figure 2.5 [27] shows a relationship of BER and SNR for various modulation schemes in 802.11 WLANs. From these results, it is evident that higher order modulations incur more bit errors even at better SNR values. This higher BER is a result of close packing of symbol bits to achieve higher transmission rate. When a noise pulse affects the actual signal for short interval of time, it introduces more number of errors in densely populated symbols then in lower order modulations. Moreover, decoding higher order modulation requires more sensitive antenna for correct sampling of received signal. The static width channelization can offer very little to improve the quality of a communication link. Any stationary node with static channel conditions will have almost constant BER throughout its communications. In this work, we have emphasized that, if a node has poor link quality and corresponding lower SS values, it should operate on narrower width channel.

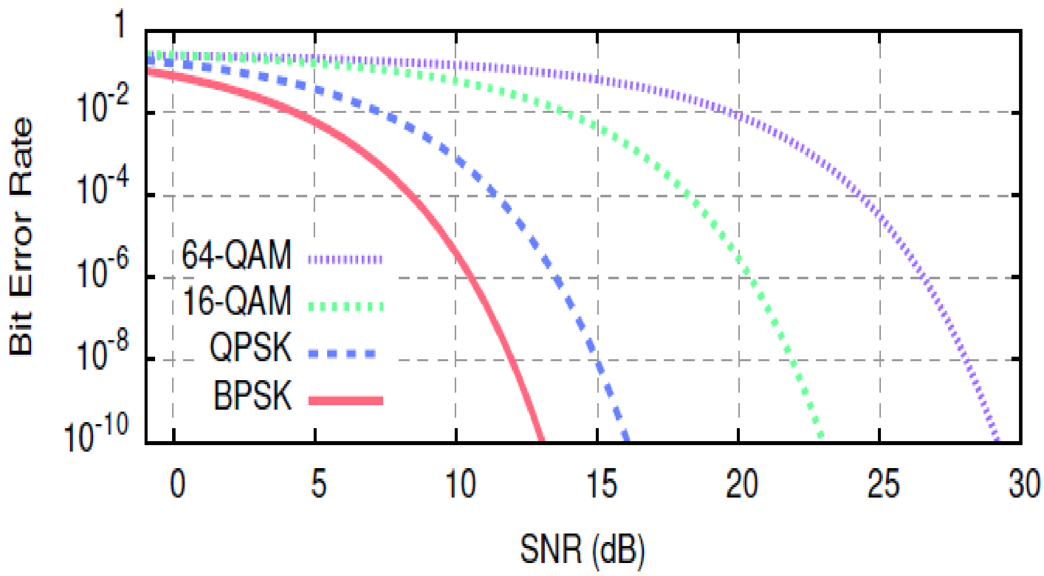


Figure 2.5: SNR and corresponding bit error rate for different 802.11 modulation schemes.

Since narrow width channels have higher spectral efficiency, it can substantially decrease BER. Moreover, narrower channels will have more transmission power available (The lesser number of sub-carrier frequencies will increase per MHz transmission power), therefore, SS values will improve significantly at longer distances. However, a critical trade off between transmission power and communication range will also need to be analyzed, as higher per MHz power will also increase the interference radius of a node.

2.3.6 Delay Spread

Majority of 802.11 appliances use omni-directional antennas for transmission. Therefore, RF energy originating from a transmitter, radiates in every direction and reflected/refracted from various surfaces along the way before finally reach at receiver antenna. In this way, different waves travel variable distances to reach the receiver resulting in time varied signal reception. The resultant wave converging at receiver antenna will be simply a sum of all reflected/refracted waves. The time interval lapsed between the reception of first wave and

Table 2.3: Root mean square delay spread (in ns) for various 802.11 WLANs

	Room	Hallway	Stairs	Theatre
802.11a	41.57	16.87	59.72	80.75
802.11b	49.43	25.90	58.61	73.57
802.11g	52.46	56.82	60.02	70.17
802.11n	28.94	52.56	30.27	58.83

last echo copy of the same wave at receiver is called delay spread. Typical 802.11 compliance transmission systems can bear a delay spread of 500 ns with reduced transmission rate [48]. Most vendors state that, delay spread should not be more than 65 ns to operate at maximum data rate. We have calculated delay spread values for various 802.11 networks which are presented in Table 2.3 WLANs using static width channelization with stationary channel conditions and static nodes bear almost same amount of delay spread. The channel bandwidth of a communication system is a major factor contributing to the calculation of delay spread. Narrow bandwidth channels incur lower delay spread than wider width channels. Therefore, it has been suggested that, for network scenarios with large number of obstacles in communication path should use narrow width channels to decrease delay spread. This will help in reducing BER and subsequently reduced PDR and frame retransmissions.

2.3.7 Transmission Range

The transmission rate of a node has a direct relationship with SS values at receiver antenna. SS decreases substantially with the increase in distance between sender and receiver. Several factors contribute to this decrease in SS such as multi-path fading, attenuation, signal energy dissipation and obstacles in path of communication. Table 2.4 cited in [53] presents typical values for attenuation while passing through obstacles of various materials. Prediction of range in 802.11 network is fairly complex as compared to wired links whose distance

Table 2.4: Typical signal attenuation for building materials at 2.4 GHz frequency

Range	Materials	Loss (dB)
Low	Non tinted glass, Wooden doors, Cinder block walls, Plaster	2-4
Medium	Brick wall, Marble, Wire mesh, Metal tinted glass	5-8
High	Concrete wall, Paper, Ceramic bullet-proof glass	10-15
Very high	Metals, Silvering (Mirrors)	>15

limitations are well understood. The free space propagation of 802.11 signals and interaction of these signals with various objects in communication path make the range calculations nearly random. The free space propagation model given in [32] is a simplified way to estimate the range of any wireless communication system. Equation 2.1 presents this model.

$$P_{rx} = P_{tx} G_{rx} G_{tx} \left(\frac{\lambda}{4\pi d} \right)^2 \quad \text{so} \quad P_{rx} \propto P_{tx} \left(\frac{1}{d} \right)^2 \tag{2.1}$$

where, P_{rx} is the received power, P_{tx} is the transmitter power, G_{rx} and G_{tx} receiver and transmitter antenna gains respectively, λ is the wavelength of transmission frequency and d is the distance between transmitter and receiver. Since the values of P_{rx}, P_{tx}, G_{rx}, G_{tx} and λ remains constant, hence the received power has an inverse relationship with distance. Though equation 2.1 was originally developed for free space signal propagation, authors in [18] have showed that it can be used for range approximation of 802.11/g networks.

2.4 GHz frequency band has substantially low penetration power and high attenuation which results in lower transmission range of WLANs. Table 2.1 provides typical transmission ranges for indoor and outdoor environments for various 802.11 standards. The limited range of 802.11 WLANs has many positive aspects. There are several cases when it is desired that signals should not pass the proximity of a building for security considerations and restricted access to the network. This reduced transmission range helps us in achieving this goal. Moreover, in network scenarios where nodes have dense deployment, it is essential to deploy higher number of APs to maintain user experience. This reduced range also make it possible to reuse the frequency channels in different wireless cells in close vicinity.

The width of communication channel has an inverse relation with transmission range. More number of sub-carrier frequencies having variable rate of attenuation fade out more readily. This fading consequently decreases SS and thus it is beneficial to use narrow width channels at longer distance to minimize BER.

2.3.8 Power Consumption

Power consumption is one of major factor that affects the efficiency of any wireless network. This factor becomes more important in case of hand held devices such as smart phones and PDAs. These devices have limited power supply provided through a rechargeable battery. The factor of power consumption is critical in smart phones due to the fact that they use upto 50% of total power in using Wi-Fi and their batteries can be drained quickly while transmitting at peak rates [52].

Power consumption management has been an essential part of 802.11 specification since 1999 when 802.11/b was established. Minimizing power consumption in WLANs has been implemented on MAC layer. 802.11 standard broadly defines four states of a typical transceiver which are transmitting, receiving, idle and sleep modes. The idle and sleep states have been considered as power saving states and major source of power consumption is the activity of transceiver i.e transmitting or receiving data. Therefore, power consumption can be reduced by minimizing transceiver activity time. Any transmitter in power saving

Table 2.5: Power consumption of NICs in mW (multimode 802.11 standards)

Device/Vendor	802.11 Standard	Power (mW)			
		Sleep	Idle	Rx	Tx
Mini-PCI VIA WLAN Module	b/g	90	311	712	825
Mini-PCI Realtek WLAN Module	b/g	114	407	1004	1122
Mini-PCI Ralink WLAN Module	a/b/g	91.5	393	983	1072.5
(USB) module with VIA WLAN Card	b/g	102	443	1525	1910
PCIe mini card WLAN Module	b/g	115	627	924	1386
Belkin Dual-Band WLAN Network Card	a/b/g	190	822	825	1848
Belkin Dual-Band PCMCIA Card	a/b/g	190	822	825	1848
Dell Wireless 1350 miniPCI	b/g	20	740	800	1000
D-Link AirPlus Wireless G PCI Adapter DWLG510	b/g	15.4	92.4	630	818.4
Cisco CB20A Wireless LAN PCCard Bus AIRCB20A	a	66	130	1716	1914
Intel PRO/Wireless 3945ABG Card	a/b/g	30	150	1400	1800
Cisco Linksys Dual-Band WirelessN Express-Card WEC600N	b/g/n	396	712	1980	2640

mode spends most of the time in sleep mode and consumes very small amount of power. Transition to the idle state is only made for listening to the management frames called beacons at a certain intervals and for receiving frames from the AP. A typical survey of power consumption in WLANs for transmitting, receiving, idle and sleep states for various vendors is given in Table 2.5. The width of transmission channel has a direct impact on power consumption. The cumulative power consumption of Wi-Fi usage increases, as the width of transmission channel increases, resulting in rapid depletion of stored power. The situation becomes even worse if required throughput is substantially low which is true most of the times [7]. In this dissertation, we have provided a detailed analysis of power consumption on different channel widths.

2.4 Chapter Summary

In this chapter, we have thoroughly explored various physical layer properties of 802.11 networks employing static width channelization. It has been explained, how width of a communication channel affects various performance parameters of WLANs?. The contents of this chapter can be summarized as follows:

1. Achievable transmission rate of any wireless communication channel is directly proportional to its width and modulation order. Wider channel widths and higher order modulations at short distances with ideal channel conditions provide higher transmission rates and vice versa. We can embed flexibility in transmission rate of WLANs by implementing support for variable width channels.

2. Cumulative throughput of any wireless communication system can be substantially enhanced by intelligent distribution of frequency spectrum in different cells of the network. Width of communication channel plays an important role in enhancing individual throughput of sender/receiver pairs.

3. Current WLANs operate in 2.4 GHz ISM frequency spectrum and total available bandwidth is considerably limited. The use of ISM by several home appliances make the situation of spectrum scarcity even worse. Static width channelization employed in trivial WLANs cause under utilization of limited frequency resource that results in sub-optimal network capacity.

4. Interference foot-prints of fixed width channels remains static under stationary channel conditions due to invariable number of sub-carriers in a channel. The amount of internal interference experienced by a node is a function of overlapping sub-carrier frequencies in a specific channel. Hence, we can manage the interference by manipulation of sub-carrier frequencies that constitute a communication channel.

5. The width of a communication channel has a significant impact on BER of a wireless link. WLANs operating on static width channels have constant BER under stationary network conditions. Narrow width channels have higher spectral efficiency and are less susceptible to interference effects and vice versa. In hostile channel conditions, decreasing the width of communication channel can decrease BER to a large extent and may enhance the effective throughput.

6. Delay spread of a communication channel has a significant impact on the BER and packet drop ratio of a link. Delay spread has close relationship with the width of channel. More number of subcarrier frequencies amassed in a single channel incur large delay spread and thus negatively affect the performance of WLANs.

7. Measuring transmission range of a transmitter is essential for effective planning and deployment of any network. Static width channels in identical network conditions have similar transmission range. The width of communication channel has strong impact on transmission range and SS of a transmitter. For instance narrow width channels have high spectral efficiency resulting in better SS values at relatively longer distances.

8. Wider width channels require higher input power to maintain a minimum threshold of SS at a specific distance. Power management can be incorporated in 802.11 WLANs by intelligent management of channel widths.

Chapter 3

Background and Related Work

The rapid advancements in the field of wireless communication have instigated researchers and industry professionals to fine tune several performance parameters of wireless networks. The advent of high speed WLANs and their widespread deployment acted as catalyst to draw more and more attention of researchers. The primary objective of all research activities is targeted to achieve experience similar to wired connectivity while communicating through a wireless medium. Since, performance of wireless networks unlike their wired counterparts is affected by large number of factors, hence a substantially more efforts are required to accomplish this task. Several techniques for performance enhancement of wireless networks have been reported in literature. We can broadly categorize these techniques into two distinct subsets: physical layer techniques and MAC layer techniques. Physical layer techniques involve the maneuvering parameters such as frequency bandwidth, modulation, transmission rate and signal strength etc. On the other hand MAC layer techniques use matrices such as channel access, contention window adjustment and frame size etc.

In this chapter, we present an overview of those techniques reported in literature which are inline with this dissertation. The literature survey presented here focuses on achieving optimal data rate, network capacity enhancement, interference management, dynamic channel width adjustment, range enhancement and power consumption.

3.1 Channel Access Mechanism in 802.11 WLANs

The shared nature of transmission medium in wireless networks requires a scheduling mechanism for granting transmission opportunity to a node. WLANs use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism to implement such scheduling of transmission. Unlike wired networks, collision in WLANs is a receiver based phenomenon and sender cannot detect it while transmitting [5]. In order to avoid collisions, CSMA/CA uses two types of coordination functions for awarding channel access to a specific node. These are Point Coordination Function (PCF) and Distributed Coordination Function (DCF) [1]. PCF is a centralized function that resides on AP over DCF. It provides channel access to multiple nodes centrally by polling mechanism in contention free fashion.

On the other hand, DCF provides channel access distributively based on "listen before you talk" strategy. In DCF, a node ready to transmit first senses the channel for an ongoing transmission for Distributed Inter-Frame Spacing (DIFS) time. If channel remains idle for DIFS time, the transmitter can send its data. If channel is sensed busy, the transmitter backs off for a random amount of time based on its Contention Window (CW) and senses the channel again after elapsing this time. The initial size of CW ranges from 0 to 16 time slots (Each time slot is of 20 μS) and exponentially increase on each collision till reaches to 1024 time. DCF optionally implements Request to Send/Clear to Send (RTS/CTS) mechanism as virtual carrier sensing function. In this mechanism, a node ready to transmit first sense the channel for an ongoing activity. If channel is free for DIFS time, sender node transmits an RTS frame embedding its transmission rate and size of the packet. On receiving RTS, receiver node sends a CTS frame embedding the time required for this specific packet transmission. Other nodes overhearing the CTS frame hold their transmission for this specified time by setting a counter commonly known as Network Allocation Vector (NAV). RTS/CTS is an optional mechanism and has not been widely deployed due to large overheads. Similarly, PCF is also occasionally used and DCF has the most widespread implementation as compared to DCF-PCF implementation [20].

3.2 Achieving Optimal Data Rate

In response to ambient conditions, 802.11 WLANs adapt their transmission rate (data rate) using Auto Rate Fall-Back (ARF) [37] and Receiver Based Auto Rate (RBAR) [30] algorithms. In ARF, a transmitter starts its communication on basic data rate (2 Mbps for 802.11/b, 6 Mbps for 802.11 a/g and 7.2 Mbps for 802.11/n) and sets a timing counter. After the expiration of counter (pre-specified value) or consecutive successful transmissions on N (specified threshold value) packets, the data rate is increased to next higher transmission rate. If 2 consecutive packets drop, data rate readily falls back to old rate (priori rate). ARF considers bad channel conditions as the only source of packet drop. Since PDR in WLANs is a receiver based phenomenon and several factors like collisions, receiver antenna sensitivity and like wise can cause frames to drop, ARF may cause under-utilization of network resources.

RBAR mechanism makes use of RTS and CTS control frames to estimate the optimal transmission rate. At start of a communication, each sender reserves the channel by sending RTS frame to receiver node by embedding a heuristic data rate (e.g data rate of last successful transmission) and packet size of current transmission. On reception of RTS, receiver node examines the associated SS and calculates its optimal transmission rate that can be correctly decoded. It embeds this transmission rate in CTS frame and transmit it to sender. On overhearing RTS/CTS frames, other nodes in network sets a back-off counter based on channel reservation time in CTS frame. The implementation of RBAR mechanism requires a mandatory use of virtual carrier sensing function (RTS/CTS mechanism). However, due to large overheads, RTS/CTS are not widely deployed in WLANs. Secondly, it also suffers the same dilemma of packet drop differentiation of ARF and cannot successfully identify the source of packet drop.

In addition to standard transmission rate control algorithms, several other mechanisms for transmission rate adaptation [43][9][25][41] have been proposed in literature.

In [43], authors present an insight on factors that must be accounted in development of an effective transmission rate selection algorithm. They have divided the network nodes in latency tolerant and latency intolerant categories based on applications running on these nodes and proposed Adaptive Auto Rate Fallback (AARF) for improvement of WLANs performance under ideal channel conditions. AARF like ARF uses PDR as rate adaptation function but reduces the oscillations of transmission rate by implementing adaptive threshold for successful transmission counter. A sender increases its transmission rate on N successful transmission and if two consecutive frames drops, it doubles the threshold to $2N$ for next rate increase. In this way, the time interval between two consecutive rate adaptations increases thus incur fewer fluctuations in rate increase/decrease. However, this rate adaptation mechanism is only applicable to static channel condition. If ambient conditions and respective PDR varies to a large extent, AARF will perform very poorly due to reduced number of rate enhancements.

In [9], authors have proposed SampleRate algorithm and concluded that key challenge in bit rate selection is the estimation of transmission rate that will lead to highest possible throughput. The proposed mechanism selects a transmission rate it considers, will provide highest throughput in current channel conditions. To finalize the transmission rate, SampleRate probes different bit rates by transmitting data and measuring respective Packet Drop Ratio (PDR). If PDR at any transmission rate is higher than its current PDR, it switches to next transmission rate. If PDR of transmission rate is smaller than PDR of current transmission rate, it switches to current transmission rate and starts probing again. Authors have claimed that SampleRate performs significantly better than ARF and RBAR. However, it is obvious that probing an optimal transmission rate will consume substantial amount of time and hence will not be suitable to deploy under saturated network conditions.

In [25], authors have proposed automatic rate adaptation (ARA) technique that do not require feed back from receiver about channel conditions and PDR. Authors claim that some simple modifications to current modulation and decoding schemes implemented through ARA will cancel the noise effect in transmitted signal. The mechanism of ARA involves the change in minimum distance transformation mechanism. Since, current coding scheme use fixed minimum distance threshold specified for different combinations of modulation and transmission power, it can correct small number of bit error. However, if we set a relatively high threshold value for minimum distance, more number of bit errors can be corrected. This has been achieved by setting minimum distance between nearby constellation points in the modulation above a threshold to tolerate distortion due to noise. However, it is evident that increasing the distance threshold will increase the probability of incorrect bit detection and hence will increase PDR.

In [41] authors have propose a two stage modulation and coding adaptation scheme and name it 802.11/n Dual Instance Rate Adaptation (nDIRA). It involves the use of physical and MAC layer matrices to decide about MCS to be used. In first stage physical layer decides the optimal MCS based on SNR, PDR and an efficiency measure proposed by authors in [29]. The proposal of selected MCS is then forwarded to MAC layer. On the basis of statistics (PDR, Missing acknowledgments) of X precious communications with the same receiver, MAC either accepts the MCS or overrule it by proposing another MCS, it considers, will maximize the throughput. However, in our understandings, this technique can only be used in static network scenarios where channel condition do not change for longer intervals of time. Since MAC layer proposal has high priority which almost nullifies the current channel state information. Hence channel state becomes almost irrelevant, thus proposed mechanism cannot be implemented in rapidly varying channel state scenarios.

3.3 Network Capacity Enhancement

Throughput/capacity enhancement is probably the most discussed topic in domain of WLANs. A large number of techniques and protocol designs have been presented in literature for increase in throughput of these networks. The presented techniques can be broadly divided in two categories: physical layer and MAC layer techniques.

3.3.1 Physical Layer Techniques of Capacity Enhancement

Some of the most accepted mechanisms for capacity improvement at physical layer of 802.11 WLANs have been presented in [26][42][21][51].

Gupta and Kumar [26] have analyzed the maximum achievable capacity of wireless networks under various channel and topology considerations with arbitrary traffic patterns. This work presents a theoretical model and derive upper and lower bounds on achievable capacity of wireless networks. Authors have concluded that, maximum achievable capacity of a link is a function of transmission rate and distance between sender and receiver stations. This analysis further states that the capacity of wireless link increases if signal power decays rapidly with distance. However, authors have not considered the effect of interference and overheads associated with communication in WLANs.

In [42], authors have implemented Space Division Multiple Access (SDMA) mechanism to improve throughput of 802.11 a/g networks. SDMA forms group of closely placed nodes within a specific distance from an AP. A transmission slot of 10ms SDMA window is initiated by an AP to award channel access to a specific node. In this paper, authors have also evaluated the effect of channel state information such as SNR, delay spread and spatial correlation. It has been concluded that network capacity can almost be doubled by using proposed mechanism of SDMA.

Authors in [21], have proposed a hybrid mechanism for capacity improvement by combining spatial multiplexing and space time block coding using MIMO antennas at 802.11a/g networks. The proposed algorithm uses zero force suppression technique for interference management in MIMO-OFDM system. It has been concluded that, both increased throughput and decreased PDR can be achieved by using MIMO antennas in conventional 802.11a/g networks.

The work presented in [51] have emphasized that throughput of any WLAN is a function of Received Signal Strength Index (RSSI) and interference cause by other nodes in the network. In this paper, authors have proposed a link adaptation algorithm that makes use of RSSI to vary transmission rate based on ambient conditions and interference. The key concept of proposed algorithm is that, each transmitter should adapt its transmission rate based on average values of its RSSI without considering rapid fluctuations of the SNR. It has been claimed that SNR has a linear relationship with RSSI and a threshold can be set for change in transmission rate based on it. The proposed algorithm stores the RSSI of last 12 received packets and averages these to calculate optimal transmission rate. The RSSI has been stored in a sliding window and when average RSSI decreases below specified threshold the transmission rate is adapted accordingly. Authors concluded that proposed technique is highly efficient in scenarios with rapid changes in link conditions and high node mobility.

3.3.2 MAC Layer Techniques of Capacity Enhancement

There is a catholic consensus among researchers that channel access mechanism deployed in conventional WLANs is a major bottleneck in performance of these networks. A wide range of capacity enhancement techniques targeting the MAC layer of WLANs is reported in literature. The research work presented in [8] [40][12][4][11] is of notable importance.

Authors in [8], have theoretically analyze the performance of contention based DCF deployed at MAC layer of WLANs for a finite number of network nodes operating under ideal channel conditions. Contrary to other performance evaluation techniques that only consider static or geometrically distributed CW with two stages of back off, the proposed model provides an accurate measure of saturation (asymptotic) throughput performance of WLANs for all possible stages of back off. This model is based on discrete-time markov state transition model employing multi-stage back off CW. Authors have concluded that, the throughput performance of WLANs is strongly dependent on network parameters like CW and number of nodes in the network.

The work presented in [40] has emphasizes that MAC layer overheads such as physical and MAC layer headers, binary slotted exponential back off, inter-frame spaces (SIFS, DIFS) and ACK transmission are the major sources of below-par performance in WLANs. Since these overheads are applied to each frame, the performance degradation becomes higher for smaller size of frames. To minimize the transmission overheads associated with frames, authors have proposed a frame aggregation technique that combines several small size frames into a single large frame by modifying device drivers of commodity NICs. This frame aggregation can be implemented at MAC or upper layers. It has been concluded that throughput can be increased with a factor of 2 to 3 Mbps for 802.11/b networks with implementation of frame aggregation.

In [12] authors have proposed a mechanism for dynamic tuning of CW to minimize the time wastage in contention. The said tuning is achieved by implementing a static CW without exponential increase. The size of CW is tuned for each transmission based on the number of nodes in network. Since traditional CSMA/CA treats every packet loss as congestion which results in exponential increase of CW. However the wireless medium is inherently more susceptible to channel induced errors, fixing the size of CW reduces the effect of channel induced packet loss over size of CW.

The work presented in [4] states that, the decrease in CW with each successful transmission, increases the risk of collision and hence wastes substantial time in retransmissions. Authors proposed that instead of sudden decrease in CW to its original size after each successful transmission, the CW should be decreased slowly. It has been concluded that, slow decrease in CW is very efficient in noisy channel conditions and enhances the throughput and fairness among contending nodes while simultaneously minimizing the probability of collisions.

In [11] authors have implemented a joint rate control and frame aggregation method on flat fading and additive white gaussian noise channels. The key concept of proposed method involves the frame size determination based on SNR and subsequently updating transmission rate as a function of frame size. It is proposed that under low SNR conditions, large frames should be divided into two or three frames transmitted at relatively lower bit-rate. Similarly large size frames should be transmitted over channels having high values of SNR.

3.4 Interference Management

Interference management is probably the most discussed research topic in wireless networks. Research in [54] has proposed FLUID algorithm aimed to evaluate the impact of flexible width channelization on interference management of enterprise wireless networks. Authors modeled conflicts between transmitter/receiver pairs, and proposed an efficient interference management technique based on SNR. To best of our knowledge it is the only research work made to enumerate the interference measurement and management in variable channel width scenarios. Authors in [24] proposed a game theoretic technique that exploits transmission power and scheduling for interference management. This research work claims that complexity and signaling overhead can be substantially minimized through proposed mechanism. Similarly, many other interference management methodologies are proposed in [47] [33] [50]. Since all these techniques are applicable to static channel width scenarios, it is essential to manage interference in adaptable channel width environments.

3.5 Dynamic Channel Width Adjustment in WLANs

On the fly channel width adaptation is a relatively newer area of research which was first proposed in 2008 by work done in [15]. In this research, a comprehensive analysis of flexible width channels in WLANs is presented. The suggested mechanism divides the available spectrum into channels of 5, 10, 20 and 40 MHz and decision for allocation of a specific width channel is based on throughput requirement of a node. Authors have evaluated the impact of various channel widths on throughput, range and power consumption in WLANs. This work also propose a SampleWidth algorithm used to calculates the required bandwidth of a specific node/AP. SampleWidth distributively runs on each transmitter. It selects a specific width channel based on ambient conditions taking into account the optimization required in sense of throughput, range and power consumption. It has been concluded that the key challenge in implementation of such algorithms is to determine which data rate and modulation will be best suited for a particular width channel. However, the major drawback of this approach is priori channel width adjustment before actual transmission. Since authors simply divided the spectrum into variable width channels and the dynamism is only in allocation of channels. Moreover, discrete and steep steps increase/decrease of channel width, limits the maximum possible advantage of width adaptation.

Authors in [63] have propose a Fine Grained Spectrum Allocation (FSA) algorithm, that adapts channel width on per frame basis. FSA decreases/increases the width of a channel by specifying the subcarrier bandwidth accordingly. For instance, a 5 MHz channels will contain 52 sub-carriers of 78.1 KHz each while a 20 MHz channel will have same number of sub-carriers of 312.5 KHz each. The proposed mechanism has been evaluated on Microsoft Research Software Radio (SORA) and channel width of 5, 10 and 20 MHz have been implemented and evaluated for throughput, channel detection accuracy and SNR. Authors pointed out that the key challenge in width adaptation is the detection of variable channel width by a receiving node. However, it is relevant to mention here that reducing the bandwidth of sub-carriers and fixing their number in a channel results in wastage of precious spectrum resources. The decrease in sub-carrier bandwidth results in increased guard band. Although a wide guard band increases SNR but simultaneously decreases the useful spectrum for transmission. Moreover, adapting channel width on frame basis introduces huge amount of complexity and incur large switching delays. We found that switching of narrower to wider channels and vice versa should be minimal to achieve maximum performance benefit.

In [23], authors have propose a Fine-grained Channel Access Algorithm (FICA). FICA divides a transmission channel into several sub-channels of varying widths and a node selects a sub-channel according to its bandwidth requirement. The width of sub-channels has been designed in coherence with the physical layer data rates and allowed frame sizes. The allocation of a specific width channel to a node is made, based on its current SNR. Authors claimed that FICA ensures several simultaneous transmissions in parallel thus reducing the channel access delays to a large extent. This work also suggests modifications in channel access mechanism to make parallel transmission possible. The proposed channel access mechanism implements frequency domain contention method that uses RTS/CTS signaling and frequency domain back off to efficiently coordinate sub-channel access. The proposed architecture of physical and MAC layer has been implemented on software defined radios and evaluated for achieved throughput, network efficiency and BER. However, it is obvious that the proposed architecture can only work in ad-hoc mode of operations where multiple senders can transmit simultaneously to different receivers. It can also be implemented in scenarios where nodes have multiple distinct receiving radios.

Research in [54] proposes FLUID algorithm, to evaluate the impact of flexible width channelization on throughput improvements and interference in enterprise wireless networks. Authors modeled conflicts between transmitter/receiver pairs, and proposed an efficient interference management technique based on SNR. It has been concluded that interference index of whole network varies greatly with the change in channel width between a sender and receiver. The proposed mechanism used same approach of channel adjustment as given in [15] by using off the shelf commodity WLAN NICs. In this way, it also encounters the same performance limitations as discussed earlier in this section.

Majority of the research work proposed to dynamically adapt channel width still fixes the width of channel in advance, prior to actual communication and only presents a limited set of channel widths that can be assigned. This advance fixation of channel width limits the benefits of dynamic adaptation.

Some of the new 802.11 standards like 802.11/n [2] support channel width flexibility through channel bonding. A brief overview of channel bonding is given as below:

3.5.1 Channel Bonding in 802.11/n

To deal with ever increasing capacity demands of Wi-Fi users, 802.11/n networks under ideal channel conditions, optionally use 40MHz channel by combining two non-overlapping 20 MHz channels as given in Figure 3.1.

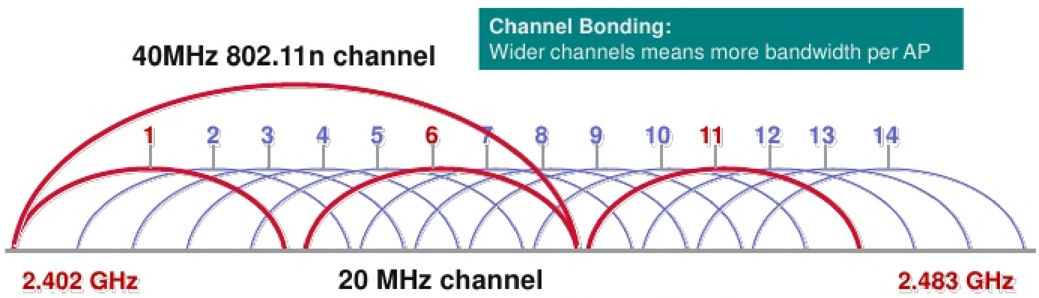


Figure 3.1: Channel Bonding in 802.11/n Networks

This combining of multiple narrow width channels to achieve a wider width channel is called channel bonding. Channel bonding increases the available bandwidth to users and increase their achievable throughput. However, it simultaneously decreases transmission range and increases susceptibility to interference. Authors in [19] have evaluated the CCI and transmission range of channel bonding in 802.11/n WLANs. The regulatory compliance dictates that the transmission power of WLAN NICs must be under a specific threshold, therefore deploying 40 MHz channels significantly decreases the effective SNR at relatively longer distances. This decrease in SNR results in higher number of bit errors thus effectively decreasing the throughput. Moreover, The steep step increase/decrease in channel width with a factor of 20 MHz do not serve the purpose of effective channel width assignment in WLANs.

3.6 Power Consumption

Power consumption and range calculations of fixed channel width networks are thoroughly discussed in [15][13][56]. The power consumption analysis given in [15] is based on calculation made through employing a resistor in series with the NIC power supply and measuring the current passed through the resistor. These calculations are made for 5, 10, 20 and 40 MHz channels. In [13] authors calculated the power consumption of downloading and uploading of data through Wi-Fi connection in smart phones. They concluded that higher data rates and wider channel widths incur more power consumption than lower data rates. Authors in [56] have discusses the indoor range of Wi-Fi devices with different variations in channel separation.

3.7 Chapter Summary

In this chapter, background information which has been required to understand the dissertation fully has been presented. This includes the CSMA/CA protocol used as contention based channel access mechanism in current WLANs. A thorough survey of various techniques that have been proposed for implementation of flexible width channelization is also presented in this chapter. It is concluded that majority of the research carried out did not adapt channel widths purely dynamically. The channels are formulated in first step before the actual transmission and these channels are selected dynamically during the course of transmission. For example both [15] [54] used channels of 5 MHz, 10 MHz, 20 MHz and 40 MHz for their experimentation. In this way the flexibility is only of choosing the channels of desired width, absenting on the fly formulation of optimal width channels. Additionally in this chapter, a brief overview of interference management and power conservation techniques reported in literature are also presented.

Chapter 4

Adaptable Width Channelization in 802.11 WLANs

The frequency spectrum used by a wireless communication system plays a vital role in defining its performance in terms of achievable data rate, commonly know as "capacity of communication system". In [59], authors derived the capacity of a wireless communication system as a function of available spectrum bandwidth and signal to noise ratio (SNR). The SNR itself, is also affected by the width of a frequency channel. This characteristic behavior and importance of wireless spectrum necessities the in-depth analysis for achieving optimal network performance in WLANs.

During the course of this research work, we have realized that width of a communication channel affects several performance parameters of WLANs. For instance, narrow channel width has lower BER and longer transmission range as compared to wider channel widths. Similarly, wider channel widths are more susceptible to attenuation, delay spread and fading effects as compared to narrow width channels. Owing to these distinctive properties of channel width, we have thoroughly explored the effect of channel width on exhaustive list of network parameters. Based on these investigations, we propose a novel mechanism that assigns spectrum resource to nodes dynamically based on their throughput requirement and ambient conditions. Through analytical modeling and rigorous experimentation, we have observed that adaptable channel width assignment in WLANs substantially increases network wide performance.

4.1 The Concept of Adaptable Width Channelization

In conventional WLANs, each 22 MHz frequency channel is constituted of 52 sub-carriers. Out of these, 4 sub-carriers are used for control signals (pilot sub-carriers) while rest of 48 sub-carriers are used for data symbols (data sub-carries) [1]. The physical layer of 802.11 b/g networks spread the data symbols on these 48 sub-carriers through OFDM or Direct Sequence Spread Spectrum (DSSS). The DSSS is only used to support legacy Wi-Fi devices like 802.11/b. The sub-carrier arrangement in frequency domain is given in Figure 4.1.

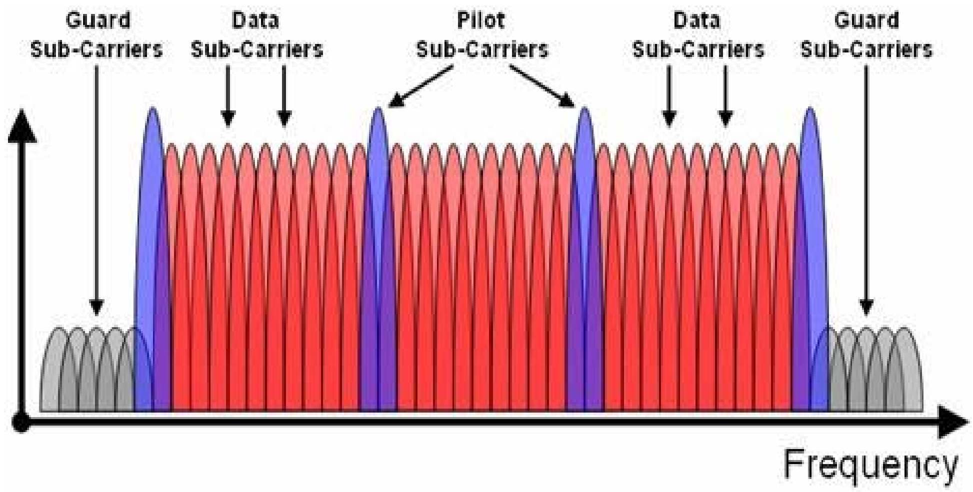


Figure 4.1: Sub-Carrier Arrangement in Frequency Channel

The proposed concept of channel width adaptation involves the use of variable number of overlapping and non-overlapping sub-carriers to nodes based on their transmission rate. A comprehensive working mechanism of proposed model in given in Section 4.2.

4.1.1 Throughput and Interference of Adaptable Width Channels

Assume that a network consists of J nodes (J_1,J_2,....,J_s) with J_i representing i^{th} node and K APs (K_1,K_2,.....,K_t) with K_i representing i^{th} access point. These K APs use L transmission channels (L_1,L_2,....,L_u) for communication with L_i representing i^{th} communication channel. In conventional Wi-Fi networks, there are 14 channels available for communication, therefore L_u ranges from 1 to 14. Since the association of a node to a specific AP is independent of each other, therefore this association can be modeled as Poisson distribution with arrival rate function λ and can be expressed as given in equation 4.1.

$$\Pr\{J_n \rightarrow K_i\} = \frac{\lambda^{J_n} e^{-\lambda}}{J_n!} \tag{4.1}$$

Where J_n denotes the total number of nodes associated with an AP K_i and $\rightarrow$ expresses the association of node to AP.

The close packing of 52 sub-carriers in a single channel causes overlap between same channels as well as between adjacent channels. This overlapping results CCI. Implementation of adaptable width channelization requires several communication factors to be addressed. One prominent factor among these is, CCI. Since, using channels of flexible widths, the frequency locations of channels change frequently resulting in the change in CCI. The CCI for a fixed width channels can be computed directly by modifying SINR model as follows:

$$SINR(J_i) = \frac{P\, d(J_i, K_i)^{-\alpha}}{N + P \sum \varphi(L_i, L_j)\, d(J_i, K_j)^{-\alpha}}$$
$$\begin{cases} \forall \;\; L_i \,\&\, L_j \,\in\, L, \;\; K_i \,\&\, K_j \,\in\, K \; and \;\; L_i \,\rightarrow\, K_i,\, L_j \,\rightarrow\, K_j \\ and \; i \,\neq\, j \end{cases} \tag{4.2}$$

where P is the transmission power, $d(J_i,K_i)$ is the distance between node J_i and AP K_i and α is the path loss factor that is an integer value typically ranges from 2 to 4 for WLANs. Note that N is the power spectral density of ambient white noise, and $\varphi(L_i,L_j)$ is the overlapping degree between channel L_i and L_j. The expression $L_i \rightarrow K_i$ denotes that channel L_i is associated to AP K_i. Equation 4.2 holds under the assumption that network is operating in saturation mode. That is, all bandwidth resources are assigned. The $SINR$ of the i^{th} node for generalized case can be written as,

$$SINR(J_i) = \frac{P\, d(J_i, K_i)^{-\alpha}}{N{+}P\, \beta\,(L_i) \sum \varphi(L_i, L_j) d(J_i, K_j)^{-\alpha}} \tag{4.3}$$

where, $\beta(L_i)$ is the probability of using channel L_i for transmission and $L_t \;\leq\; L_i \;\geq\; 1$. In saturation mode this probability becomes 1 as all available channels will be occupied by APs. Based on these calculations the achievable data rate for static width channels can be calculated by Shannon-Hartley rate equation [60] $R \;=\; B\; log_2(1 + SINR(dB))$ and $SINR(dB) \;=\; 10log\;(SINR)$ where R is the data rate and B is the bandwidth of the communication channel. Since throughput of a node is a function of its achievable data rate, the throughput (T) for i^{th} node can be given as below:

$$T(J_i) = B\log_2(1 + 10\ \log_{10} SINR(J_i)) \tag{4.4}$$

$$= B\log_2\left(1 + 10\ \log_{10} \frac{P\ d(J_i,\ K_i)^{-\alpha}}{N + P\ \beta\ (L_i)\ \sum\ \varphi(L_i,\ L_j)\ d(J_i,\ K_j)^{-\alpha}}\right) \tag{4.5}$$

The second term in the denominator of equation 4.5 represents the interference $I(J_i)$ experienced by Node J_i from all the APs due to overlapping of subcarrier frequencies in multiple channels. The interference for static width channels in 802.11 wireless networks is then,

$$I(J_i) = \sum P\ \varphi(L_i,\ L_j)\ d(J_i,\ K_j)^{-\alpha} \qquad i \neq j \tag{4.6}$$

The interference for variable width channels can be evaluated as follows,

The channel bandwidth B is a sum of overlapping and non-overlapping sub-carriers. Let us assume that a channel consists of X overlapping sub-carriers $(X_1, X_2, ..., X_u)$ and Y non overlapping sub-carriers $(Y_1, Y_2, ..., Y_v)$ with X_i and Y_i be the i^{th} overlapping and non-overlapping sub-carriers respectively. Then

$$B(L_i) = \sum_{i=1}^{u} X_i + \sum_{i=1}^{v} Y_i \tag{4.7}$$

The objective of proposed mechanism is to construct channels of variable width with maximum utilization of non-overlapping sub-carriers. This maximum utilization of non-overlapping sub-carriers will minimize the use of overlapping sub-carriers and consequently increases SINR of transmitting node. This objective can be achieved by using the following optimization

$$B(L_i) = \arg \min_{i \in (1,u)} \sum X_i \; + \; \arg \max_{i \in (1,v)} \sum Y_i \tag{4.8}$$

Notice that first term in equation 4.7 is actually an overlapping degree of channels that is determined by number of overlapping sub-carriers.

$$\sum_{i=1}^{u} X_i = \sum \varphi(L_i, L_j) \tag{4.9}$$

Then the throughput of a node J_i with variable channel width becomes

$$T(J_i) = \left(\sum \varphi(L_i, L_j) + \sum_{i=1}^{v} Y_i \right) \log_2 \left(1 + 10 \log \frac{P\, d(J_i, K_i)^{-\alpha}}{N + P\, \beta\, (L_i) \sum \varphi(L_i, L_j)\, d(J_i, K_j)^{-\alpha}} \right) \tag{4.10}$$

Since an AP serves several nodes through CSMA/CA mechanism, therefore, the cumulative throughput of an AP will be the sum of throughput of all nodes associated with it. If n nodes are connected to an access point K_i, its throughput will be the average of all nodes

$$T(K_i) = \frac{1}{n} \sum_{i=1}^{n} T(J_i) \quad \forall\, J_i \rightarrow K_i \tag{4.11}$$

$$= B\, \frac{1}{n} \sum_{i=1}^{n} \log_2 \left(1 + 10\, \log_{10} \frac{P\, d(J_i, K_i)^{-\alpha}}{N + P\, \beta\, (L_i) \sum \varphi(L_i, L_j)\, d(J_i, K_j)^{-\alpha}} \right) \tag{4.12}$$

Substituting value of B from equation 4.8, we have

$$T(K_i) = \left(\sum_i^u \varphi(L_i, L_j) + \sum_i^v Y_i\right) \frac{1}{n} \sum_{i=1}^{n} \log_2 \Big(1 + 10\log_{10} \frac{P\, d(J_i, K_i)^{-\alpha}}{N + P\, \beta\,(L_i) \sum \varphi(L_i, L\, j)\, d(J_i, K_j)^{-\alpha}}\Big) \tag{4.13}$$

and the achievable capacity C of whole network will be,

$$C = \sum_{K_{i\in K}} \left(\sum_i^u \varphi(L_i, L_j) + \sum_i^v Y_i\right) \frac{1}{n} \sum_{i=1}^{n} \log_2 \Big(1 + 10\log_{10} \frac{P\, d(J_i, K_i)^{-\alpha}}{N + P\, \beta(L_i) \sum \varphi(L_i, L\, j)\, d(J_i, K_j)^{-\alpha}}\Big) \tag{4.14}$$

4.1.2 Capacity Planning Through Adaptable Width Channelization

Let us assume that K APs construct K identical circles, in which their SS is greater than or equal to a certain threshold. Each AP is configured to use flexible channelization algorithm described in section 4.2. The J nodes are distributed randomly across these K circles. As given earlier in equation 4.1, probability of any node J_i belonging to a circle K_i follows Poisson distribution. The objective function is to maximize $\sum_{i=1}^{n} T_i$ subject to $\sum_{i=1}^{J} T_i < C$, $where T_i \geq 0, 1 \leq i \leq n$, where, T_i is the achieved throughput of node J_i, n is the number of users sharing the radio resource in K_i circle and C is the capacity.

If offered load on any AP K_i is $D_i = \sum_{n=1}^{N} \sum_{k=1}^{K} n_{ik} r_{ik}$ where n_{ik} is the load of any node n_i on AP of ring K_i and r_{ik} is the total load of n nodes on AP of ring K_i then the objective function can be obtained by maximizing the utilization of frequency resource and minimizing interference. If currently W width channel is available to an AP K_i, then the capacity enhancement will have to consider different traffic scenarios. These cases are discussed as follows.

Case 1

let n uniformly distributed nodes are ready to send data to an AP K_i. If we assume that these n nodes share available frequency resource equally with maximum cumulative data rate R and have packet drop ratio PDR which is caused by interference of APs $K_i + 1....k$ of adjacent rings, and R_i is an achievable rate by spreading signal over X overlapping and Y non-overlapping sub-carriers i.e.

$$R_i = \sum_{i=1}^{X} X_i \times r + \sum_{i=1}^{Y} Y_i \times r \tag{4.15}$$

where r is the transmission rate at a sub-carrier. Then

$$\mathrm{C} = \max_{(\mathrm{R}_1,\ldots,\mathrm{R}_n)} \sum_{i=0}^{n} (1 - PDR(J_i))R_i \tag{4.16}$$

Case 2

let n uniformly distributed nodes are ready to send data to an AP K_i. If we assume that these n terminals are allowed to transmit uniform amount of data at rate R with a target amount of interference and resulting PDR, sharing available frequency resource equally. The capacity of this specific ring is given as,

$$C = \sum_{i=0}^{n} \left(\frac{1 - PDR(J_i)}{\max_{(R_1,\ldots,R_n)} \sum_{i=0}^{N} \frac{1}{R_i}} \right) \tag{4.17}$$

Case 3

Let us consider that n uniformly distributed wireless nodes are ready to send data to an AP K_i. If we assume that each of these n nodes have variable load and any node n_i has t_i amount of traffic to send at a data rate R_i with a packet drop ratio PDR. The capacity of this specific ring is given as,

$$C = \max_{(R_1,\ldots,R_n)} \sum_{i=0}^{n} \left(\frac{1}{n} + \frac{t_i}{\sum_{i=1}^{n} t_i} \right) (1 - PDR(J_i))R_i \tag{4.18}$$

4.2 Optimal Spectrum Sharing Algorithm (OSSA)

In this Section we propose a novel algorithm of adaptable with channelization in WLANs aiming to increase capacity, throughput, and spectrum utilization with minimal interference. The spectrum assignment to an AP is based on analytical calculations made in Section 4.1.

OSSA adds channel flexibility by using different number of sub-carriers for variable channel widths. For instance, a narrower channel consists of less number of sub-carriers as compared to a wider channel. A detailed overview of number of sub-carriers per specific width channels and other corresponding physical layer parameters is given in table 4.5. OSSA divides total transmission area into K identical circles, and places APs at the center of each circle. All APs have omnidirectional antennas, which make a circular transmission and

Table 4.1: Number of Sub-carriers on Different Channel Widths and Frame Transmission Parameters

Channel Width (MHz)	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**22.5**	**25**	**27.5**	**30**
Number of Sub-carriers	12	18	24	30	36	42	48	54	60	66	72
Symbol Duration (μS)	16	12	8	7	6	5	4	3.5	3	2.5	2
SIFS (μS)	40	30	20	17	15	13	10	8	6	5	4
DIFS (μS)	50	40	30	20	17	15	13	10	8	6	3
Slot Duration (μS)	20	20	20	20	20	20	20	20	20	20	20
Guard Interval (μS)	3.2	2.4	1.6	1.2	1	0.8	0.7	0.6	0.5	0.4	0.3

interference radius around each AP. At network initialization phase, the three deployed APs use standard non-overlapping channels. All APs are connected to a spectrum allocation and management server through wired links. This server manages the spectrum resources, based on calculation made in Section 4.1. Two packet windows are being maintained at each AP. Let us name these windows as Receiver Window (RW) and Transmitting Window (TW). Both of these windows refresh their status after each 60 seconds to remain updated. TW and RW helps in calculating the required uploading and downloading throughput of each AP at any given time. At central server, OSSA takes interference, SS and required throughput as inputs and calculates optimal channel width and number of sub-carriers as output. The SS values are calculated through channel reciprocity [44]. If throughput requirement is changed at any instance, AP communicate this change to management server. If bandwidth requirement of an AP increases or decreases, it demands or releases spectrum resource accordingly. In case of spectrum demand, central management server checks status of available sub-carriers that are not assigned to any other AP. OSSA running on central management server measures the impact of increase in channel width in terms of throughput and interference. Based on threshold values of these measurements, management server decides about the increment of channel width. If sub-carriers are available, and subsequent change of increasing channel width keeps interference under a predefined threshold, then sub-carrier frequencies are communicated to AP. After increase in channel width, AP start spreading its signal to new sub-carrier frequencies in addition to already in-use sub-carriers. If an AP releases spectrum resource, management server adds the sub-carriers to available pool for on-demand dissemination to other APs. If throughput requirement of an AP decreases at any given time, it sends its new state of TW and RW to the management server. The management server in turns, checks the prior in-use sub-carriers and ask the AP to reduce its channel width by spreading its signal on lesser number of subcarrier frequencies.

Whenever cumulative spectrum demand exceeds than available spectrum, management server assigns channel width to achieve maximum network capacity with minimum interference. In this way an AP having better SNR and lower interference index will use wider channel width and vice versa. Implementing flexible channelization required efficient width detection mechanisms at participating nodes. This detection mechanism involves the use of physical layer frame preamble as discussed in chapter 3. Algorithm 6.2 presents pseudo-code of our proposed algorithm based on best effort sharing of available frequency spectrum.

The use of flexible channelization in Wi-Fi networks affect several important physical layer parameters like central frequency, transmission range, achieved throughput, RSS, delay spread and modulation schemes. Since narrow channels have higher spectral efficiency, longer transmission range and are less susceptible to delay spread, the proposed algorithm recommend higher modulation schemes on these channels. We have defined in our implementation that, if channel width is below a certain threshold then AP should use highest modulation rate irrespective of RSS values. In majority of the cases this implementation increases the throughput to a great extent.

```
Result: Required Channel Width(CW_(req))
Transmission Parameters (TP)
Input   :R(J_i), SINR(J_i)
begin
    for J_i ∈ J_s do
        if SINR(J_i) ≤ SINR_(Max) && R(J_i) ≥ R_(Min) then
            CW_(req) ← CW_(current)
            && TP ← TP for CW_(req)
        else
            if SINR(J_i) > SINR_(Max) && R(J_i) > R_(Max) then
                do
                    CW_(new) ← CW_current − 1.875MHz
                    && TP ← TP for CW_(new)
                while R(J_i) > R_(Max)
            else
                CW_(req) ← CW_(new)
            end
        end
        if SINR(J_i) ≥ SINR_(Min) && R(J_i) < R_(Min) then
            do
                CW_(new) ← CW_(current) + 1.875MHz
                && TP ← TP for CW_(new)
            while R(J_i) < R_(Min)
        else
            CW_(req) ← CW_(new)
        end
    end
end
```

Figure 4.2: Optimal Spectrum Sharing Algorithm

Table 4.2: Common Command Line Instruction in USRP

Command	Common Description	Type	Example	Interpretation
rate	Used to set the host sample rate	double	4e6	Stream at 4 MSPS(complex)
nsamps	Numbers of samples to process/transmit/receive	double/int	100e3	Stream 100,000 samples
secs	Duration to run the test, or delay start of streaming.	double	5	Stream for 5 seconds
args	Address arguments	string	addr= 192.168.10.2	
freq	Center frequency	double	400e6	Set center freq to 400 MHz
Ant	Antenna selection (i.e. "TX/RX", "RX2")	String	TX/RX	Use TX/RX port
ampl	Baseband amplitude (min = 0.0, max 1.0)	double	0.5	Baseband amplitude is 0.5
bw	Bandwidth setting of daughterboard in Hz	double	60e6	Set daughterboard BW to 60 MHz
ref	Reference clock selection	string	external	Use external clock
gain	Daughterboard rx or tx gain range depends on dB	int	25	Set gain to 25dB

4.3 Experimental Setup and Implementation

In this section, we have discussed details about our experimental test-bed and implementation of proposed algorithms.

For empirical evaluation of OSSA, we deployed an indoor network of three USRP kits connected to laptops running GNU radio software on Linux operating system (OS). As proof of concept, implementation of OSSA for $802.11/g$ wireless networks has been made by significantly modifying transceiver implementation provided at Comprehensive GNU Radio Archive Network (CGRAN) [14] and better explained in [17] [5]. TThis implementation can be extended to any 802.11 standard by simply modifying its parameters at physical layer. A brief overview of some of the parameters that can be adjusted and their data types is given in table 4.2. It is worth mentioning that USRP GNU supports a wide range of tuning parameters that can be manipulated to run a specific experiment and table 4.2 merely depicts few of these parameters. A central management server constituted of Dell T-620 computer running OSSA on Linux OS has been placed for implementation of flexible channelization. Each USRP2 kit contained a 2400 RX/TX daughter card with omnidirectional antennas. The specifications of USRP kit and daughter cards are available at [22]. Interference measurements have been made by implementing similar setup, constituting of four USRP2 kits acting as APs, attached to management server. There is a gigabit wired link between each AP and management server running OSSA on Linux OS. Variable number of wireless enabled nodes are attached to each AP. The APs and the wireless nodes are located in an area of 200 X 200 square feet. There is no interference of any other Wi-Fi network operating in close vicinity. The physical layer of each AP is customized in such a way that an AP can switch to any of narrower or wider channel widths at the end of current frame transmission. The wireless nodes detect the width of channels based on the preamble being transmitted by APs before the transmission of each frame. The deployed network diagram is shown in Figure 4.3.

Detailed measurements of throughput enhancements, interference, bit error rates, power consumption, spectrum utilization and transmission range have been made using deployed network. A thorough discussion on achieved results have been made in section 4.4.

4.4 Performance Results and Discussions

Using the experimental setup explained in section 4.3, a series of experiments has been conducted to enumerate the effect of deploying OSSA on essential network performance parameters. The obtained results are averaged out by collecting traces of all APs for accurate efficiency measurements. For comparison of spectrum utilization, throughput and interference with SampleWidth [15] and FLUID [54] algorithms, we have implemented these on our test-bed to ensure identical ambient conditions for all mechanisms under evaluation.

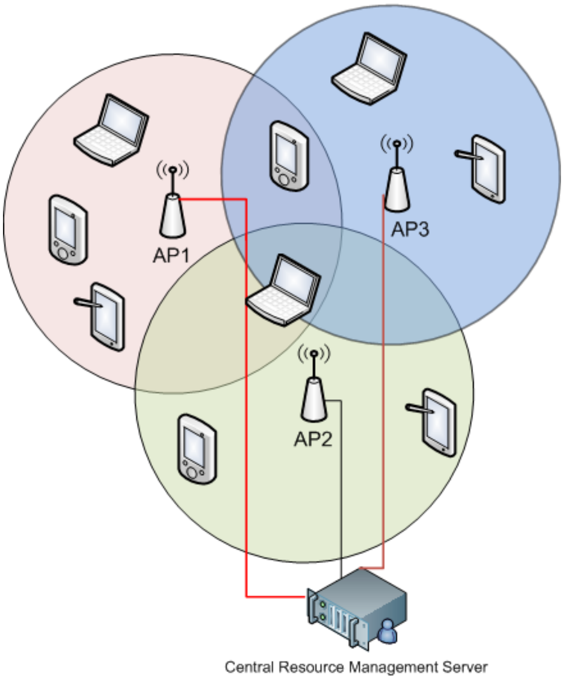


Figure 4.3: Conceptual Architecture of Deployed Network

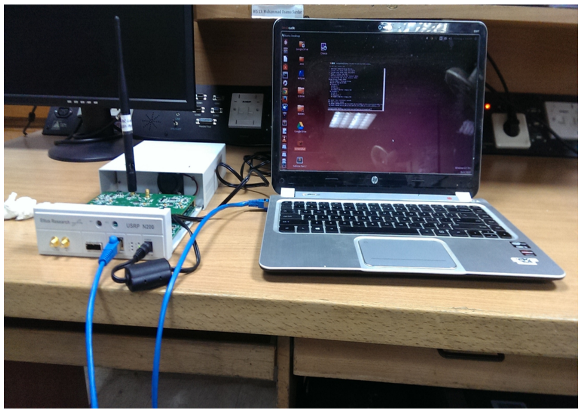


Figure 4.4: An Access Point Constituting of USRP Kit

4.4.1 Spectrum Utilization

Increased spectrum utilization with minimized interference enhances network throughput and capacity. This calculation can be made by analyzing effect of spreading transmission signal over wide range of channel widths, and constructing spectrogram of these channels. Although, this work does not focus on using standard fixed width channels, still spectrogram of these channels can help in measuring the efficiency of OSSA in spectrum utilization. Figures 4.5 and 4.6 depicts this spectrogram and time course of channel occupation. The results presented in Figures 4.5 and 4.6 have been obtained by using wifisurveyor Wi-Fi spectrum analyzer.

Figure 4.5: Channels Spectrogram by Deploying OSSA

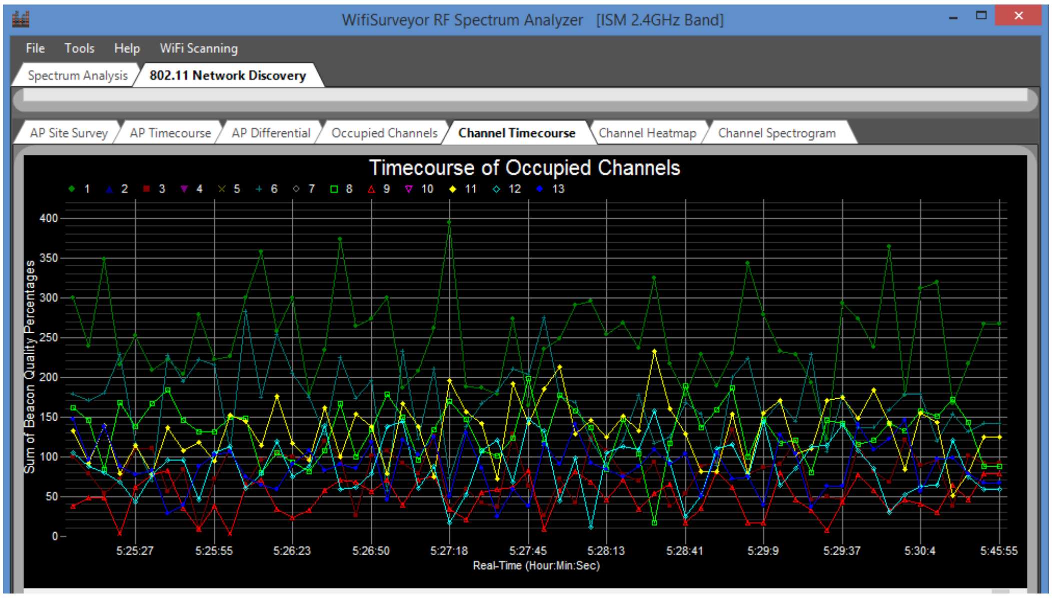


Figure 4.6: Channels Time-Course by Deploying OSSA

These results show that spectrum utilization is significantly enhanced and nodes are spreading their signals even on overlapping channels. The use of overlapping channels, can be explained by the operational mechanism of OSSA. Since OSSA considers spectrum resource as combination of frequencies instead of discrete channels, and these frequencies are assigned irrespective of channels. Therefore, spectrogram shows the use of overlapping channels in addition to standard non-overlapping ones.

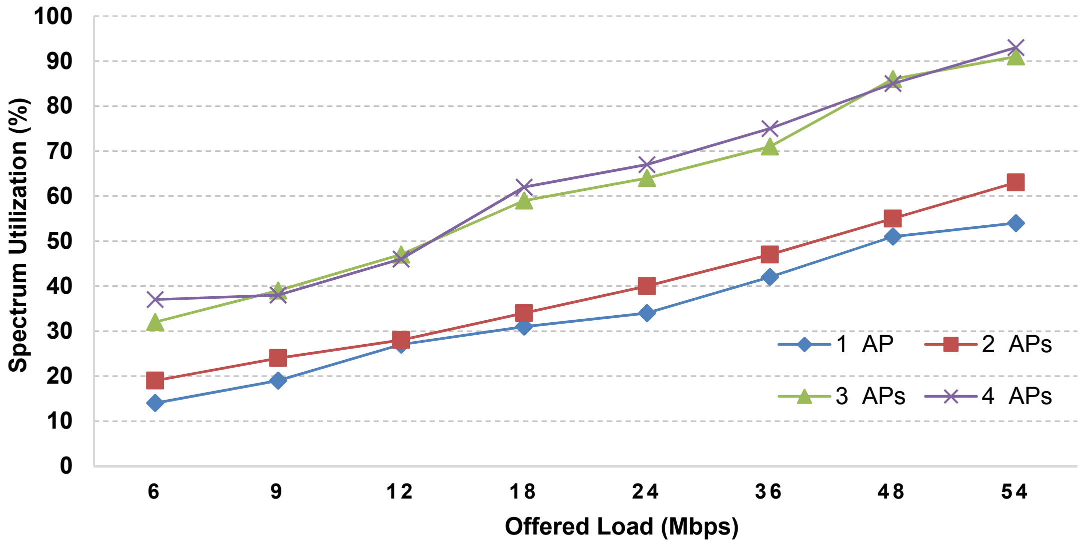


Figure 4.7: Spectrum Usage by Implementing OSSA on Different number of APs

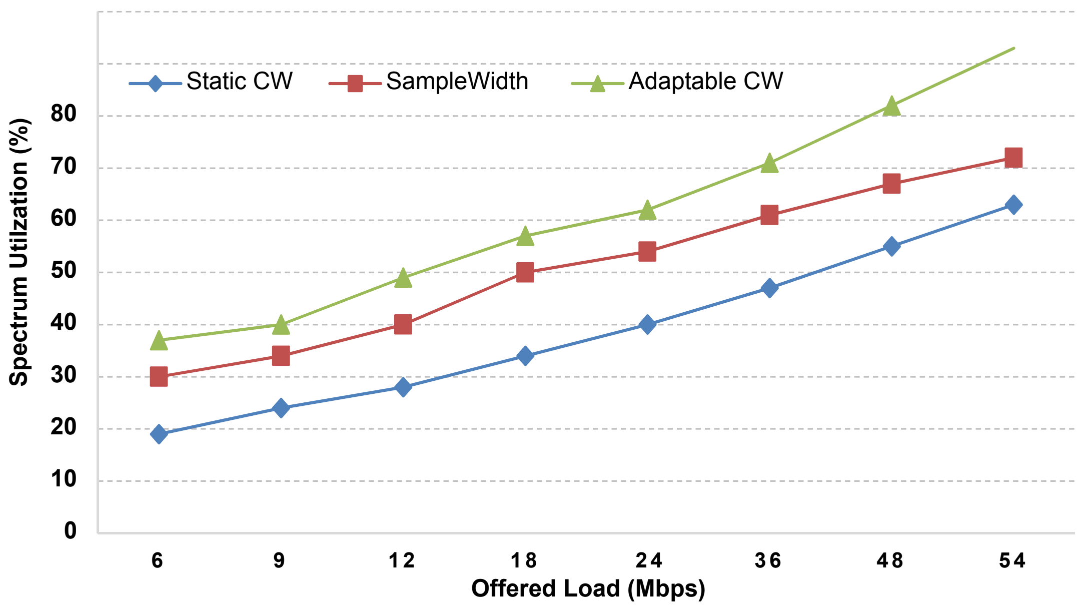


Figure 4.8: Comparison of Spectrum Usage

Figure 4.7 enumerate the effect of implementing OSSA on 1, 2, 3 and 4 APs in interference range of each other. It is appraised that, if we use 4 APs, the spectrum utilization is more than 90 %. Since OSSA minimizes interference by implementing flexible channelization, it results in significantly increased spectrum utilization. Figure 4.8 presents a comparison of spectrum use of OSSA with static and SampleWidth channel allocation schemes. It has been noted that OSSA performs significantly better than its counterparts. This performance gain is due to the maximum utilization of sub-carrier frequencies and high granularity in channel adaptation mechanism.

4.4.2 Throughput Analysis

One of the most important factor in measuring network efficiency is achieved throughput. We have evaluated our proposed algorithm for throughput gains, and compared the results with achieved throughput of standard implementation and with SampleWidth . The achieved throughput is averaged out on all APs for accurate calculation of network capacity.

Figure 4.9 and Figure 4.10 present effects of channel width variations on TCP and UDP traffic by using different modulation schemes.

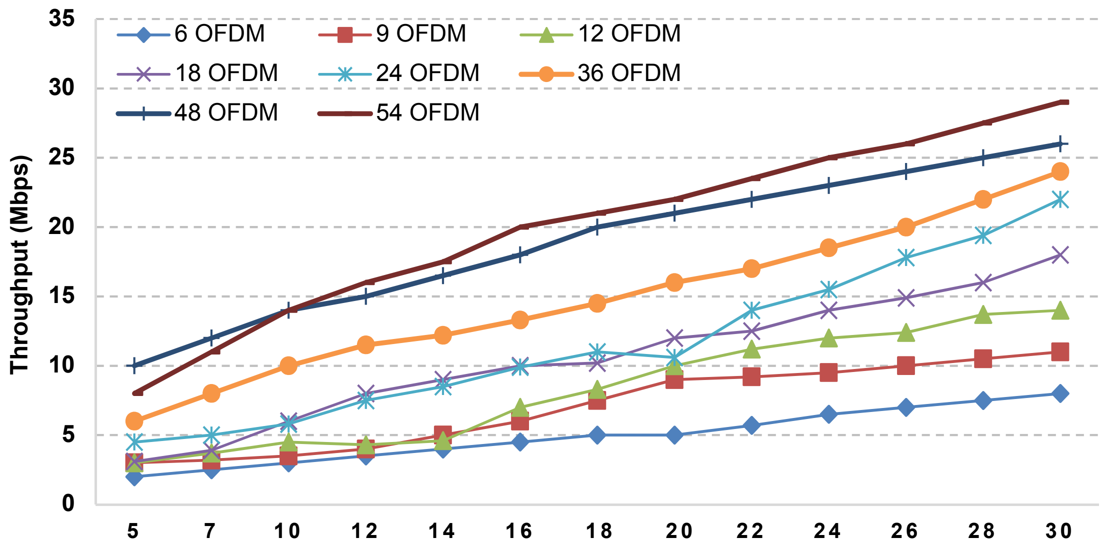


Figure 4.9: Effect of Channel Width with Different Modulations on TCP Traffic

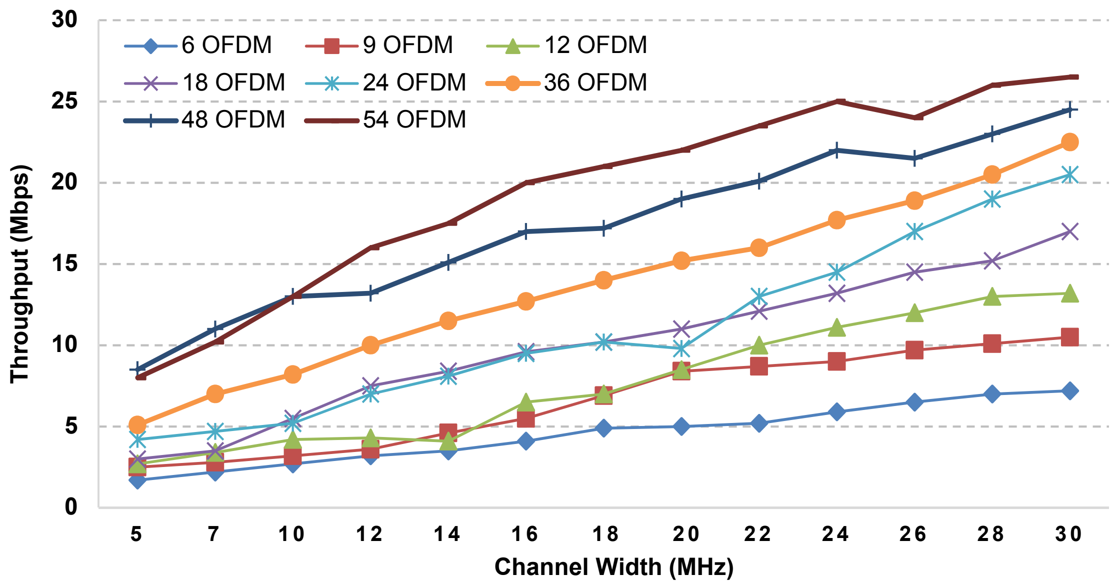


Figure 4.10: Effect of Channel Width with Different Modulations on UDP Traffic

The results show that throughput does not have linear relationship with channel width. For example in achieved results, throughput at channel width of 5 MHz using 54 OFDM modulation is 8 Mbps, while width of 10 MHz does not exactly doubles the throughput. We have observed that wider channels are inherently more susceptible to interference, delay spread and bit error rates resulting in decreased throughput. Another prominent factor involves in this behaviour is channel switching overhead. Moreover, preamble based detection mechanism is not very proficient in estimation of channel width which may result in frame losses due to inaccurate width detection.

Figure 4.11 and Figure 4.12 show results of implementation of guaranteed data rate at different APs. We implemented OSSA by fixing data rate of one, two and three participating APs in different experiments to evaluate its effect on other APs. These results can be used to evaluate the effect of OSSA in implementing quality of service classes. Figure 4.13 shows the results of OSSA when all participating APs are working in saturated conditions.

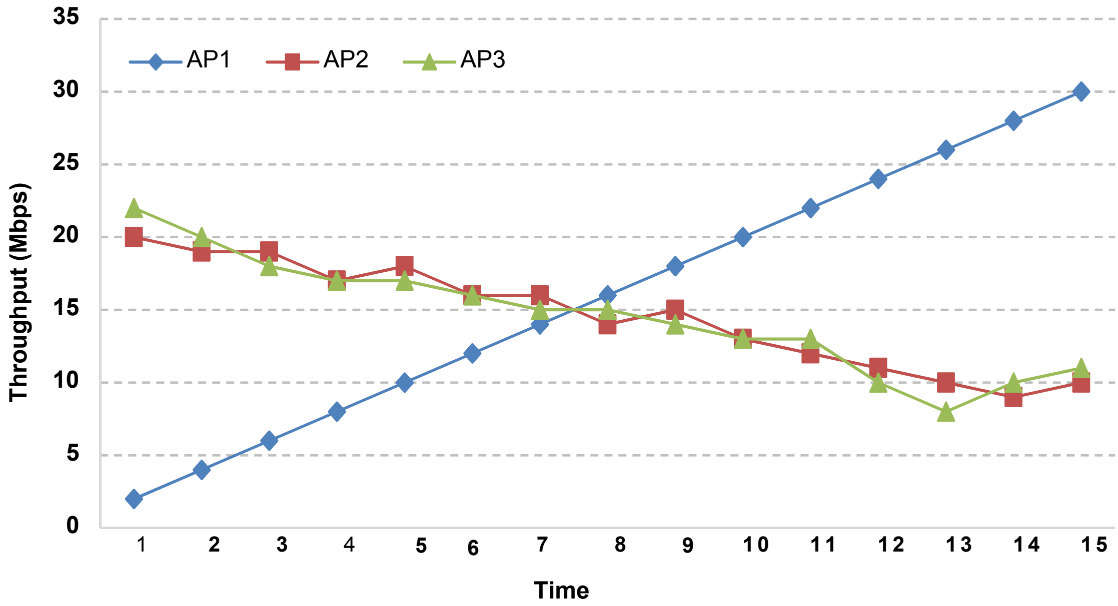


Figure 4.11: Throughput Analysis When AP 1 is Fed Data Rate While AP 2 and AP 3 are Working in Saturation Mode

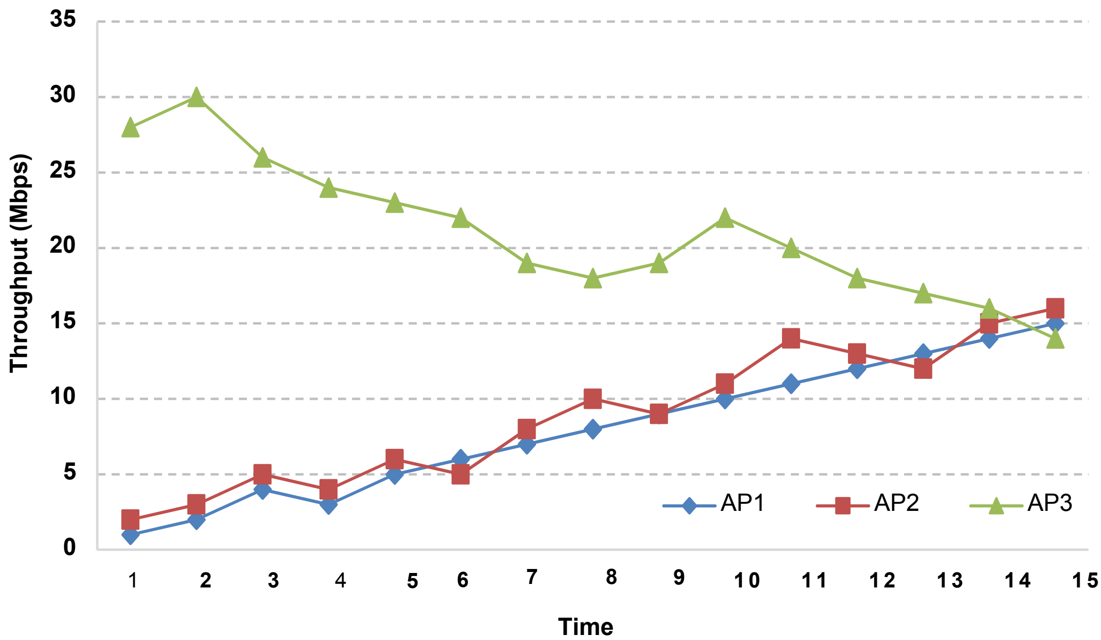


Figure 4.12: Throughput Analysis When AP1 and AP2 are Fed Data Rate and AP3 is Working in Saturation Mode

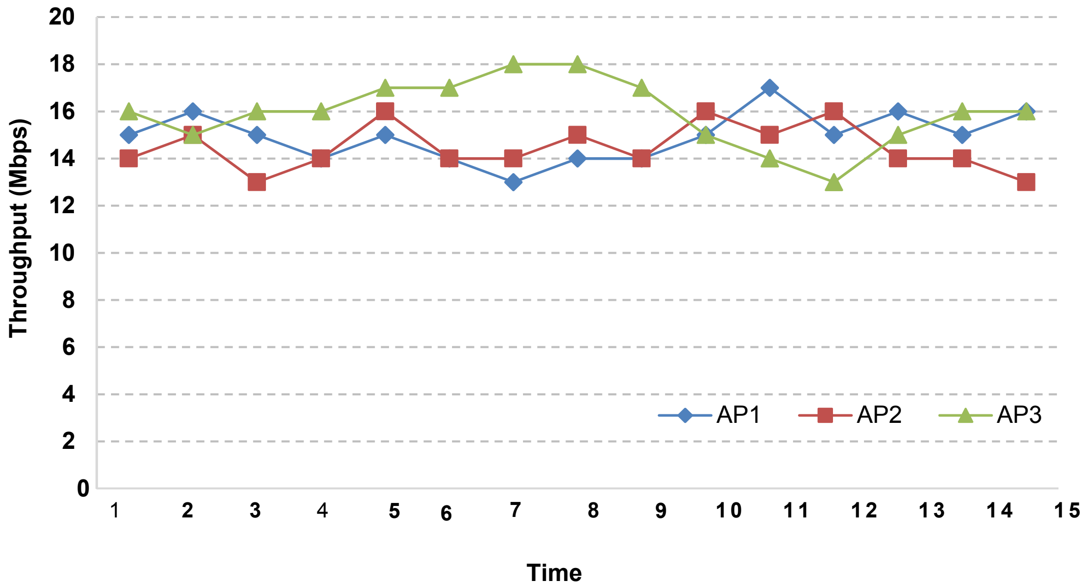


Figure 4.13: Throughput Analysis When All APs are Working in Saturation Mode

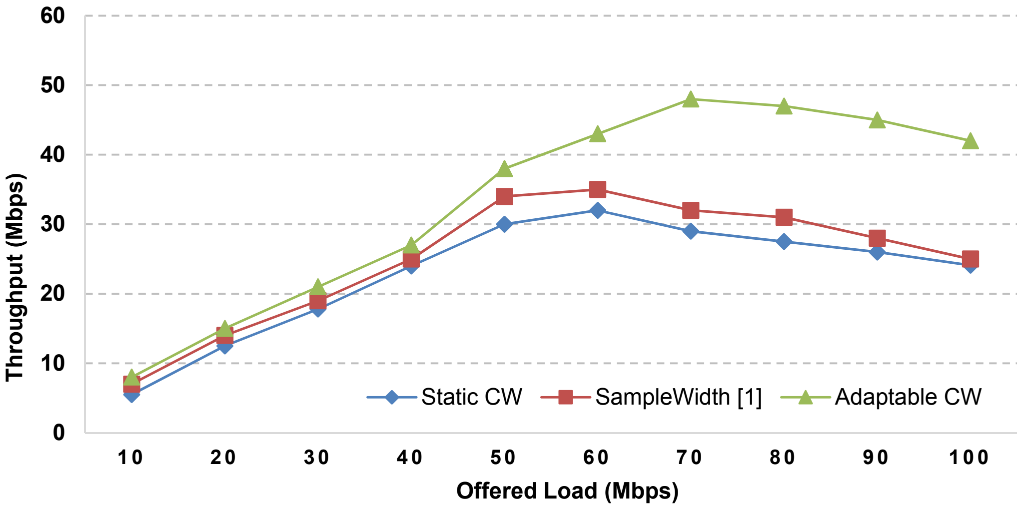


Figure 4.14: Throughput Comparison with Standard and SampleWidth Algorithms

The achieved results show that available spectrum can be shared efficiently and fairly among APs by implementing OSSA. Figure 4.14 presents a comparison of OSSA with standard implementation and SampleWidth algorithms. From this comparison it is evident that OSSA outperforms the standard implementation and is also better than SampleWidth algorithm.

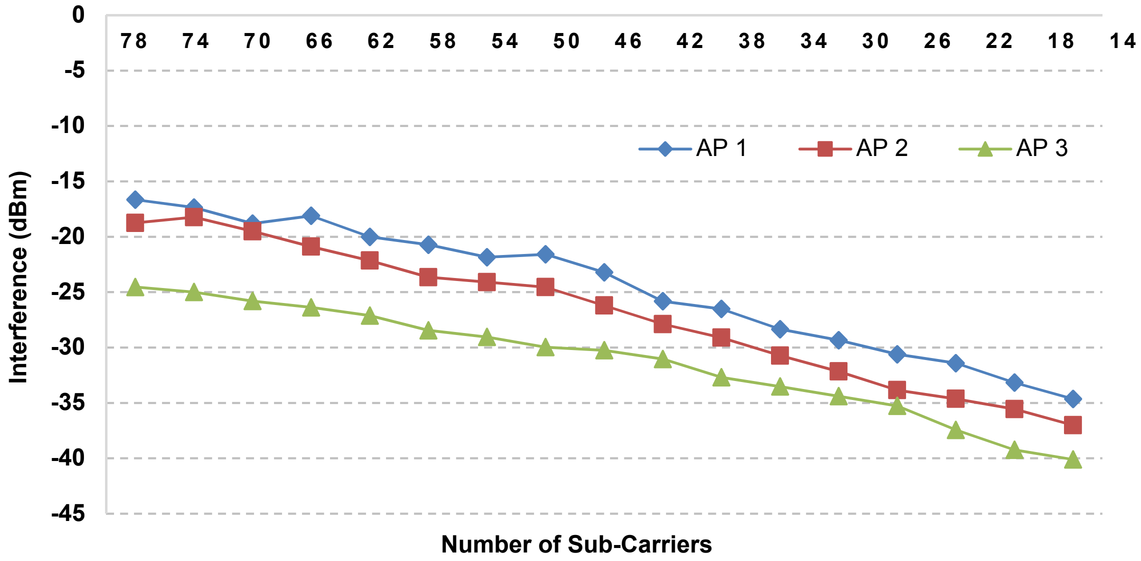


Figure 4.15: Channel Width Assigned to AP 1 is Varied from 30 MHz (78 Sub-Carriers) to 5 MHz (12 Sub-Carriers) While Channel Width of AP2 and AP3 are Fixed at 20 MHz (52 Sub-Carriers)

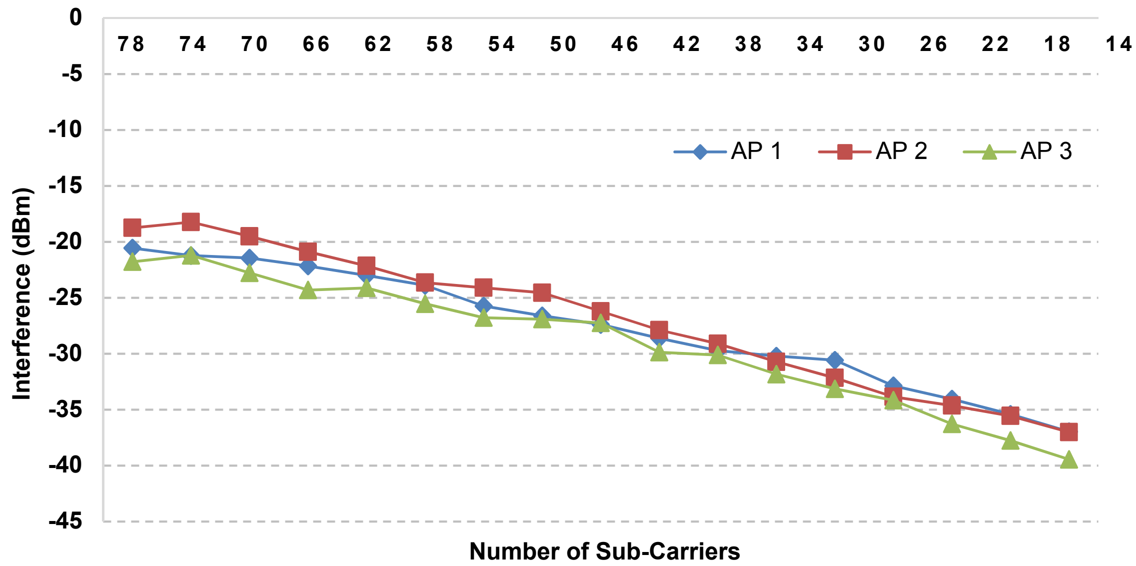


Figure 4.16: Channel Width Assigned to AP2 is Varied from 30 MHz (78 Sub-Carriers) to 5 MHz (12 Sub-Carriers) While Channel Width of AP1 and AP3 are Fixed at 20 MHz (52 Sub-Carriers)

When achieved throughput is compared with standard implementation, the improvement becomes equal to 30%. This high performance gain is a direct result of efficient and enhanced spectrum utilization which is a distinctive characteristic of OSSA over its contemporary techniques.

4.4.3 Interference Management

Flexible channelization can play a vital role in interference management of wireless networks. Considering the importance of this aspect in performance of wireless networks, we carried out a detailed analysis of OSSA on interference management. This evaluation has been made by conducting series of experiments with different variations in number of APs, Offered load and required throughput.

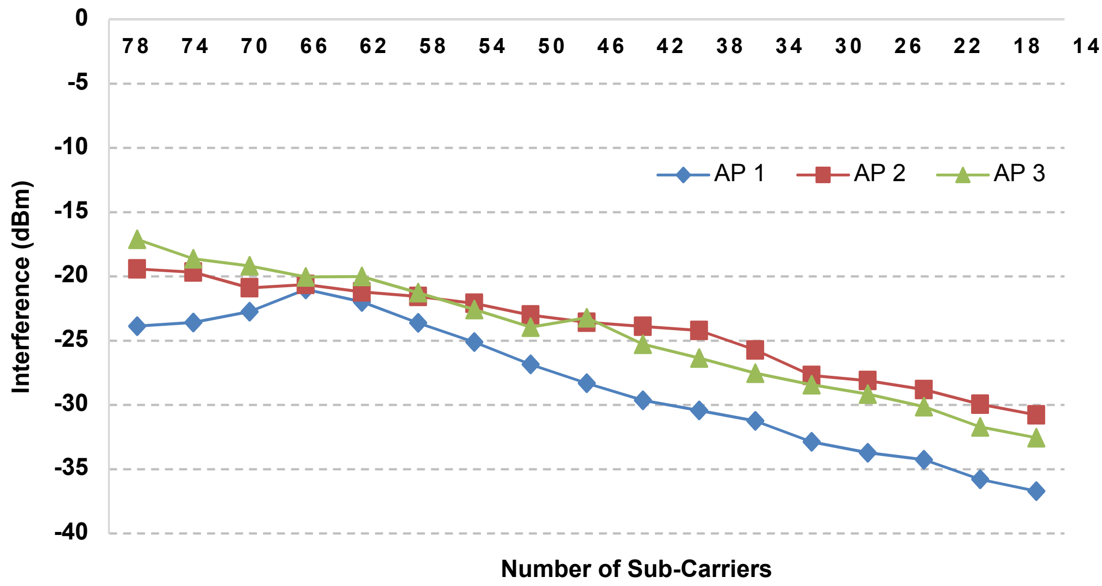


Figure 4.17: Channel Width Assigned to AP3 is Varied from 30 MHz (78 Sub-Carrier) to 5 MHz (12 Sub-Carriers) While Channel Width of AP1 and AP2 are Fixed at 20 MHz (52 Sub-Carriers)

Figure 4.15, Figure 4.16 and Figure 4.17 demonstrate the interference calculations when flexible channelization is implemented in parallel to standard implementation while Figure 4.18 present results when all APs are configured using flexible channelization.

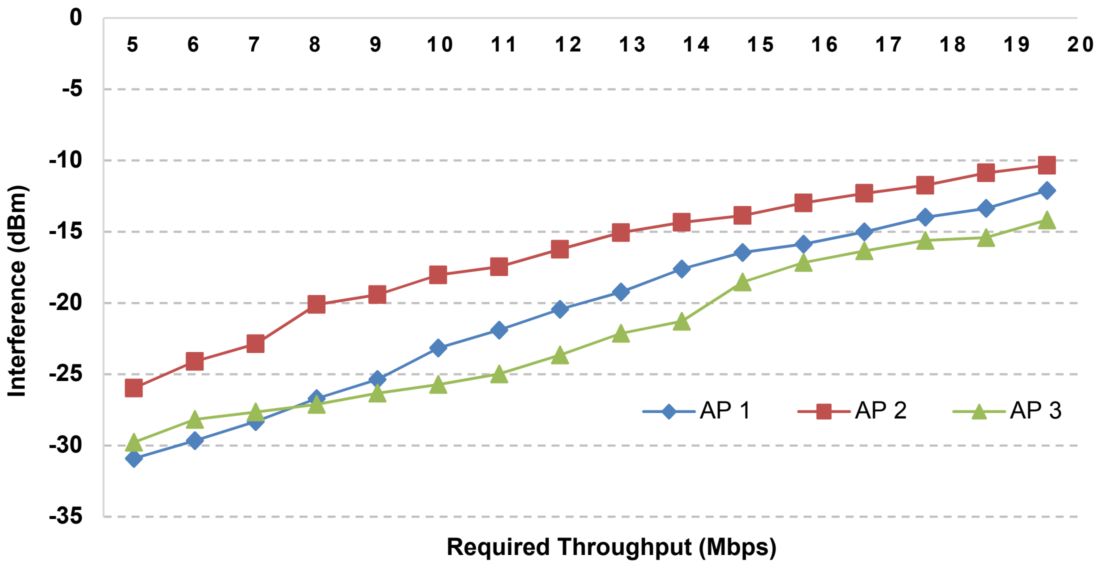


Figure 4.18: Interference Calculations with Employing Varying Number of Sub-carriers at Different APs

The results presented in Figure 4.15 through 4.18 show that wider channel widths cause relatively high interference as compared to narrower widths. These results are quite obvious in a sense that more number of overlapping sub-carriers increases interference. However, this effect can be minimized by employing flexible width channels to all APs across the network. The results of this setting is given in Figure 4.18. Implementation of OSSA on all APs in a network reduces interference by almost 25 % as compared to static width channel assignment. The comparison has been given in Figure 4.19 and Figure 4.20.

This minimized interference is a result of adaptable subcarrier assignment to APs. When channel width of one AP increases, it triggers a subsequent decrease in channel width of adjacent AP(s). In this way the spectrum resource is shared optimally with an added advantage of reduced interference.

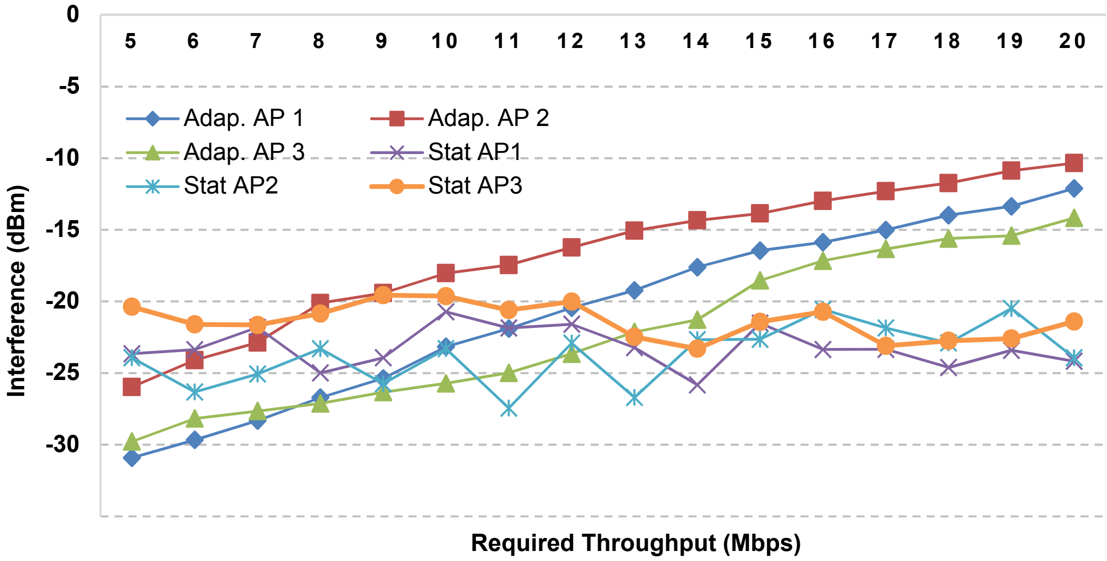


Figure 4.19: Interference Comparison of OSSA with Static Channel Assignment

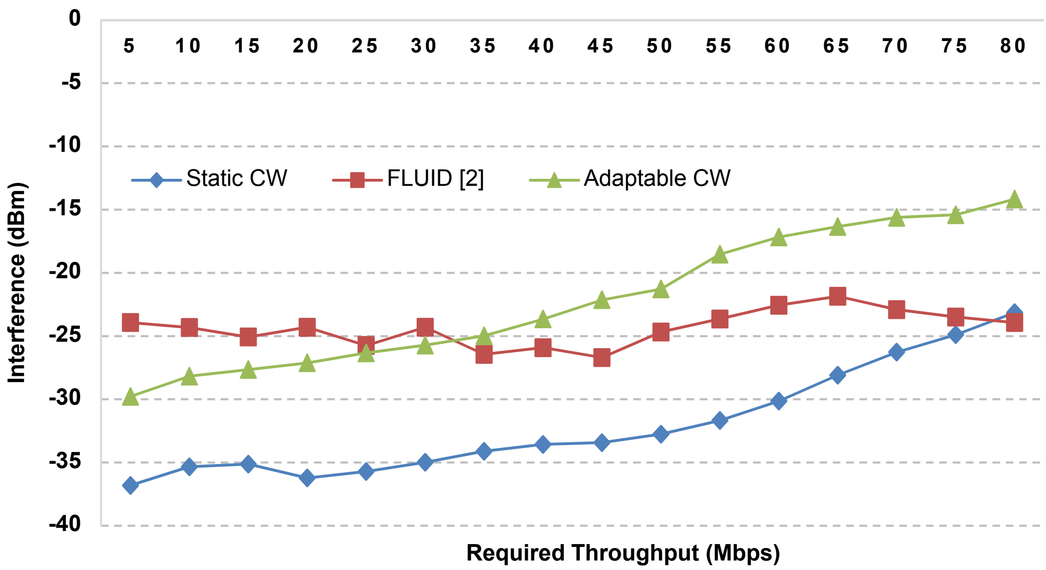


Figure 4.20: Interference Comparison of Measured, Actual and FLUID algorithm

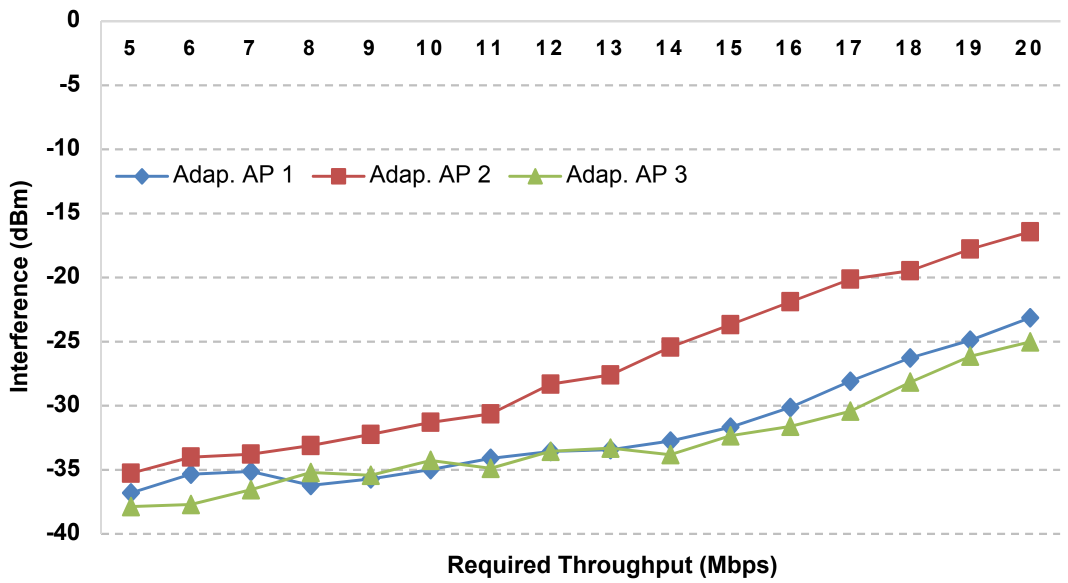


Figure 4.21: Interference for Adaptable Channel Assignment having Maximum Separation of Frequencies

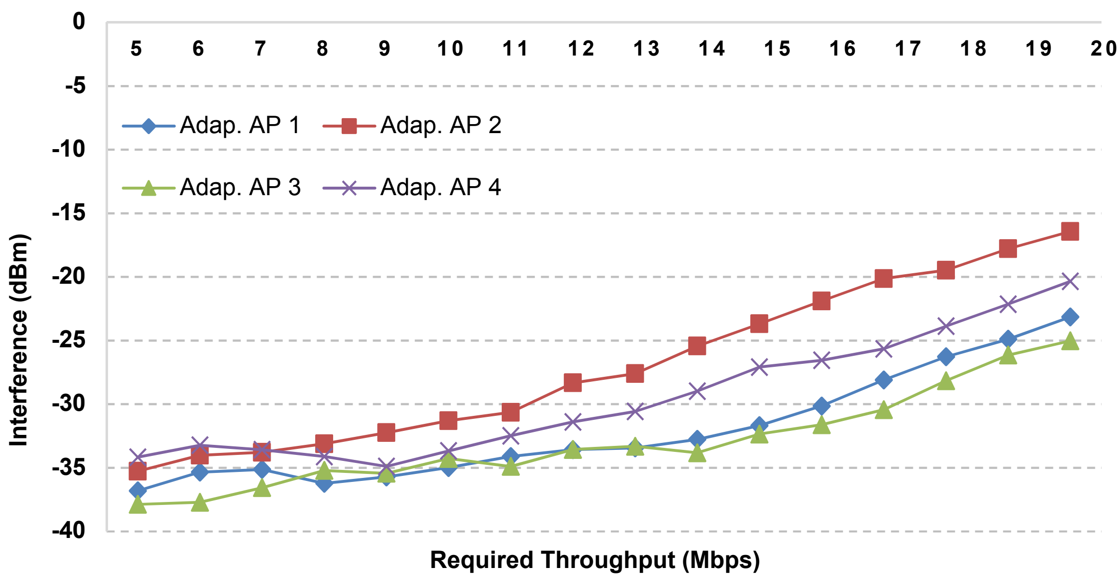


Figure 4.22: Interference When Fourth AP is Introduced with OSSA Implementation

We have evaluated the packing of flexible width channels based on maximum separation of subcarrier frequencies. This maximum separation ensures that transmission channels are as far apart as possible. This maximum separation further reduces the interference. Figure

4.21 demonstrate the interference for OSSA implementation with maximum separation of frequencies.

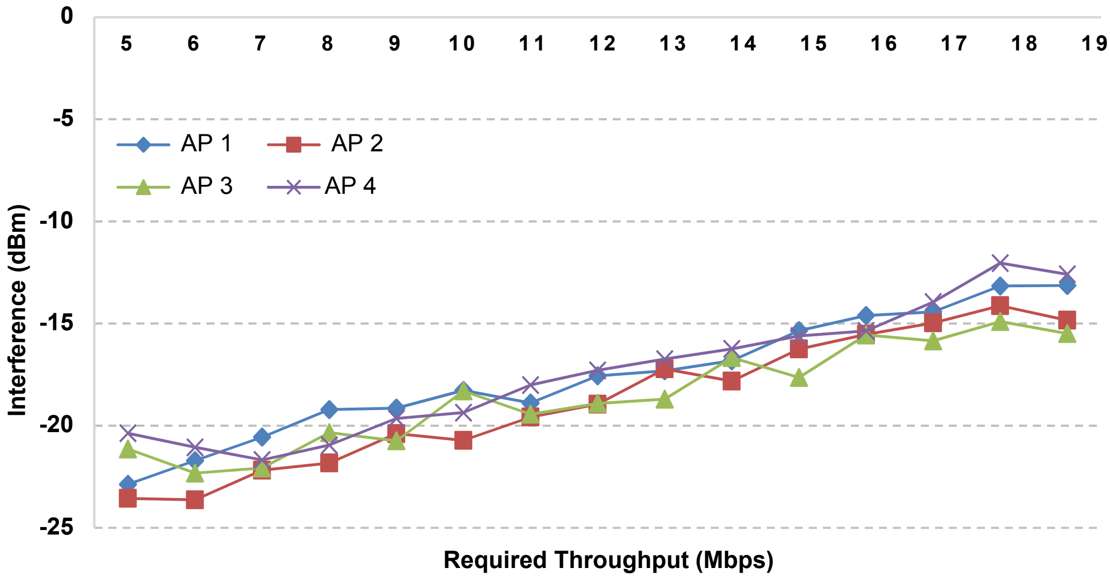


Figure 4.23: Interference When Fourth AP is Introduced in Static Channelization Mode

As explained in Section 1.2, the density of wireless nodes is very high in public networks. This large user base can only be provided connectivity by deploying large number of APs. To assess the performance of OSSA implementation in such scenarios, we have deployed four APs in interference range of each other. The results gathered are presented in Figure 4.22. We have also implemented standard channels to these APs in different experiment for comparison. The results for standard implementation is given in Figure 4.23. The implementation of OSSA on these 4 APs can manage quite efficiently as compared to standard channel assignment. It has been marked that OSSA decreases channel width optimally of all APs in case of increase in interference over a threshold. Through this experiment it is also evident that OSSA is scalable and efficient for networks with high AP density in a relatively small area. The insignificance in increase of number of APs is a result of automatic adjustment of channel widths that reduces channels overlapping and consequent interference reduction.

4.4.4 Analysis of Bit Error Rate and delay spread effect

The width of transmission channel has a significant impact on bit error rates. Wider channels employing higher order modulations incur high bit error rates compared to narrower channels with lower order modulations. The bit error calculations for different channel widthd employing varied modulation orders is given in Figure 4.24. No error correction or detection mechanisms have been deployed and a single bit error in header, payload or checksum can cause the frame to drop. The total sent and received frames are collected at all the nodes by using Wireshark packet sniffer. An exclusive-OR operation is performed for the dropped and originally transmitted frames to calculate the bit error. As shown in Figure 4.24, the wider channel widths and higher modulation schemes are more prone to errors. The reason behind the high BER is CCI and frame preamble based frequency detection as explained earlier.

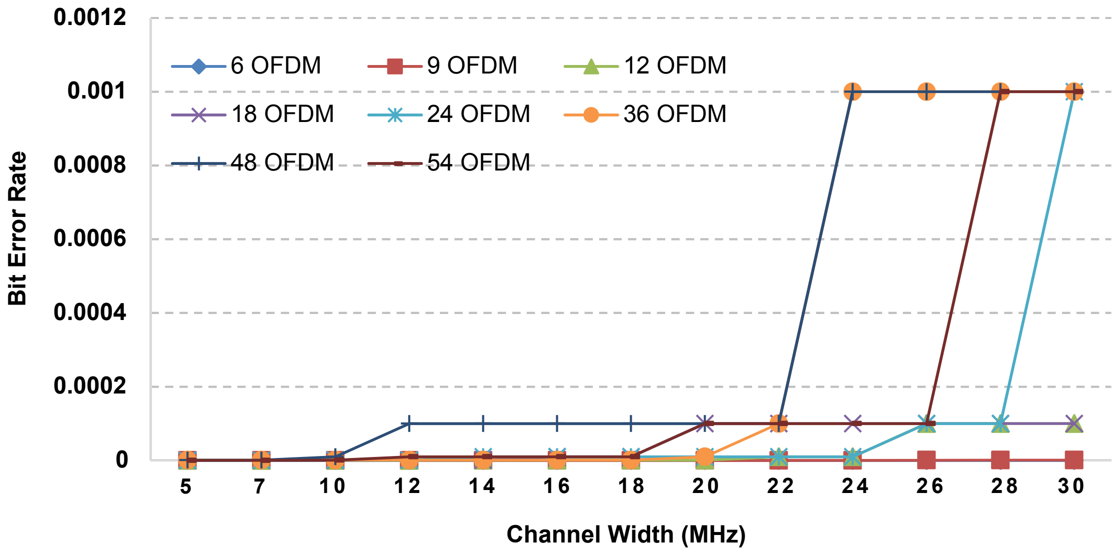


Figure 4.24: Bit Error Rate of Channel Widths Using Different Modulation Schemes

For calculations of signal delay spread we have implemented a nano-second counter on one AP. Since all the APs are placed in closed proximity within the same room, therefore, it is assumed that delay spread is same for each deployed AP. The time difference between the first and last received signal is calculated by using the nano-second counter. Since, wider channels have more number of allied frequencies, they experience more delay spread as compared to narrower channels. The effect of delay spread for different channel widths is shown in Figure 4.25.

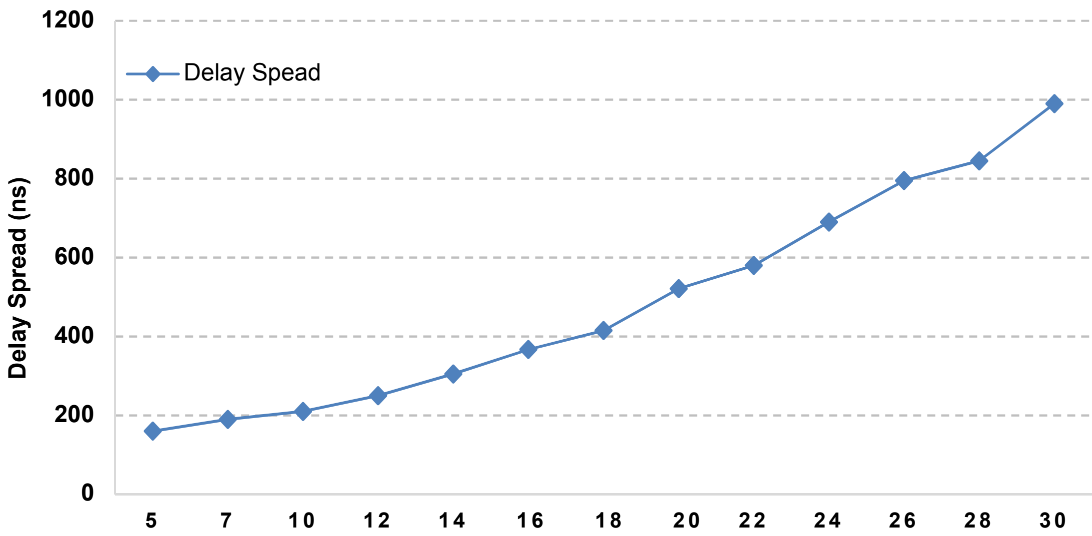


Figure 4.25: Delay Spread on Different Channel Widths

4.4.5 Analysis of Range and Power Consumption

Power consumption of Wi-Fi enabled devices is critically importance especially in case of hand held Wi-FI gadgets. For calculations of power consumption, we have connected the transceiver USRP daughter cards with digital power supply. The power consumption of standard WLAN adapter in transmitting mode ranges from 1400 mW for 3Com WLAN PCI Card with XJACK Antenna to 2750 mW for Cisco Aironet 350 WLAN PCI adapter [16]. Effect of implementing OSSA on power consumption has been analyzed by varying power supply from 800 mW to 2800 mW for different channel widths and SS has been measured at different transmission distances. The obtained results have been shown in Figure 4.26 and Figure 4.27. The minimum power sensitivity of receiver antenna was -96dBm (very low). From achieved results it is evident that we can save substantial amount of power by employing narrower channel widths without significantly decreasing SS. The reason behind this high power efficiency is high spectral efficiency of narrow bandwidth channels. Narrow channels require less amount of per MHz power and experiences lower channel fading effects.

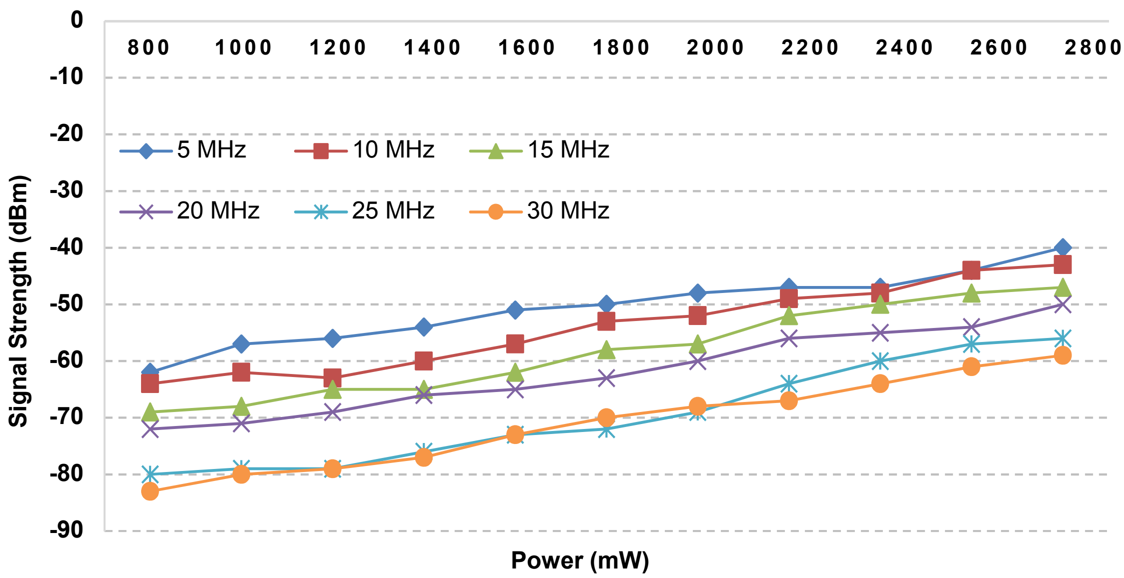


Figure 4.26: Power Consumption and Signal Strength of Different Channel Widths

For calculations of transmission range of different channel widths, we have performed experiments by placing connected nodes at different distances in both Line of Sight (LOS) and Non Line of Sight (NLOS) settlement. The SS of different channel widths has been measured to enumerate the effect of distance and obstacles in path of transmission signal. The transmission power has been kept constant at 2000 mW for both LOS and NLOS settlements. The results for LOS communication are given in Figure 4.28. For calculation of NLOS communication for two scenarios (with one and two brick walls of 7 inches thickness each) between sender/receiver pair are given in Figure 4.29 and Figure 4.30 respectively. The achieved results show that both transmission range and penetration capability of narrow band channels is significantly higher than wider width channels.

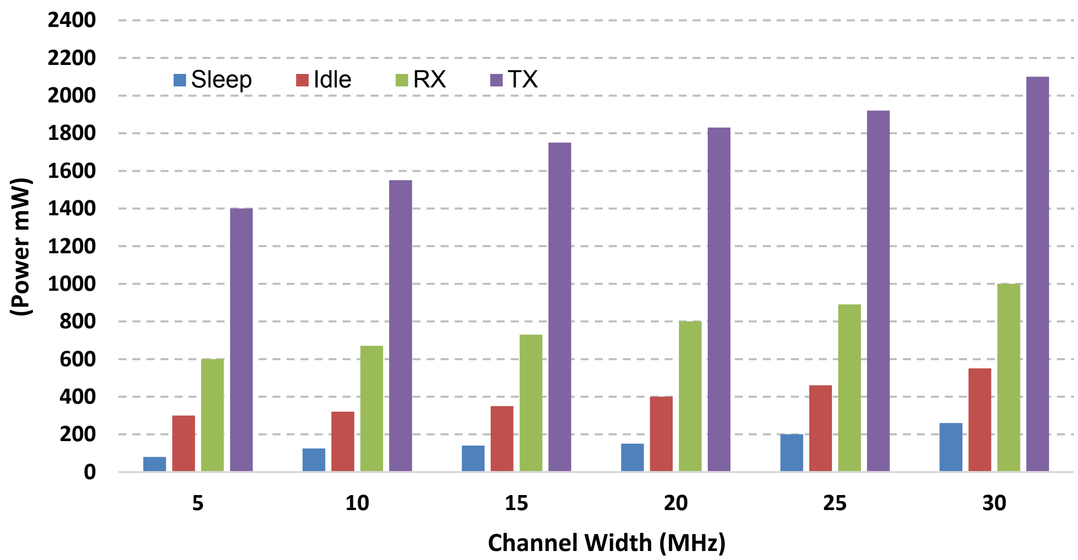


Figure 4.27: Power Consumption in Different Operational Modes

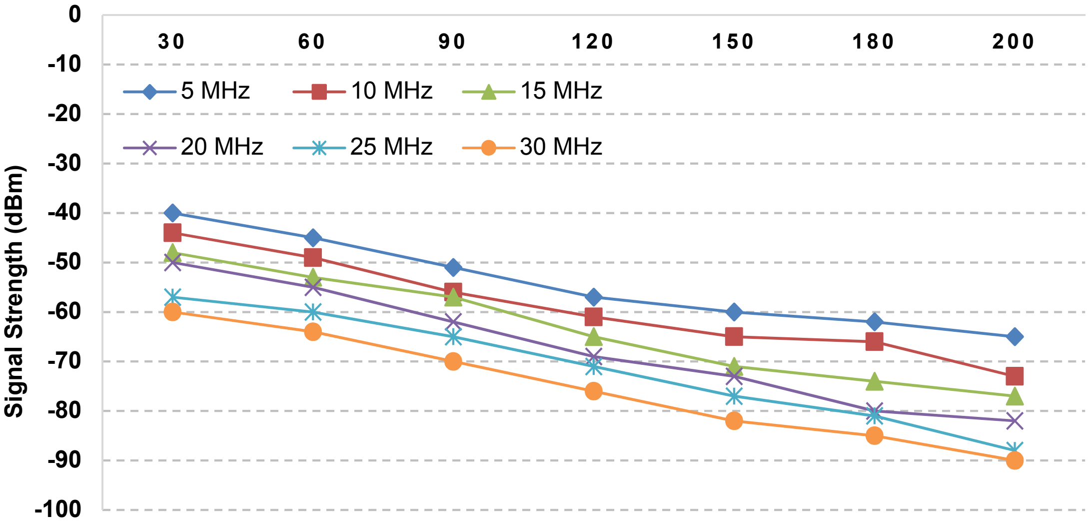


Figure 4.28: Signal Strength at Different Distances for LOS Communication

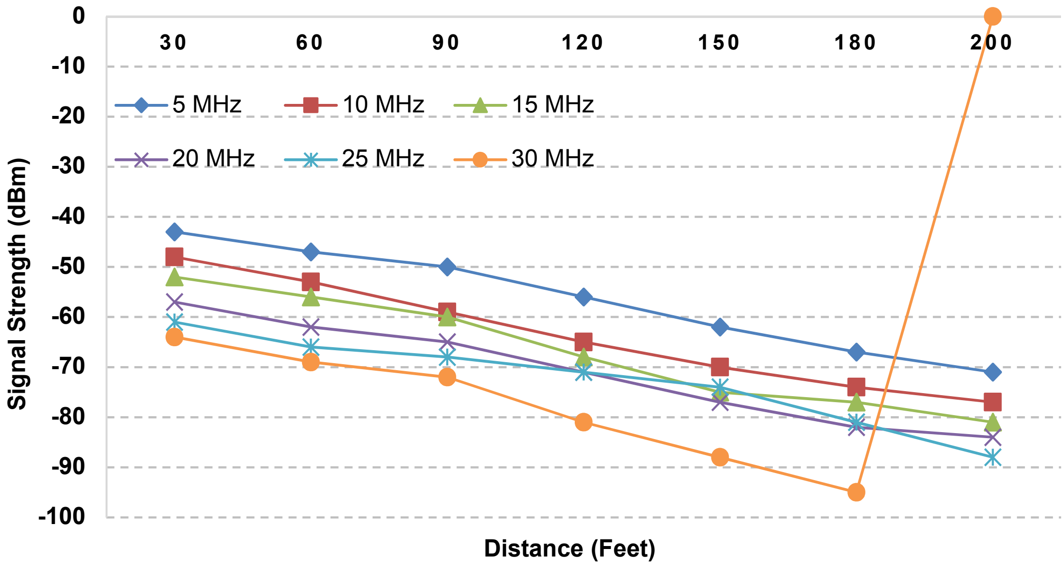


Figure 4.29: Signal Strength at Different Distances for NLOS Communication With One Obstacle

This effect can be explained on the basis of per MHz available power and spectral

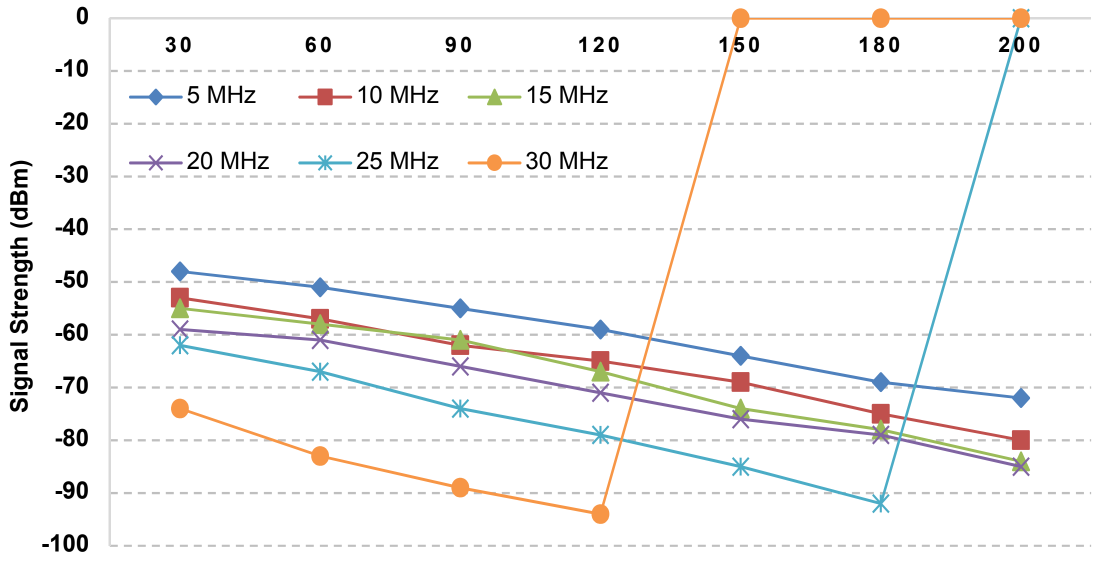


Figure 4.30: Signal Strength at Different Distances for NLOS Communication With Two Obstacle

characteristics of narrow and wide width channels. Since narrow width channels have more per MHz available power than wide width channels and have high spectral efficiency,therefore, better SS values are achieved. The vertical jump of signal strength as given in Figures 4.29 and Figure 4.30, are the points where no signal power is present.

4.5 Confidence Interval of Achieved Results

The confidence interval and allied statistical properties for achieved results of throughput, interference and spectrum utilization are give in table 4.3, table 4.4 and table 4.5 respectively.

Table 4.3: Confidence Interval and Statistical Properties of Throughput Analysis

Measure	Throughput (Mbps)											
Algorithm	OSSA						SampleWidth					
Channel Width (MHz)	5	10	15	20	25	30	5	10	15	20	25	30
Sample Size	8	8	8	8	8	8	8	8	8	8	8	8
Mean	10.41	14.31	20.3	22	25.3	30	9.5	12.5	17.1	20.6	22.1	26.0
Standard Deviation	1.00	0.91	1.14	1.15	1.06	1.20	1.33	1.25	1.71	1.56	1.38	1.40
Sample Variance	2.06	0.84	1.3	1.33	1.14	1.44	1.78	1.56	2.93	2.43	1.91	1.97
Range	3	2.4	3.2	3.4	2.8	3	3.3	3.4	4.3	4.1	3.7	4.1
Minimum	8.7	13.1	18.5	20.3	23.7	28.5	7.9	10.9	15.1	18.4	20	23.7
Maximum	11.7	15.5	21.7	23.7	26.5	31.5	11.2	14.3	19.4	22.5	23.7	27.8
Standard Error	0.35	0.32	0.40	0.40	0.37	0.42	0.47	0.44	0.60	0.55	0.48	0.49
Confidence Level (95 %)	0.83	0.76	0.95	0.96	0.89	1.0	1.11	1.0	1.43	1.30	1.15	1.17

Table 4.4: Confidence Interval and Statistical Properties of Interference Analysis

Measure	Interference (dBm)											
Algorithm	OSSA						FLUID					
Offered Load (Mbps)	5	8	11	14	17	20	5	8	11	14	17	20
Sample Size	8	8	8	8	8	8	8	8	8	8	8	8
Mean	-28.9	-27.4	-25.3	-17.0	-15.0	-12.1	-26.0	-25.1	-24.4	-23.9	-20.4	-25.4
Standard Deviation	1.43	1.53	1.27	1.16	1.56	1.19	1.42	1.73	1.71	1.43	0.79	1.61
Sample Variance	2.04	2.34	1.62	1.36	2.46	1.42	2.03	2.99	2.95	2.04	0.62	2.60
Range	3.8	4	3.4	2.9	4	3.2	4	4.4	4.4	4.3	2.4	4.1
Minimum	-31	-29.4	-27.3	-18.7	-17.1	-13.9	-28.1	-27.3	-26-5	-26.1	-22	-27.5
Maximum	-27.2	-25.4	-23.9	-15.8	-13.1	-10.7	-24.1	-22.9	-22.1	-21.8	-19.6	-23.4
Standard Error	0.50	0.54	0.45	0.41	0.55	0.42	0.50	0.61	0.60	0.50	0.28	0.57
Confidence Level (95 %)	1.19	1.27	1.06	0.97	1.31	0.99	1.19	1.44	1.43	1.19	0.66	1.34

Table 4.5: Confidence Interval and Statistical Properties of Spectrum Utilization

Measure	Spectrum Utilization (%)											
Algorithm	OSSA						SampleWidth					
Offered Load (Mbps)	12	18	24	36	48	54	12	18	24	36	48	54
Sample Size	8	8	8	8	8	8	8	8	8	8	8	8
Mean	49	59	62.12	71.12	81	94	40.25	50.25	57.37	62.25	70.25	75.12
Standard Deviation	2.39	2.39	2.53	2.03	2.16	1.30	1.90	1.90	1.92	1.66	2.43	2.16
Sample Variance	5.71	5.71	6.41	4.12	5.14	1.71	3.64	3.64	3.69	2.78	5.92	4.69
Range	6	6	6	6	6	4	5	6	5	5	6	6
Minimum	46	56	59	68	78	92	38	47	55	60	67	72
Maximum	52	62	65	74	84	96	43	53	60	65	73	78
Standard Error	0.84	0.84	0.89	0.71	0.80	0.46	0.67	0.67	0.67	0.59	0.86	0.76
Confidence Level (95 %)	1.99	1.99	2.11	1.69	1.89	1.09	1.59	1.59	1.60	1.39	2.03	1.81

4.6 Chapter Summary

In this chapter, we have proposed an efficient flexible channel width adaptation algorithm OSSA, that uses measures of interference, required throughput and SS values to assign adaptable and variable width channels to APs. Thorough analytical and experimental evaluation has been carried out to evaluate the affect of OSSA on essential physical layer parameters. These parameters include throughput, network capacity, interference, BER, spectrum utilization, power consumption and transmission range. We have concluded that OSSA use available frequency spectrum optimally to achieve best possible network performance. It also adds benefit of channel width flexibility while simultaneously reducing interference. Achieved results shows a significant improvement of almost 30% in achieved network capac-ity with different combinations of channel widths and interference measurements.

It has also been observed that proposed algorithm reduces interference by almost 25 % as compared with interference of static channel assignment. It has been concluded that, use of flexible width channels increase network capacity and reduce interference simultaneously, while both of these quantities are conflicting in standard implementation and a trade off is required for optimal performance.

Chapter 5

Mitigation of MAC Layer Performance Anomaly in 802.11 WLANs Through Adaptable Channelization

Current 802.11 WLANs support multiple data rates at physical layer based on SNR between sender/reciever pairs to minimize the number channel induced errors. This support is provided by using adaptive MCS. However, the differential data rate capability introduces a serious performance anomaly in WLANs. In a wireless cell, comprising of several nodes with varying transmission rates, nodes with lower data rate (slow nodes) degrade the throughput of nodes with higher data rates (fast nodes). The primary source of this anomaly is rooted in channel access mechanism of WLANs which ensures long term equal channel access probability to all nodes irrespective of their transmission rates. In this chapter, we investigate the use of adaptable width channelization to minimize the effect of this irregularity in performance. It has been observed that, surplus channel-width due to lower transmission rate of slow nodes can be assigned to fast nodes connected to other APs. This diversion of spectrum resources can increase the overall throughput of the whole network.

5.1 MAC Layer Performance Anomaly

Authors in [28] provide a detailed analysis of this performance anomaly at MAC layer of WLANs. If a wireless cell contains nodes with varying data rates, the throughput performance of fast nodes decreases substantially due to longer channel capturing of slow nodes. The theoretical model presented in [28] is applicable to any multi-rate 802.11 network that uses contention based channel access mechanism [1] at MAC layer. If X_s and X_f are the throughput of slow and fast nodes respectively, these can be measured as given in equation (5.1),

$$X_s = X_f = \frac{S_d}{(N-1)T_f + T_s + P_c(N) \times t_{jam} \times N} \tag{5.1}$$

where S_d is frame size, N is the number of wireless nodes and T_f and T_s is the transmission time of fast and slow nodes respectively. P_c(N) is collision probability and t_{jam} is the time elapsed in collision.

Equation (5.1) is applicable only to single cell networks. However, rapid improvements in wireless technologies have shifted the paradigm of few users, single AP networks to several APs and numerous users per AP environments. It has been observed that substantial increase in network performance can be achieved if we direct resources of network from cell with limited need to an other resource hungry cell. Adaptable width channelization [35] has been used to achieve this intelligent diversion of resources.

5.2 Contemporary Techniques for Mitigation of MAC Layer Performance Anomaly

A substantive research on mitigating the effect of MAC layer performance anomaly in multi-rate WLANs has been presented in literature. The work proposed in [39][46][36][10][38] are of premier importance to this dissertation.

In [39] authors have proposed an algorithm for performance anomaly reduction using open flow APs. The proposed model deploys a network with overlapping transmission areas and classifies the RSSI for a particular node in three categories namely low quality, medium quality and high quality. Since data rate of any transmitter is a function of RSSI, a handoff mechanism is adopted based on transmission rate of a node. If a node lies in category of low quality RSSI, the model checks if its RSSI is higher at some other AP. If RSSI is higher at some other AP then, the node is handed over to the AP with better RSSI thus increasing its transmission rate. The hand off procedure resides at AP controller which is deployed for monitoring of RSSI and other control parameters according to OpenFlow mode of operation. Authors claimed that proposed mechanism jointly reduces the effect of performance anomaly and number of hand offs thus maximizing throughput by 26.7%. However, it is evident that overlapping of transmission range at an enterprise level will require large number of APs to be deployed. Moreover, interference in overlapping regions will also increase due to reuse of same frequency channels in close vicinity.

The research work given in [46] presents a cooperative mechanism to minimize the effect of said performance anomaly. This mechanism implements modified virtual carrier sensing mechanism and proposes a modification to CTS packets. On reception of an RTS frame, the receiver samples the RSSI and estimates the data rate it can successfully decode. It embeds this estimated data rate information in CTS frame. Other network nodes overhearing the CTS frame set their NAV according to modified CTS frame. Additionally in response to CTS frame, the nodes also adjust the initial value of contention window (CW_{min}) according to the data rate of neighboring nodes. The authors evaluated the proposed mechanism by performing simulations on NS-2 and compared the results with RBAR [31] mechanism. It is concluded that, proposed mechanism outperforms RBAR and efficiently solve the MAC layer performance anomaly. However, the modifications in initial value of CW introduces a fairness problem, where nodes in the same cell will have different values of initial CW with variable probability of channel access.

In [36] authors claim that the performance anomaly model presented in [28] is only valid for networks having static channel characteristics. However, if channel conditions vary frequently, they also affect the channel access rate of wireless nodes. The nodes with better SNR have higher channel access rate as compared to nodes having lower SNR. Since nodes with low SNR suffers more packet losses than node with higher SNR. Due to inherent incapacity, the MAC layer of WLANs cannot differentiate between channel induced and congestion induced packet losses. It considers that packet loss is only resulted due to congestion and tries to minimize it by exponentially increasing its CW. Authors have concluded that after a small interval of time the nodes with lower SNR have substantially large CW sizes and thus their probability of channel access is very low. This assertion ensures that the effect of MAC layer performance anomaly can be substantially reduced by using time-varying and time-correlated channels with rayleigh fading effects. However, since majority of WLANs specifies flat fading channels for communication thus the proposed mechanism cannot be implemented in traditional WLANs.

The work presented in [10] mitigates the effect of MAC anomaly by controlling the value of back off contention window based on SS of a node. Authors concluded that, lower values of contention window for nodes having higher SNR considerably reduces the effect of MAC anomaly. This mechanism controls the channel access rate of nodes based on their SNR with nodes having higher SNR have high channel access rate and vice versa. However, this mechanism again introduces the fairness problem with differential channel access rates for different nodes and breaks fair channel access semantics of WLANs.

In [38] an anomaly mitigation scheme for TCP Friendly Rate Control (TFRC) protocol is presented. For simplicity, we have named this approach as Channel Occupancy Time based Anomaly mitigation (COTAM). In this approach nodes estimate their share of leftover channel occupancy time and only make their communication in that slot. In this way each node shares the channel equally thus minimizing the effect of performance anomaly. However, this approach is not viable in scenarios where some nodes do not have data to send. In such cases, the nodes having data to send will not transmit beyond their share of channel access time even if channel is free. Hence the network resources will remain under-utilized.

Majority of the techniques for mitigation of MAC layer anomaly restricts the channel access rate of nodes having lower transmission rate. This methodology adds further disadvantage to already poor performance of these nodes. This below par performance of slower nodes, in turns negatively affects the overall performance of complete network. However, use of adaptable channelization can simultaneously mitigate the MAC performance anomaly in addition to rescuing slower nodes from starvation of network resources.

5.3 MAC Layer Independent Anomaly Prevention (MIAP)

In this section, we have investigate the use of adaptable channelization to minimize the effect of this performance anomaly. We observed that, if channel width is assigned to nodes on basis of their transmission rates, it can substantially increase the overall capacity of whole network. The proposed solution implements MAC layer independent anomaly prevention (MIAP) algorithm that assigns channel width to nodes based on their transmission rate.

5.3.1 Network Model

Consider a network of N_t nodes operating at transmission rate R. The set of N_t nodes is divided in two subsets of N_s and N_f such that $N_s, N_f \in N_t$ and $(N_s \cup N_f) = N_t$, where N_s consists of all the nodes transmitting below a threshold transmission rate R_s and referred as slow nodes. The other subset of N_f nodes transmit above the threshold transmission rate (R_s) and referred as fast nodes. The N_t nodes of network are associated with K_t access points with K_i denoting any i^{th} AP. The maximum number of nodes associated to any AP K_i is n_t such that $n_t = n_s + n_f$ and $n_t \in N_t, n_s \in N_s$ and $n_f \in N_f$, where n_s and n_f are the number of slower and faster nodes attached to any single AP K_i. The K_t access points of network form K identical circles in which their transmission can be received and decoded correctly. The association of nodes with an AP is independent of each other and follows Poisson distribution with probability density function λ as given by equation (5.2),

$$\Pr\{n_t \rightarrow K_i\} = \frac{\lambda^{n_t} e^{-\lambda}}{n_t!} \tag{5.2}$$

where $n_t \rightarrow K_i$ denotes the total number of nodes (n_t) associated to an access point K_i.

Consider the probability of a slow and a fast node connected to an AP K_i is ρ and $(1-\rho)$ respectively. Then the joint probability distribution of slower and faster nodes attached to any AP K_i is given by,

$$\Pr\left\{(n_s \wedge n_f) \rightarrow K_i\right\} = \rho^{n_s}(1-\rho)^{n_t - n_s} \tag{5.3}$$

The probability that exactly s number of slow nodes are attached to any AP K_i at any given time t_i can be given as,

$$\Pr\{(n_s = s) \rightarrow K_i\} = \begin{pmatrix} n_s \\ s \end{pmatrix} \rho^s (1-\rho)^{n_s - s}, \tag{5.4}$$

for $s = 0, 1, 2, ...n_s$ and $n_s = 0, 1, 2, ...n_t$

The probability that maximum number of slow nodes attached to any AP K_i at any given time t_i is less than s can be given as,

$$\Pr\{(n_s < s) \rightarrow K_i\} = \sum_{s=0}^{n_s} \begin{pmatrix} n_s \\ s \end{pmatrix} \rho^s (1-\rho)^{n_s - s}, \tag{5.5}$$

In a similar way the probability that exactly f number of fast nodes are attached to any AP K_i at any given time t_i will be,

$$\Pr\left\{(n_f = f) \rightarrow K_i\right\} = 1 - \left\{ \begin{pmatrix} n_s \\ s \end{pmatrix} \rho^s (1-\rho)^{n_s - s} \right\} \tag{5.6}$$

and the probability that maximum number of fast nodes attached to any AP K_i at any given time t_i will not exceed f, can be given as,

$$\Pr\left\{(n_f < f) \rightarrow K_i\right\} = 1 - \left\{ \sum_{s=0}^{n_s} \begin{pmatrix} n_s \\ s \end{pmatrix} \rho^s (1-\rho)^{n_s - s} \right\} \tag{5.7}$$

for $f = 0, 1, 2, ...n_f$ and $n_f = 0, 1, 2, ...n_t$

Similarly, the probability for slow and fast nodes operating in whole network at any given time t_i can be calculated by using equation (5.8) and (5.9) respectively.

$$\Pr\{(N_s \leq S) \to K_t\} = \sum_{S=0}^{N_s} \begin{pmatrix} N_s \\ S \end{pmatrix} \rho^S (1-\rho)^{N_s - S} \tag{5.8}$$

for $S = 0, 1, 2, ...N_s$ and $N_s = 0, 1, 2, ...N_t$

$$\Pr\left\{(N_f \leq F) \to K_t\right\} = 1 - \left\{ \sum_{S=0}^{N_s} \begin{pmatrix} N_s \\ S \end{pmatrix} \rho^S (1-\rho)^{N_s - S} \right\} \tag{5.9}$$

5.3.2 Mitigating the Effect of MAC Performance Anomaly

The bandwidth (B) of a channel is a sum of individual bandwidths of its sub-carriers. We can increase or decrease the width of channel by varying the number of sub-carriers in that channel using adaptable channelization. In this work, we have varied the number of sub-carriers from 12 (5 MHz channel width) to 72 (30 MHz channel width).

Let us consider that N_t wireless nodes are distributed randomly across K_t APs. The transmission probability of a slower node is τ_s and transmission probability of faster node will then be $(1-\tau_s)$. The probability that at any given time, only slow nodes are transmitting in each cell will be $(\tau_s)^{K_t}$. Similarly, the probability that only faster nodes are transmitting in a cell will be $(1-\tau_s)^{K_t}$. The joint probability distribution that only fast or slower nodes will be transmitting at any time t_i will be given as

$$\Pr\{\tau_s \vee \tau_f\} = (\rho)^{K_t} + (1-\rho)^{K_t} \tag{5.10}$$

This implies that both slower and faster nodes are transmitting in same or different cells will have the probability as given in equation (5.11)

$$\Pr\{\tau_s \wedge \tau_f\} = 1 - \{(\rho)^{K_t} + (1-\rho)^{K_t}\} \tag{5.11}$$

Since contention based CSMA/CA protocol ensures equal long term probability of channel access to all nodes irrespective of their transmission rate, equation (5.11) implies that, the overall efficiency of a network is dependent on number of slower and faster nodes in that network. In this way, we have three possible scenarios. (1) Number of slower nodes is larger than number of faster nodes that results in $\tau_s > (1-\tau_s)$. (2) Number of slower nodes is equal to the number of faster nodes that results in $\tau_s = (1-\tau_s)$. (3) Number of slower nodes is less than number of faster nodes that results in $\tau_s < (1-\tau_s)$.

If adaptable channelization is implemented and bandwidth assigned to one AP can be diverted to other AP(s) based on difference of transmission rates then we can modify theoretical model presented in chapter 4. The equation 4.10 can then be modified as follows:

$$T(n_f) = (B - B_l)\log_2\left(1 + 10\log\frac{P\,d(J_i,K_i)^{-\alpha}}{\delta + P\,\beta\,(L_i)\sum\varphi(L_i,L_j)\,d(J_i,K_j)^{-\alpha}}\right) \tag{5.12}$$

where $T(n_s)$ is the throughput of any slower node and (B_l) is the surplus bandwidth that is not required by slower node. Similarly the throughput of faster node will be,

$$T(n_f) = (B + B_l)\log_2\left(1 + 10\log\frac{P\,d(J_i,K_i)^{-\alpha}}{\delta + P\,\beta\,(L_i)\sum\varphi(L_i,L_j)\,d(J_i,K_j)^{-\alpha}}\right) \tag{5.13}$$

from equation (5.12) and (5.13), it is evident that use of adaptable channelization ensures that total throughput of the network remains same. The loss in throughput of one cell operating at slower transmission rate is rectified by the gain in throughput of another cell that is operating on higher transmission rate.

5.4 MAC Layer Independent Anomaly Prevention (MIAP) Algorithm

The elementary concept of MIAP algorithm is to divert the surplus frequency bandwidth from a cell of limited need to more resource hungry cell(s). The proposed algorithm analytically calculates the bandwidth requirement of a specific wireless node (client or AP) based on its current transmission rate. If a node is operating on lower transmission rate, its bandwidth requirement will be less as compared to the node operating at higher transmission rate. MIAP calculates the RSS and subsequent transmission rate of any node through channel reciprocity [44]. Based on these calculations, MIAP estimates the bandwidth requirement of a specific node and assigns channel of that width. The width of a channel is determined by the number of sub-carriers in that channel. For example, a narrower channel can be constituted with fewer sub-carriers compared to a channel which is wider.

MIAP divides total transmission area into K identical circles by placing an AP at the center of each of them. All APs have omnidirectional antenna limiting the transmission range and interference within the radius of the circle around each AP. We have created a scenario by assuming such a wireless network of four APs. At the initialization phase all the four APs use standard non-overlapping channels. All APs are connected to a back-end management server through a wired link which controls all the activities like spectrum allocation, transmission rate determination etc. MIAP runs at this sever. The server calculate the optimal channel width and number of sub-carriers for the spectrum allocation to AP dynamically based on the transmission rate and RSS values.

Result: $Required\ Channel\ Bandwidth(CB_{(req)})$
input : $Transmission\ Rate(TR),\ RSS$
output : $Channel\ Bandwidth\ (CB),\ Transmission\ Parameters\ (TP)$

begin
    for $N_i \in N_t$ **do**
        if $RSS(N_i)\ \leq\ RSS_{(Max)}$ **then**
            Calculate $TR_{(current)}$ && $TP \leftarrow TP\ for\ CB_{(current)}$
        else
            if $TR\ <\ TR_{(Min)}$ && $RSS\ \geq\ RSS_{(Min)}$ **then**
                do
                    $CB_{(new)} \leftarrow CB_{current} + 1.875MHz$
                    && $TP \leftarrow TP\ for\ CB_{(new)}$
                while $R(N_i) < R_{(Min)}$
            else
                $CB_{(req)} \leftarrow CB_{(new)}$
            end
        end
        if $TR\ >\ TR_{(Max)}$ **then**
            do
                $CB_{(new)} \leftarrow CB_{current} - 1.875MHz$
                && $TP \leftarrow TP\ for\ CB_{(new)}$
            while $R(N_i) \leq R_{(Max)}$
        else
            $CB_{(req)} \leftarrow CB_{(new)}$
        end
    end
end

Figure 5.1: MAC layer Independent Anomaly Prevention Algorithm

If transmission rate changes at an AP, it is communicated to the management server. The AP releases or demands spectrum resource according to its current bandwidth status. If an

AP needs more bandwidth, it notifies the server and the server check the status of available sub-carriers still not assigned to any AP. MIAP requests the server to check the demand considering the threshold values of RSS and transmission rate and decides if the increment in channel width is possible. Server then communicates the values of sub-carriers to the corresponding AP. After increasing the channel width AP starts spreading it signal by adding more frequencies to already in use sub-carriers.

On the other hand, if an AP has less bandwidth requirement it releases spectrum resource which is added by the management server in its available pool of sub-carrier frequencies for its on demand dissemination to other APs on the network. If throughput requirement of an AP decreases at any given time it sends its new status to the management server. The management server checks the in-use sub-carriers and ask the AP to reduce its channel width by spreading its signal on lesser number of sub-carrier frequencies. Algorithm 5.1 explains the working of MIAP.

5.5 Performance Results and Discussion

We have performed a series of experiments to evaluate the affect of deploying MIAP on essential network performance parameters by using varying number of network nodes on experimental test-bed given in Section 4.3. We have deployed a network of 5, 10, 15, 20, 25, and 30 nodes in each cell with varying number of slow and fast nodes. The obtained results are averaged out by collecting traces of all APs for accurate efficiency measurement of MIAP.

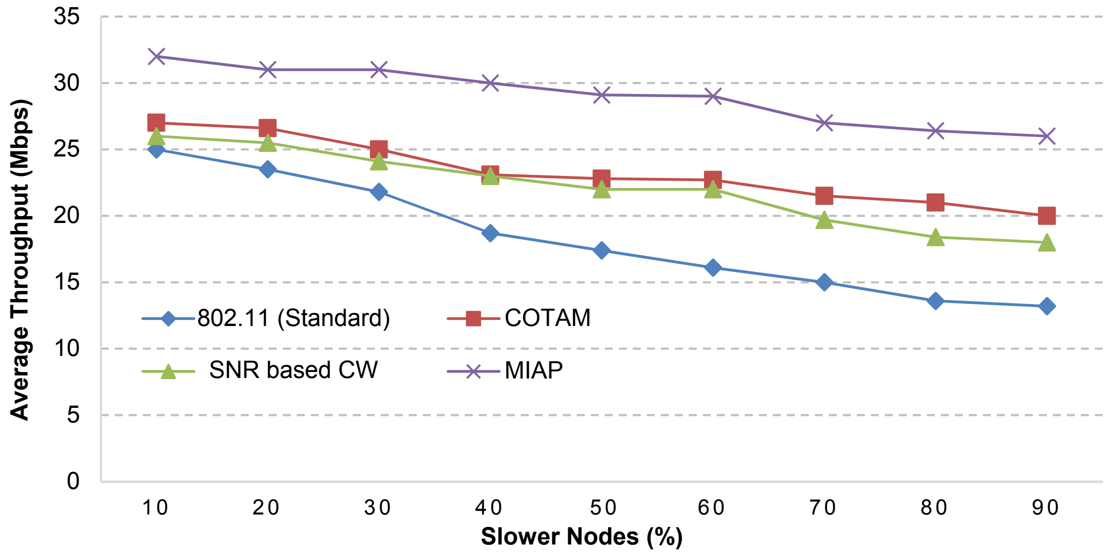


Figure 5.2: Average Network wide Throughput Comparison

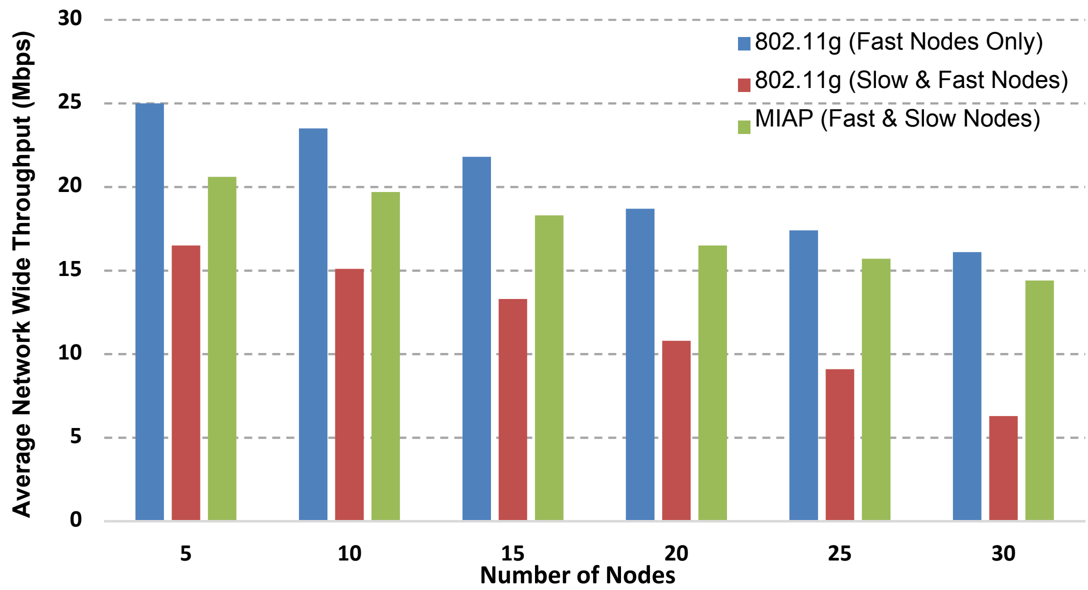


Figure 5.3: Achieved Throughput for Different Network Settlements

We have evaluated our proposed algorithm for throughput gains for various ratio of slower and faster nodes. The slower nodes randomly choose their data rate from 6, 9, 12, 18. 24 and 36(Mbps), while the faster nodes operate on maximum data rate they can achieve. In some cases it is noted that TR of faster nodes may reach to 128 Mbps. The achieved results are compared with standard 802.11/g implementation, COTAM [38] and signal to noise ratio based contention window (SNR based CW)[10].

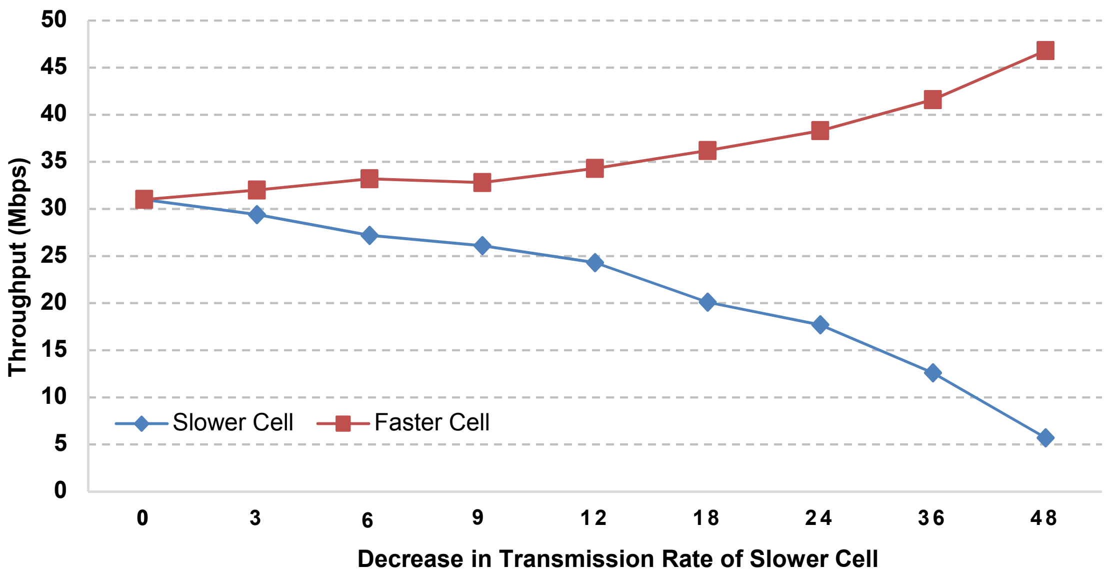


Figure 5.4: Throughput Gain in One Cell With Corresponding Decrease in Other Cell

The comparison given in Figure 5.2 demonstrate that presented algorithm outperforms all its counterparts and shows a significant improvement in achieved throughput when compared with standard implementation of 802.11/g physical layer. This improvement in achieved throughput becomes almost equal to 30% at some points. The reason behind this high throughput is the fact that, at any given time if a slower node in one cell is transmitting, the TR of faster node in other cell automatically increases. This increase in TR of faster cell diminishes the effect of slower node thus keeping the network wide average throughput on higher side. In Figure 5.6, we have evaluated the throughput performance of MIAP for slower and faster nodes and compared the results with standard 802.11 implementation. It has been observed that MIAP performs efficiently than standard implementation due to optimal utilization of network resources. Since MIAP diverts surplus resources of slower cell to a

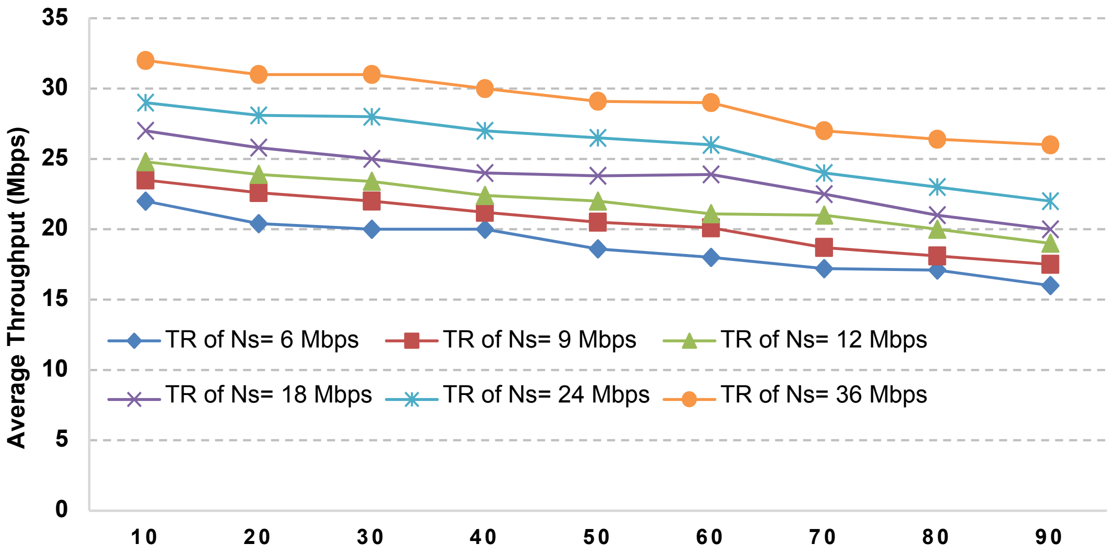


Figure 5.5: Throughput of Fast Nodes with Fixed TR of Slower Nodes

faster cell which increases the efficiency of that cell without affecting the performance of slower cell. This efficient utilization of spectrum resources increases the average throughput of faster nodes. It is observed that for longer time intervals with nodes operating in saturation mode, the efficiency gains are significantly high.

The results given in Figure 5.4 demonstrate the gain in average throughput of one cell with corresponding decrease of TR in adjacent cell. It is evident that if transmission rate of nodes in one cell decreases, it increases the TR of adjacent cell automatically. It is noted that faster cell do not gain the exact throughput loss of slower cell. The reason behind this below par throughput gain is inefficiency of channel width detection mechanism. The rapid oscillation of channel width is not detected efficiently and some frames may loss in this process. This frame loss decreases the average throughput. Figure 5.5 shows throughput of cell with faster node when TR of cell with slower nodes is fixed.

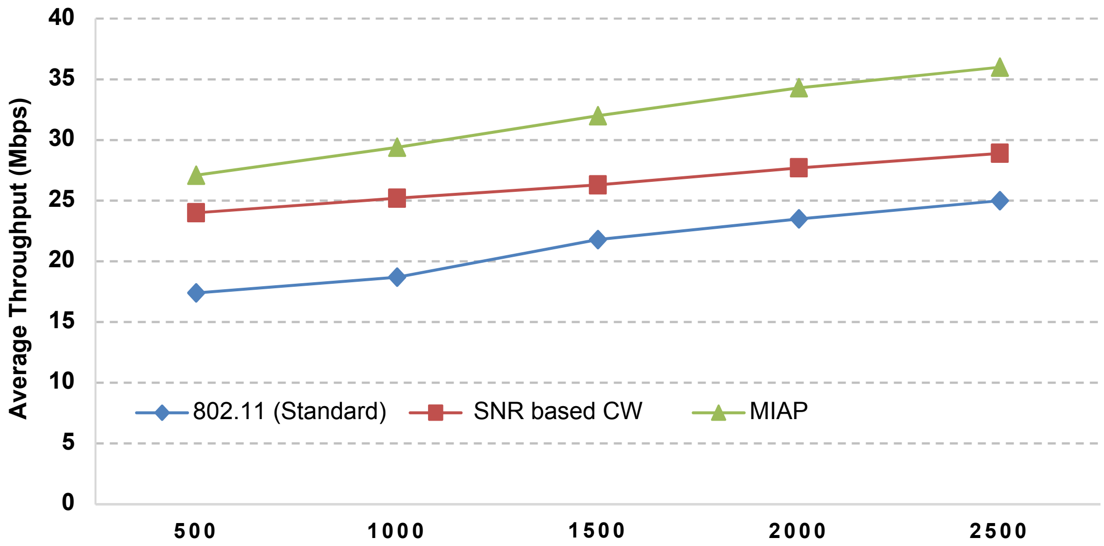


Figure 5.6: Average Throughput for Various MPDU Sizes

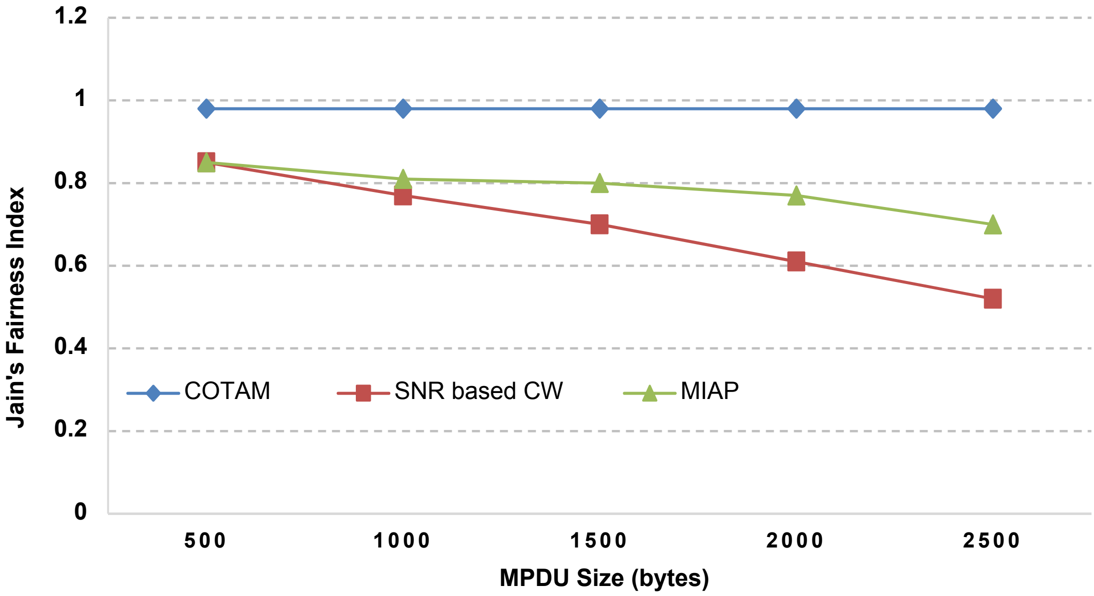


Figure 5.7: Channel Access Fairness for Various MPDU Sizes

The throughput comparison of MIAP for different sizes of MAC Protocol data unit (MPDU) is shown in Figure 5.6. The results show that longer the MAC fram, higher will be the throughput. These results are self explanatory considering that longer frames reduce the per unit time overhead of communication thus maximizing the throughput. The adaptable nature of MIAP further increases the throughput by maximum utilization of frequency spectrum.

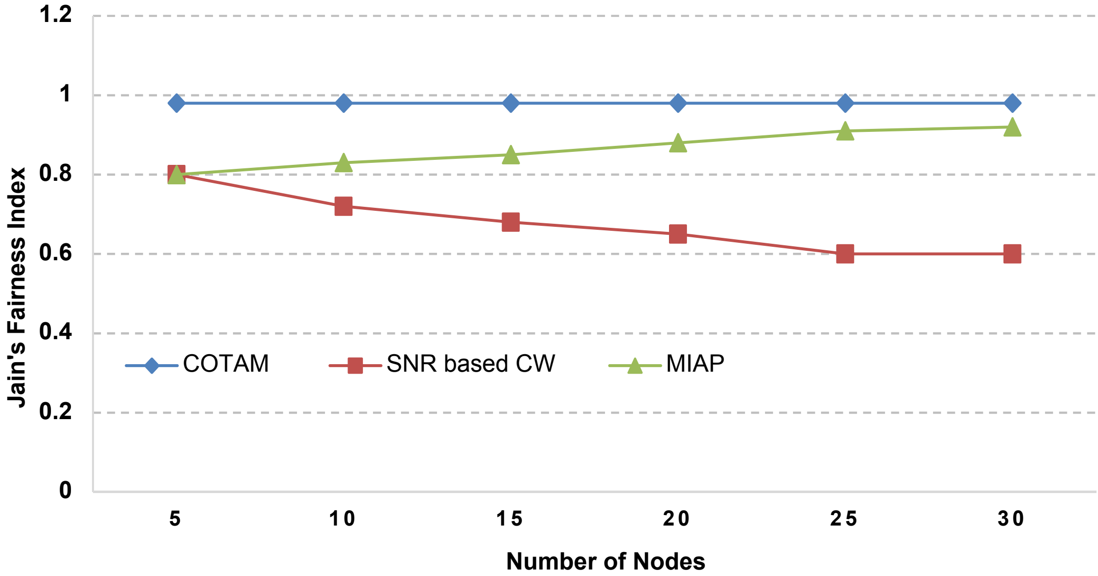


Figure 5.8: Channel Access Fairness for Different Number of Nodes

Finally, Figure 5.7 and 6.7 show channel access fairness of MIAP for various sizes of MPDU and different number of nodes respectively. The achieved results depict that fairness of MIAP algorithm in granting channel access to various nodes is near to standard implementation. It is better than SNR based CW adaptation and below the performance of COTAM. Since MIAP is MAC layer independent mechanism and it does not change the channel access mechanism, therefore the fairness remains similar to standard implementation of 801.11 MAC. On the other hand SNR based CW adaptation performs poorly due to different sizes of contention window at different nodes.

5.6 Chapter Summary

In this chapter, we have proposed an efficient mechanism to mitigate the effect of MAC layer performance anomaly by using adaptable width channelization in WLANs. The proposed algorithm assigns the channel widths based on transmission rate of nodes and divert the surplus frequency spectrum to resource hungry cells operating at higher transmission rates. We first probabilistically modeled the lower and upper bounds on number of slower and faster nodes in the network. In addition to this, we also analytically modeled the throughput and SINR of adaptable width channels. The evaluation of proposed algorithms is made based on throughput gains for different network settlements with varying number of slow and fast nodes. The throughput measurements show a significant improvement of more than 20% in achieved network capacity, with different combinations of slow and fast nodes. Moreover a detailed analysis on channel access fairness has also been presented. Since proposed algorithm is independent of channel access mechanism and do not require any change at MAC layer, thus long term channel access probability remains same for each network node.

Chapter 6

QoS Implementation in 802.11 WLANs Through Adaptable Channelization

In today's wireless assortments, the perspective of communication has gained considerable significance. Different network nodes associated with same AP have variable needs of throughput based on the applications running on these nodes. The wide spread use of media centric applications such as VoIP, video streaming and online gaming has substantially increased the importance of QoS in WLANs. QoS is the capability of a network that implements differential services for a node or set of nodes assuring a minimum level of user experience. Maintaining said level of user experience becomes critically important when network is operating in saturation mode and network resources are limited. Various applications running on Wi-Fi enabled devices have highly diversified throughput requirements and delay sensitivity. A brief overview of throughput requirements of some of the applications is given in table 6.1.

The performance of WLANs and corresponding QoS is influenced by several factors including channel bandwidth, interference, channel fading, delay spread, bit error rates, PDR and channel access and occupation time. The current static width channelization in 802.11 wireless networks and promise of fair long term channel access probability ensure equal share of network resources to all communicating nodes. However, this equal sharing of resources introduces two major drawbacks that are (1) unavailability for provisioning of differential

Table 6.1: Throughput Requirements of Various Applications

Application Class	**Required Throughput**
Web-browsing/email	500 Kbps–1 Mbps
Video Conferencing	384 Kbps–1 Mbps
SD video streaming	1–1.5 Mbps
Skype Video Call	500 Kbps
YouTube video streaming	500 Kbps
WhatsApp and Viber	540–740 Kbps
File Sharing	5 Mbps
Device Backups	Uses available bandwidth
VoIP Call Signaling	5 Kbps
VoIP Call Stream	27–93 Kbps

services to network nodes, (2) potential under-utilization of scarce network resources. The aim of research work presented in this chapter is to provide guaranteed QoS by efficient management and adaptation of wireless channel width, while simultaneously maintaining the channel access fairness in network nodes. Through detailed analytical analysis and rigorous experimentation, it has been concluded that we can embed QoS support to a set of network nodes without considerably degrading the user experience of other nodes. In this work, thorough investigations have been made to enumerate the effect of dynamic width channels on QoS defining parameters like, throughput, admission control, bandwidth reservation, delay and delay variation (jitter).

6.1 Contemporary Techniques for QoS in 802.11 WLANs

Conventional WLANs like 802.11 a/b/g/n do not support differential services for communicating nodes. In year 2005 IEEE published a distinctive 802.11/e standard for delay sensitive applications that fulfills QoS requirements by proposing a modification to standard

DCF protocol. This modified channel access mechanism was named as Enhanced Distributed Coordination Function (EDCF). A brief overview of EDCF is given as below:

6.1.1 Enhanced Distributed Coordination Function (EDCF) of 802.11/e

The EDCF channel access mechanism of 802.11/e specifications is a hybrid of two transmission coordination functions. These are Hybrid Coordination Function Controlled Channel Access (HCCA) and Enhanced Distributed Channel Access (EDCA). Both HCCA and EDCA defines priorities to transmission flows based on the nature of communication. For instance, an e-mail transmission can be assigned a low priority and VoIP call can be categorized as high priority transmission. The HCCA is more like PCF and only differs for time interval between two beacon frames. In conventional PCF the time between two consecutive beacon frames is divided into discrete contention period and contention-free period, while on the other hand, HCCA can initiate the contention-free period anytime it requires. This contention-free period is dedicated for communication of high priority transmission with minimized delays.

With EDCA, high-priority traffic is transmitted in a transmit opportunity time interval which is a bounded time allocated to a specific node. In this time slot a node transmitting high priority streams of data can transmit as many frames as it can in a contention free fashion. The transmit opportunity time is allocated by an AP and its duration can vary based on data size. In this way a high priority data has better channel access rate than low priority data.

Both HCCA and EDCA controls flow requests and admissions based on available bandwidth. If throughput requirement of QoS enabled node(s) exceeds the total available bandwidth, these algorithms block further requests of QoS flows to maintains user experience of already transmitting nodes. The blocking probability increases if QoS nodes are using applications with heavy bandwidth requirements. Moreover, these algorithms also provide bandwidth reservation capability which allocates bandwidth resources to various flows. This reservation of resources made in advance and remains static throughput the course of flow transmission.

6.1.2 Supplementary Techniques of QoS Implementation in WLANs

In addition to HCF several other QoS provisioning techniques in WLANs have been proposed in literature. The work presented in [61][57][49] is of notable importance to this dissertation.

In [61], authors have proposed a Distributed Fair Scheduling (DFS) algorithm that assigns the available bandwidth to flows based on their weights. DFS assigns weights to flows originating from distinct users based on the priority of data. It then allocates variable bandwidth to these flows based on assigned weights. DFS is a variant of self-clocked fair queuing algorithm and add decentralization to it. Authors claimed that the long term equal channel access probability characteristic of conventional DCF can be retained in DFS. However, a critical drawback is that although DFS on one hand maintains the fair channel access probability but on the other hand violates the equal resource sharing among nodes.

Authors in [51] proposed balckburst algorithm for QoS implementation in WLANs. In proposed algorithm each node having real time data to send, first senses the channel and if it finds the channel free for a specific time duration, it sends jamming pulse of a duration proportional to the time it is waiting for transmission. On overhearing jamming pulse, nodes with low priority data hold their transmission for a defined time duration. If multiple nodes with real time data try to access the channel, the priority of transmission is given to the node with longest jamming pulse. Since the longest pulse will relate to a node standing at first position in the que. After gaining the channel access the node can transmit its packet for a specific amount of time after which it will again need to contend for channel access. Authors concluded that BlackBurst can be implemented in conventional WLANs with minimal changes and it also retains fairness of channel access among nodes.

In [49] authors have presented a detailed survey of various QoS provisioning techniques incorporated at different layers of TCP/IP protocol stack with their classification. In this work authors provide a comprehensive comparison of QoS provisioning through PCF, EDCF of 802.11/e, DFS and BlackBurst. It is concluded that that PCF performance is comparably low than EDCF while the best performance is achieved by BlackBurst. In [64] authors evaluate the performance of 802.11 under QoS constraints. They have modeled the delay and pack loss rate and concluded that by controlling the total traffic rate, the original 802.11 protocol can support strict QoS requirements.

6.2 QoS implementation in WLANs

6.2.1 Network Model

Assume that a network consists of J nodes (J_1,J_2,....,J_s) and K number of APs (K_1,K_2,.....,K_t), where J_i and K_i represent i^{th} node and i^{th} AP respectively. Each AP uses L transmission channels (L_1,L_2,....,L_u) for communication, L_i representing the i^{th} channel. As conventional Wi-Fi networks use 14 channels for communication L_u ranges from 1 to 14. Let the J nodes are divided into two types of nodes O and Q where O consists of a group of ordinary nodes without any QoS guarantee while Q consists of all such nodes with a minimum threshold of QoS and user experience. The association of any node $(J_i \in O) \rightarrow K_i$ or $(J_i \in Q) \rightarrow K_i$ follows Poisson distribution with probability density function λ as given below,

$$\Pr\{(J_i \in O) \rightarrow K_i\} = \frac{\lambda^{J_i} e^{-\lambda}}{J_i!} \tag{6.1}$$

$$\Pr\{(J_i \in Q) \rightarrow K_i\} = 1 - (\frac{\lambda^{J_i} e^{-\lambda}}{J_i!}) \tag{6.2}$$

Where J_i denotes a node belonging to either ordinary set of nodes O or QoS nodes Q, $\rightarrow$ expresses the association of node to AP.

Considering that network is operating in saturation mode and every node has data to send each time it gets access of the channel then the total time $T_{(total)}$ will be

$$T_{total} = t_{tr} + t_{over} \tag{6.3}$$

where t_{tr} is the time elapsed in transmission while t_{over} is the overhead time associated with the transmission. This overhead time can be computed as given in equation (4).

$$t_{over} = t_{cont} + t_{DIFS} + t_{pr} + t_{SIFS} + t_{pr} + t_{ack} \tag{6.4}$$

where t_{cont} is the time elapsed in contention (channel access), t_{DIFS} is the distributed inter-frame spacing time which is equal to 50 μS, t_{pr} is the time required for transmission of physical layer frame preamble, t_{SIFS} is short inter frame spacing time which is 10 μS and t_{ack} is the time taken for transmission of acknowledgement. The total time taken for transmission of one packet t_{pkt} will then be

$$t_{pkt} = \frac{D}{R} + t_{over} \tag{6.5}$$

where D is the total payload of data and R is the transmission rate of node J_i. The transmission rate R of any node J_i can be calculated by Shannon-Hartley theorem [60] $R = B\ log_2(1 + SINR(dB))$ and $SINR(dB) = 10\ log(SINR)$ where R is the data rate and B is the bandwidth of the communication channel. The contention based DCF mechanism of 802.11 WLANs ensures equal long term channel access probability for all network nodes. Let's assume that all the nodes are operating under ideal channel conditions with zero collision probability, the total time (T_{total}) will be divided among all nodes equally. Then the total time occupied by any node J_i is given by:

$$T(J_i) = \frac{1}{T_{total}} \tag{6.6}$$

and the total number of packets (η) that can be transmitted are,

$$\eta(J_i) = \frac{T(J_i)}{t_{pkt}} \tag{6.7}$$

The QoS implementation requires adjustment in achieved throughput of a node. This tuning of throughput can be obtained by constructing channels of wider widths using maximum non-overlapping sub-carriers and subsequently modifying t_{over} parameters. We named the modified t_{over} parameters as tuned parameters $t_{(tune)}$. A thorough overview of $t_{(tune)}$ parameters is given in Table 4.1.

Using measurements made in this Section and adjustment of tuning parameters, we have developed CWAQ algorithm for QoS in WLANs.

6.2.2 Channel Width Adaptation for QoS

The pseudo-code of the proposed channel width adaptation algorithm for QoS (CWAQ) is presented in Figure 6.2. Let's define the nodes supporting QoS as QoS-Nodes and normal nodes as Non-QoS nodes connected with a resource allocation and management server (RAMS) through APs as shown in Figure6.1.

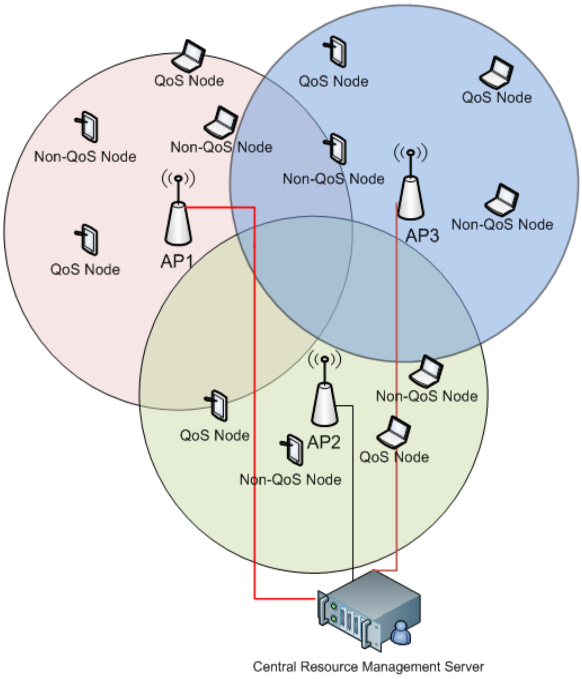


Figure 6.1: Architecture of Deployed Network

CWAQ is based on distributing available frequency spectrum to QoS nodes to meet the user demands pertaining to the quality of service class of any specific wireless node(s). At network initialization, RAMS accesses QoS nodes based on their SSIDs and assigns frequency spectrum share to ensure minimum threshold transmission rate accordingly. To validate the proposed algorithm, an indoor network comprising of three APs by configuring three USRP2 kits is deployed as shown in Figure. 6.1.

Result: *Required Channel Width* $(CW_{(req)})$
Transmission Paprameters (TP)
Input :$R(J_i)$, $SINR(J_i)$, $SSID(J_i)$

begin
  for $J_i \in J_s$ **do**
    if $SSID(J_i) = SSID_{(QoS)}$
    $\&\&\ R(J_i) \geq R_{(Min)}$ **then**
      $CW_{(req)} \leftarrow CW_{(current)}$
    else
      if $R(J_i) \leq R_{(Min)}$ **then**
        do
          $CW_{(new)} \leftarrow CW_{current} + 1.875\ MHz$
          $\&\&\ TP \leftarrow TP\ for\ CW_{(new)}$
        while $R(J_i) \leq R_{(Min)}$
      else
        $CW_{(req)} \leftarrow CW_{(new)}$
      end
    end
  end
end

Figure 6.2: QoS based Spectrum Sharing Algorithm

Each AP communicates the SSIDs of wireless nodes associated with it to the RAMS. When QoS-Node starts communication, the AP demands additional bandwidth to fulfil requirements of user experience. Based on AP demand, RAMS assigns a specific width channel, central frequency and modulation scheme to be followed by that AP. The process of calculating the bandwidth requirement of QoS-Nodes is repeated for each individual node. If RAMS finds unused frequency spectrum, it equally increases the channel widths of each AP and shifts their central frequencies accordingly to maximize the spectrum utilization . In case, if some nodes go off-line, APs communicate to RAMS which decreases their channel widths accordingly.

If the combined bandwidth requirement of all the APs exceeds the total available spectrum, RAMS makes the decision based on the number of QoS-Nodes associated with an AP. If any AP K_i has more number of QoS-Nodes then other AP K_j then channel width assigned to K_i will be wider than the channel width assigned to AP K_j. The change in channel width by an AP will be detected by the parameters communicated through physical layer frame preamble which is thoroughly discussed in [35].

6.3 Performance Results and Discussion

A series of experiments on experimental test-bed given in Section 4.3 have been performed to enumerate the effect of deploying proposed algorithms on essential network performance parameters. These parameters include medium utilization, throughput, channel access delay, channel access fairness, admission control, bandwidth reservation and jitter. The obtained results are averaged out by collecting traces of all APs for accurate efficiency measurement.

6.3.1 Medium Utilization

Figure 6.3 compares the results of medium utilization of OSSA and CWAQ with standard 802.11/g distributed coordination function (DCF), enhanced distributed coordination function

(EDCF) of 802.11/e and BlackBurst[45] for different combinations of number of QoS enabled and ordinary nodes. It is observed that OSSA and CWAQ perform significantly better than contemporary techniques pertaining to the fact that adaptable channel widths utilize spectrum more efficiently. Since both the proposed algorithms do not alter channel access mechanism of standard WLANs, therefore employing adaptable channelization on standard channel access mechanism significantly enhances the spectrum utilization. On the other hand both EDCF and BlackBurst alter contention window of standard channel access mechanism to achieve QoS guarantee with burst traffic and priority transmission ques, which results in patches of high and no medium utilization. A second factor involved in high medium utilization of OSSA and CWAQ is CCI. Since proposed adaptable channelization ensures to maintain minimum level of interference. This minimum interference causes less number of collisions resulting in relatively low values for contention window size. Thus less time is elapsed in channel access resulting in high medium utilization.

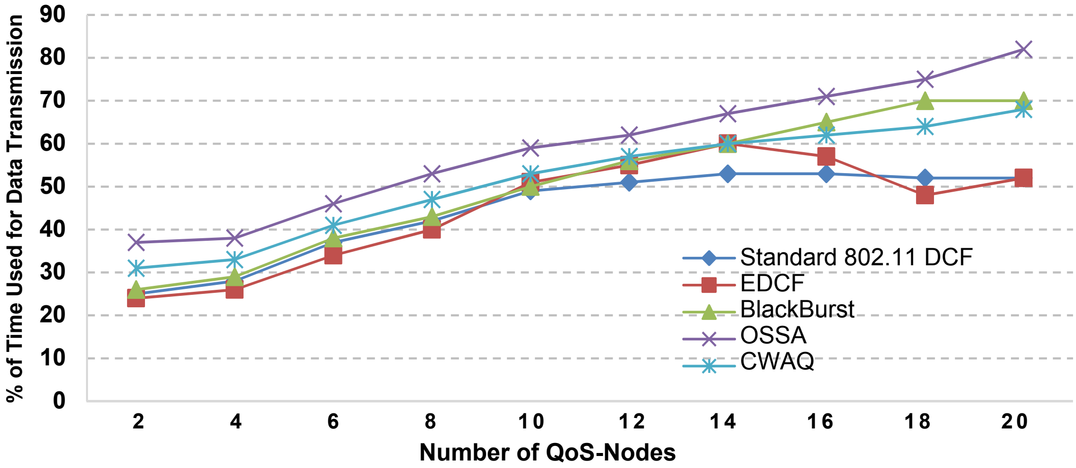
6.3.2 Throughput Analysis

Since implementation of differential services and QoS results in rapid variation of required throughput, we have focused on measuring normalized throughput. In Figure 6.4, we can see that both EDCF and BlackBurst provide very good throughput performance to high priority nodes. However, for low priority nodes their performance is drastically low, and as the number of QoS enabled nodes goes on increasing the low priority nodes suffer complete starvation. On the other hand since both OSSA and CWAQ do not give priority to any node in channel access, and QoS implementation is made possible by widening of channel width of high priority nodes. This mechanism do no affect the performance of low priority nodes to a great extent. Thus low priority nodes transmit data on narrower channels. Although narrower channels degrade the throughput performance of low priority nodes but avoid complete starvation.

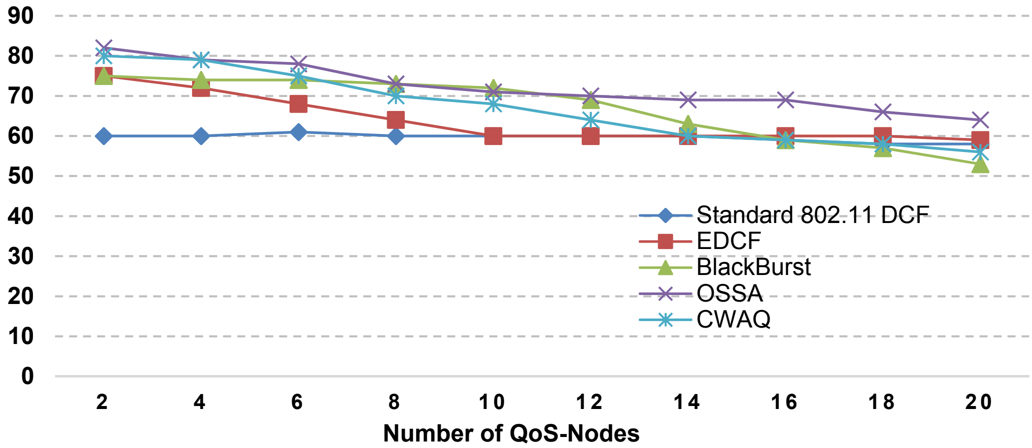
6.3.3 Admission Control and Bandwidth Reservation

Contrary to majority of QoS techniques CWAQ does not implement any admission control mechanism. The user experience of QoS nodes is maintained by adjusting channel width, therefore as the number of QoS nodes in a particular cell increases, it also triggers an increase in channel bandwidth of AP associated with that cell. However, it is important to mention that lack of admission control capability can negatively affect the performance of QoS-Nodes. Since the channel bandwidth that can be provisioned to a specific AP cannot exceed from an upper threshold, it puts a stringent bound on number of QoS-Nodes that can be serviced through this AP. If this number increases beyond the limit, the performance of QoS-Nodes starts degrading. It is evaluated that CWAQ can efficiently maintain user experience of 30 QoS-Nodes in each cell under a bearable transmission delay. As the number of QoS-Nodes increases above 30, performance degrades linearly with increase in number of QoS-Nodes.

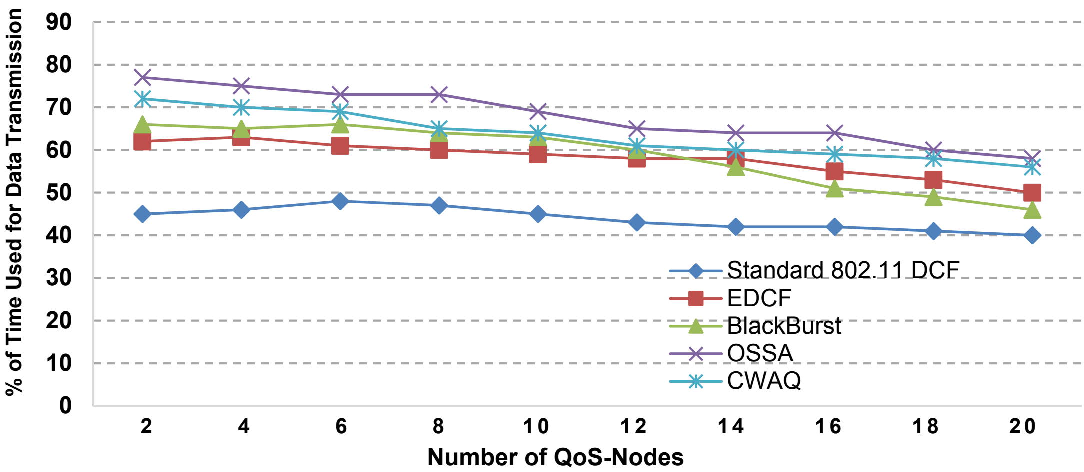
As cited earlier, most of the contemporary techniques of QoS implement bandwidth reservation which reserves per flow bandwidth resources in advance. CWAQ does not implement any explicit bandwidth reservation mechanism, however it has an implicit mechanism. Since the channel bandwidth associated to a specific AP is a function of its throughput requirement, and as bandwidth requirement changes it also elicits a change in channel bandwidth thus ensuring bandwidth reservation.



(a) Different Numbers of QoS Enabled Stations and Three Non-QoS Stations

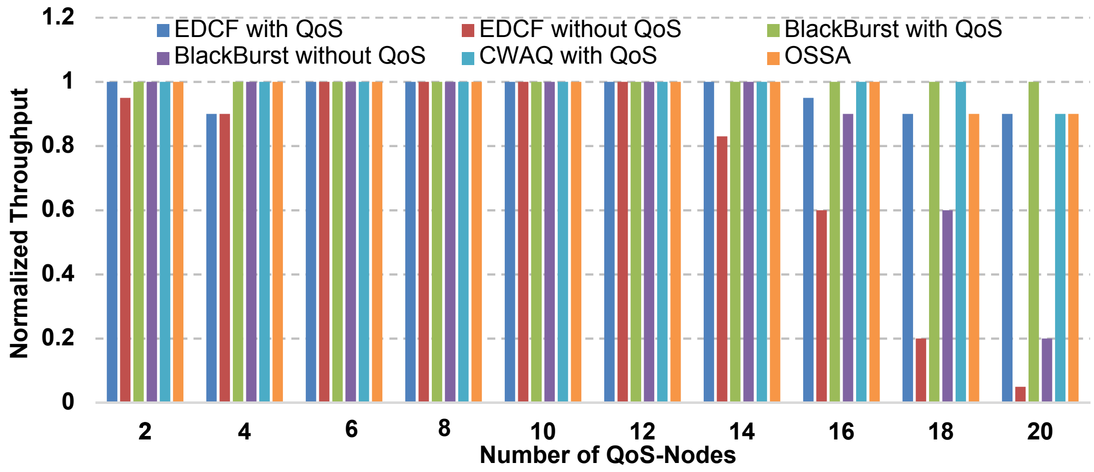


(b) Different Numbers of QoS Enabled Stations and Six Non-QoS Stations

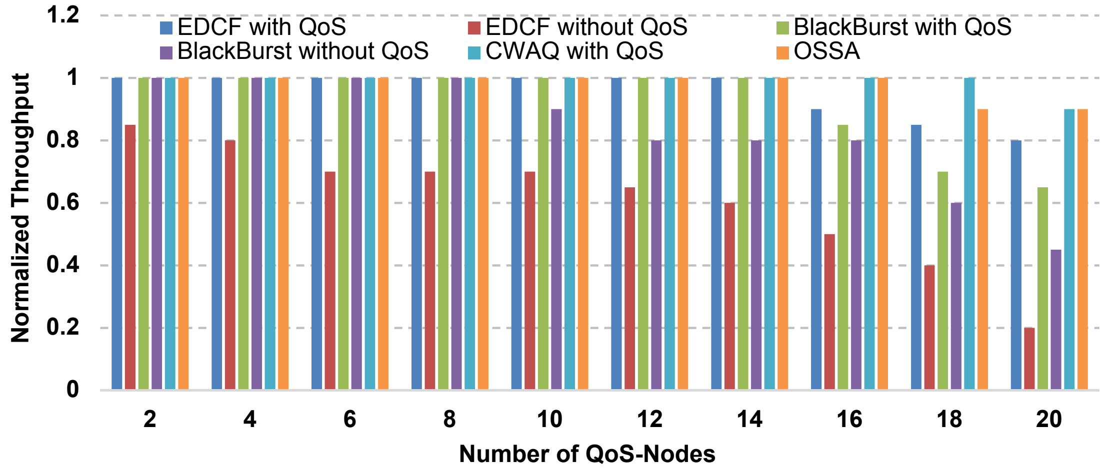


(c) Different Numbers of QoS Enabled Stations and Twelve Non-QoS Stations

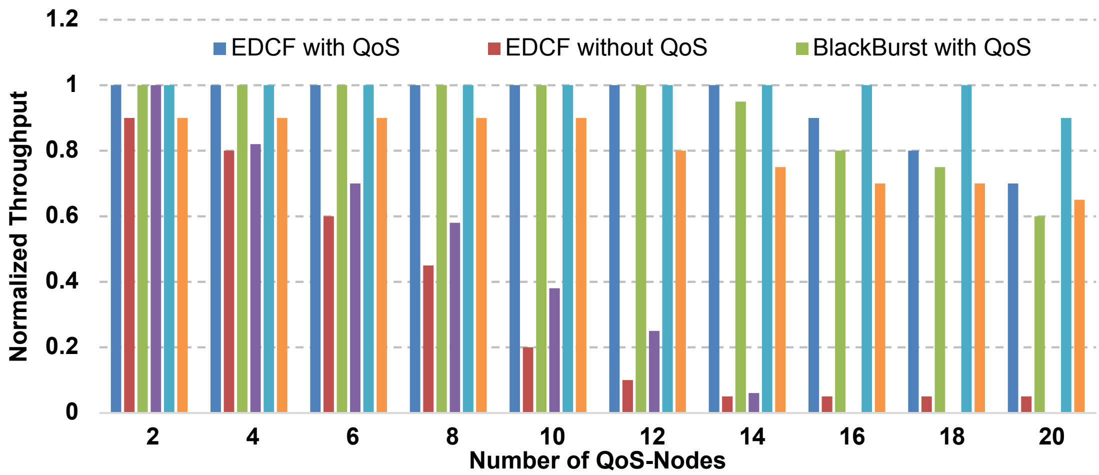
Figure 6.3: Medium Utilization for Various Combinations of QoS Enabled and Non-QoS Nodes



(a) Different Numbers of QoS Enabled Stations and Three Non-QoS Stations

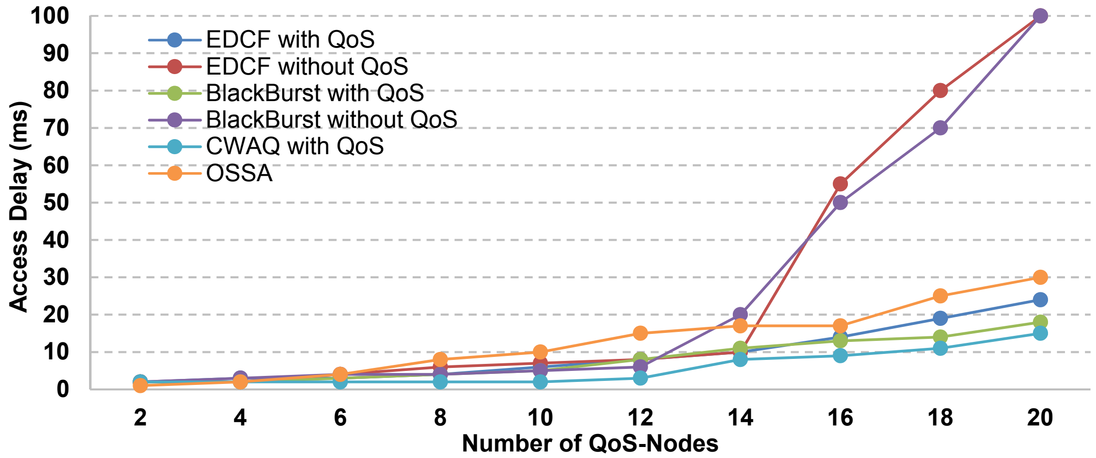


(b) Different Numbers of QoS Enabled Stations and Six Non-QoS Stations

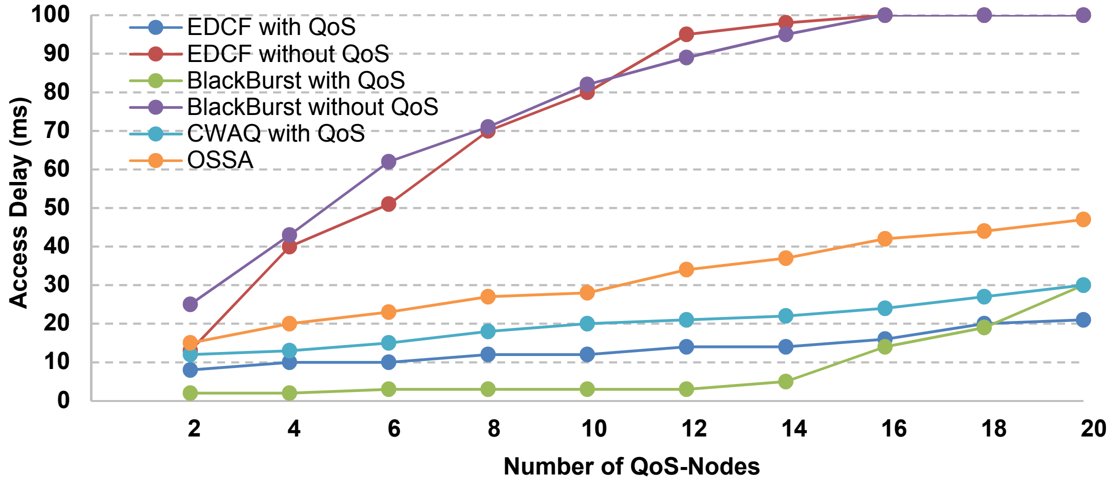


(c) Different Numbers of QoS Enabled Stations and Twelve Non-QoS Stations

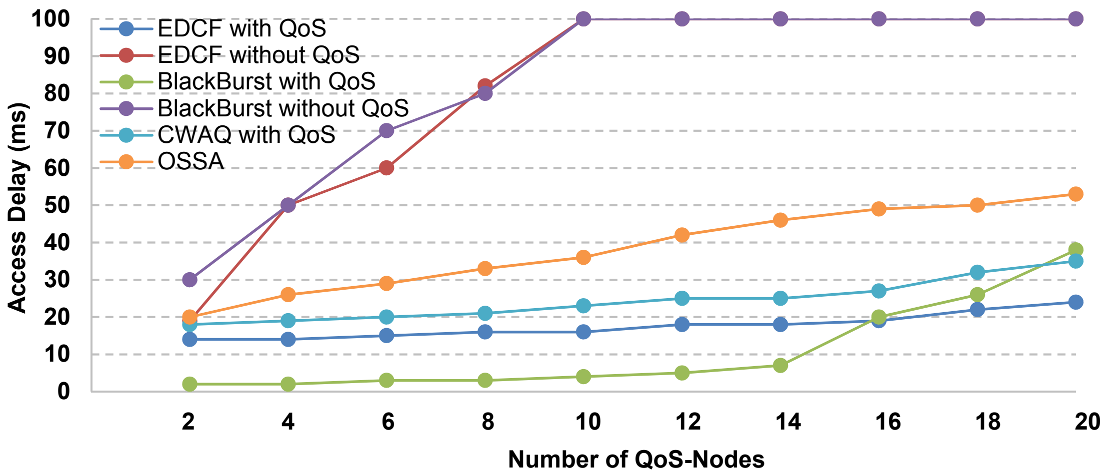
Figure 6.4: Normalized Throughput for Various Combinations of QoS Enabled and Non-QoS Nodes



(a) Different Numbers of QoS Enabled Stations and Three Non-QoS Stations

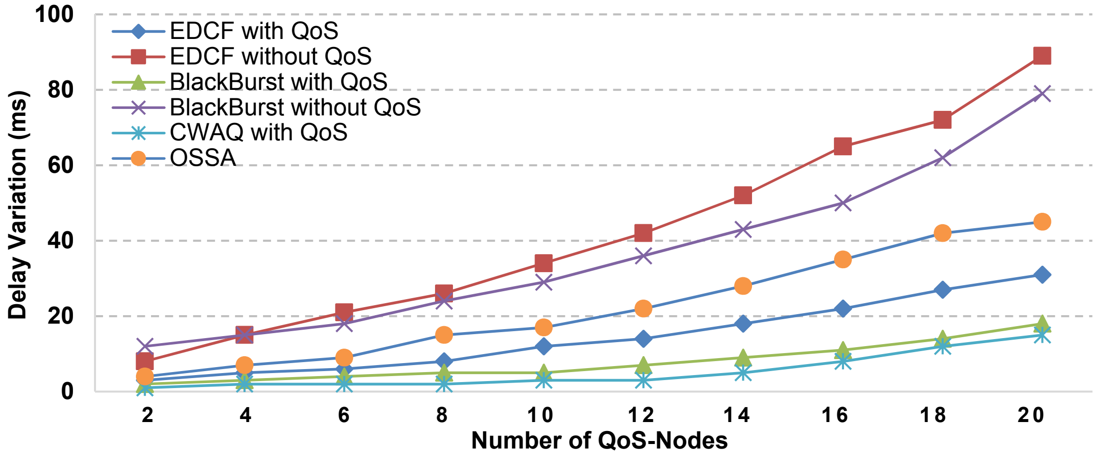


(b) Different Numbers of QoS Enabled Stations and Six Non-QoS Stations

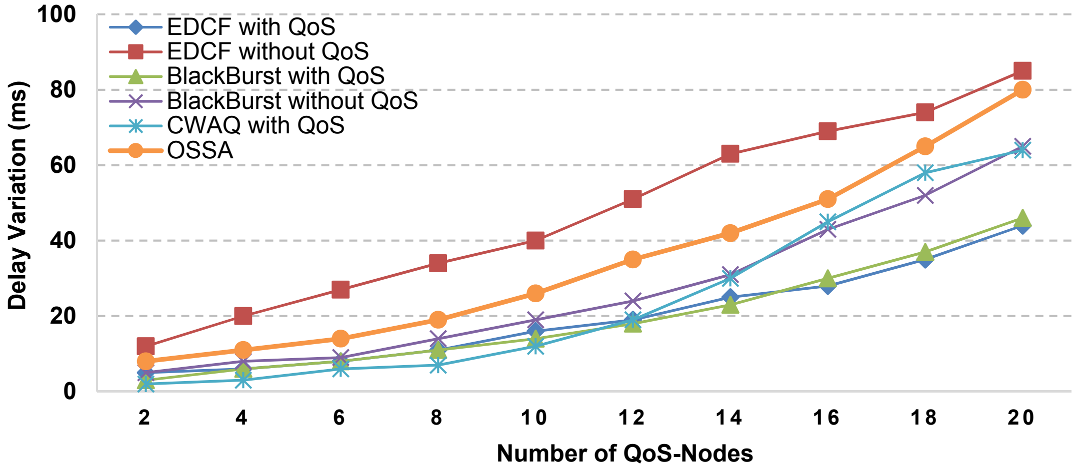


(c) Different Numbers of QoS Enabled Stations and Twelve Non-QoS Stations

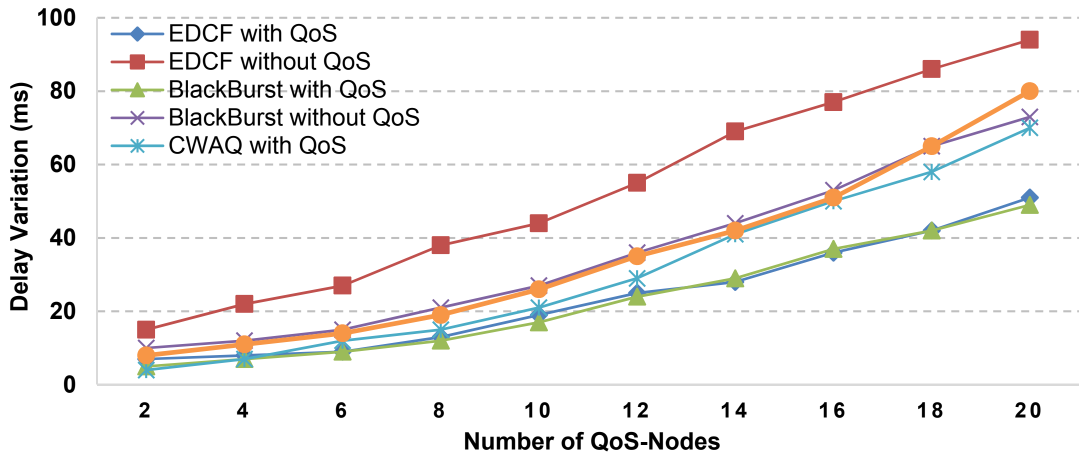
Figure 6.5: Access Delay for Various Combinations of QoS Enabled and Non-QoS Nodes



(a) Different Numbers of QoS Enabled Stations and Three Non-QoS Stations



(b) Different Numbers of QoS Enabled Stations and Six Non-QoS Stations



(c) Different Numbers of QoS Enabled Stations and Twelve Non-QoS Stations

Figure 6.6: Delay Variations for Various Combinations of QoS Enabled and Non-QoS Nodes

6.3.4 Analysis of Delay Bounds and Jitter

Figure 6.5 shows the mean beacon delay for EDCF, BlackBurst, OSSA and CWAQ. It is observed that both EDCF and BlackBurst have very low delays for high priority nodes. These low delay values can be explained by the burst transmission mechanism of these algorithms. Since packets in a burst a closely packed and are transmitted without encountering contention therefore less delay values are observed. This close packing and contention free transmission also results in low delay variations (jitter) which make it highly suitable for multimedia traffic. However these implementations increase the delay bounds and jitter of low priority node. While on the other hand the delay bounds for OSSA and CWAQ are substantially less for high priority nodes. This lower values of delay bounds can be explained by higher throughput capability of wider width channels. Since wider width channels channels can deliver more number of packets in smaller amount of time therefore incurs less delays. In case of low priority nodes the delay values are relatively high but not as high as in case of EDCF and BlackBurst.

The jitter analysis for various combinations of QoS and Non-QoS nodes for CWAQ, OSSA, EDCF and BlackBurst is presented in Figure 6.6. The obtained results show that with increased number of QoS-Nodes the delay variation also increases for all deployed algorithms. The EDCF and BlackBurst have relatively low delay variations as compared to CWAQ and as number of QoS-Nodes goes on increasing the delay variations for CWAQ are substantially high for CWAQ. We have analysed that if QoS-Nodes are dispersed across all cells the delay variations are high. However, if we can service QoS-Nodes through a single AP, CWAQ pwerforms significantly better than EDCF and BlackBurst. This behavior can be explained by opportunistic sharing of spectrum resources among APs. Both EDCF and BlackBurst employ bandwidth reservation and priority ques for QoS-Nodes, therefore major portion of network resources are assigned to these nodes thus limiting delay variations. On the other hand, CWAQ triws to maintain fair scheduling of channel access with variable spectrum resources for QoS and Non-QoS nodes. If number of QoS nodes across all APs exceeds more than a threshold, it results in huge variations of access delay.

6.3.5 Channel Access Fairness

Finally, Figure 6.7 show channel access fairness of proposed algorithms for different number of nodes respectively. The achieved results depict that fairness of OSSA and CWAQ in granting channel access to various nodes is below the standard implementation but higher than EDCF and BlackBurst. Since both EDCF and BlackBurst give prioritized channel access to a set of nodes with degrade the values for channel access fairness. OSSA and CWAQ assign channels of variable width to different nodes that results in different transmission time of same length of packets. Therefore the channel occupation of nodes with higher channel widths is lower than the nodes with narrower channel widths. Since OSSA and CWAQ is MAC layer independent mechanism and it does not change the channel access mechanism, therefore the fairness remains similar to standard implementation of 801.11 MAC.

6.4 Chapter Summary

In this chapter, we have proposed a channel width adaptation algorithm for implementation of QoS in 802.11 networks. The evaluation of proposed algorithm has been made by

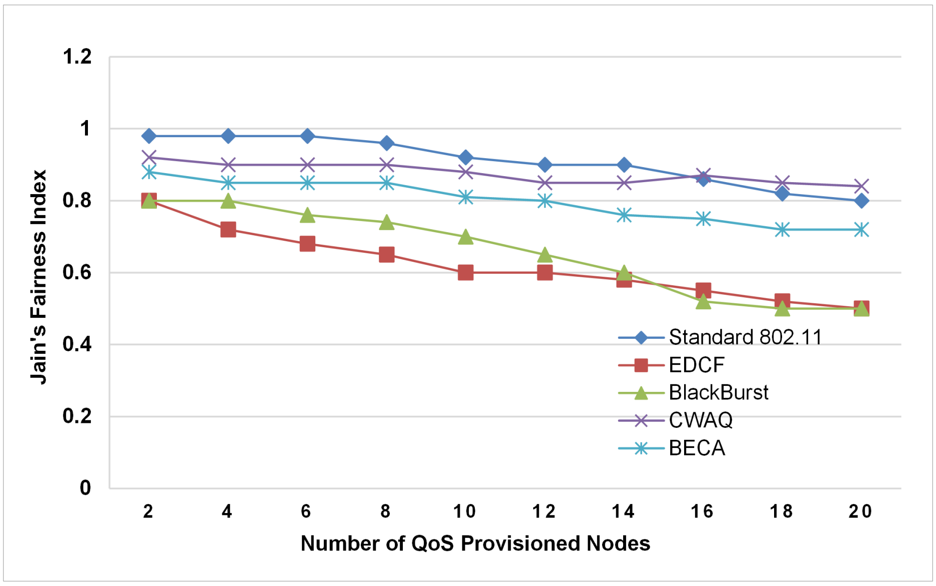


Figure 6.7: Channel Access Fairness for Different Number of Nodes

using fundamental QoS defining parameters like throughput, medium utilization transmission delay, and channel access fairness. The focus of this chapter is to embed QoS in 802.11 WLANs to a set of nodes with the aim to minimize the starvation problem of low priority nodes. It has been concluded that contemporary techniques like EDCF and BlackBurst performs fairly better for high priority nodes but results in almost complete starvation of low priority nodes. The proposed algorithms on the other hand perform significantly better in maintaining fairness of resource allocation to both types of nodes. Moreover, the proposed algorithms are also more spectrum efficient than EDCF mechanism of 802.11/e and Black-Burst and can perform well under stringent network conditions. This high medium utilization ensures optimal use of scarce spectrum resource in dense network deployments.

Chapter 7

Conclusion and Future Work

In this dissertation, we have proposed solution to spectrum scarcity problem faced in WLANs due to static width channelization. The proposed solution comprises of three novel algorithms that assigns bandwidth resource to communicating nodes with high level of granularity based on their bandwidth requirement and/or ambient conditions. Three novel algorithms have been implemented to enumerate the effect of proposed mechanism for evaluation of its impact on overall network performance.

The first algorithm named OSSA uses measures of interference, required throughput and SS values to assign adaptable and variable width channels to APs. Thorough theoretical and empirical investigations have been carried out to evaluate the affect of OSSA on essential physical layer parameters (such as throughput, network capacity, interference, BER, spectrum utilization, power consumption and transmission range). OSSA optimally uses available frequency spectrum to achieve best possible network performance with channel width flexibility while reducing interference. Achieved results show a significant improvement of almost 30% in achieved network capacity with different combinations of channel widths and interference measurements as asserted in results section. It has also been observed that proposed algorithm reduces interference by almost 25% when compared with interference of static width channel assignment. Moreover, use of flexible channel-widths considerably increases spectrum utilization which reaches to 90% at peak hours when network is fully loaded.

The second algorithm named MIAP proposes an efficient mechanism to mitigate the effect of MAC layer performance anomaly by using adaptable width channelization in WLANs. The proposed algorithm assigns the channel widths based on transmission rate of nodes and diverts the surplus frequency spectrum to resource hungry cells that are operating at higher transmission rates. We first probabilistically modeled the lower and upper bounds on number of slower and faster nodes in the network. Based on our analysis, a mechanism for re-adjustment of channel width is proposed. It ensures mitigation of MAC layer performance anomaly while simultaneously maintaining the fairness of channel access among contesting nodes. The evaluation of MIAP is analyzed on throughput gains for different network settlements with varying number of slow and fast nodes. The throughput measurements show a significant improvement of more than 20% in achieved network capacity, with different combinations of slow and fast nodes. Moreover, a detailed analysis on channel access fairness has also been presented. Since proposed algorithm is independent of channel access mechanism and does not require any change at MAC layer, thus long term channel access probability remains same for each network node.

The third algorithm named CWAQ, proposes a channel width adaptation algorithms for implementation of QoS in 802.11 networks. The evaluation of proposed algorithm has been made by using fundamental QoS defining parameters like throughput, medium utilization transmission delay, and channel access fairness. The focus of this research is to embed QoS in 802.11 WLANs to a set of nodes with the aim to minimize the starvation problem of low priority nodes. It has been concluded that contemporary techniques like EDCF and BlackBurst performs fairly better for high priority nodes but results in almost complete starvation of low priority nodes. CWAQ on the other hand performs significantly better in maintaining fairness of resource allocation to both types of nodes. Moreover, our results showed a significant improvement of almost 30% in achieved throughput with different combinations of QoS enabled and ordinary nodes. The proposed algorithm is more spectrum efficient than EDCF mechanism of 802.11/e and BlackBurst and can perform well under stringent network conditions. This high medium utilization ensures optimal use of scarce spectrum resource in dense network deployments.

Finally concluding that, flexible width channels increase network capacity and reduce interference simultaneously, despite of having conflicts in standard implementation and require a trade off for optimal performance. Moreover, the use of adaptable channelization has an inherent capability for mitigation of medium access control (MAC) layer performance anomaly. Additionally, using communication channels of adaptable width, we can also implement QoS in WLANs.

In future, we are looking forward to implementing adaptable CW in MIMO based wireless networks such as 802.11/n. Development of a distributed channel adaptation algorithm is also desired that can assign spectrum resources locally on each AP. Proposed techniques may be evaluated and analyzed on 5 GHz frequency range used by 802.11 a/ac networks. It is observed that frame preamble based channel width detection mechanism is not very efficient in estimation of rapid change in communication frequencies. This gives rise to need of a better channel width detection mechanism. Lastly, the proposed algorithms oscillate between various channel widths, with frequent variation in throughput demands entailing in possibly curbing the advantage of adaptable width channelization. Therefore, a mechanism to reduce these oscillations needs to be devised in future.

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