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Wireless communication became popular in the last decades, giving the mobility to the users. However with increased number of users and contention, network efficiency can hardly keep up with user needs. This thesis focuses on a new frequency domain contention technique called FICA. In FICA, the channel is assumed to be using Orthogonal Frequency Division Multiplex (OFDM) with multiple sub-carriers. We investigated the use of multiple channels and multiple access points (APs) in the design. First we investigated having one channel that is divided into number of sub-carriers, it shows good result, but only for limited number of users. Therefore we worked on the second scenario of having several sub-channels and each sub-channel is divided into a number of sub-carriers to communicate through one AP. And for efficient result nodes contend on the contention band and winner nodes will have the chance to send their data through the transmission band. In real world, networks have more than one AP, for that reason we investigate the third scenario, which is having more than one AP. In this setup, the result showed significant outcome, that we can divide the channel into several sub-channels to serve more than one AP and hash an ID for each AP. We further investigated optimal number of ID bits that are used to represent the hashed receiver IDs. We summarize the results as following: 1) it is possible to divide the channel bandwidth into several sub-channels that is divided into several sub-carriers to serve large number of users. 2) node contention should be partitioned into contention band and transmission band to reduce the overhead that the contending node cause when contending on the

whole channel. 3) AP ID is required when the network has more than one AP. 4) number of sub-carriers in the contention band has to increase at least to the double for higher efficiency, since more AP on the network would make the channel more loaded. 5) AP ID can be anything between 20-40 bits. Decreasing the ID to less than 40bits did not affect the throughput and efficiency of the channel.

OPTIMIZING FREQUENCY DOMAIN CONTENTION IN WIRELESS NETWORK

by

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Approved by

Dr.Jing Deng___________
Committee Chair

DEDICATION

TO

My Parent, you raised me up to be who I am & thank you for believing in me.

TO

My sisters, you were with me in each step regardless of the distance.

TO

My professors, I wouldn't reach this point without your guidance.

TO

My Friends, thanks for your support and love that made me feel like home.

APPROVAL PAGE

This thesis written by Huda Kadhem Abdnoor Al-zurfi has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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CHAPTER I

INTRODUCTION

Nowadays Internet is part of all life aspects. Internet network was once limited for the usage of military communication, then it entered some of the universities as in campus communication and now it are a part of millions of businesses as well as personal use. Many aspects of the Internet are important, but the most critical one is its speed. With increasing number of users and limited amount of bandwidth, the speed reduction can cut off communication. For instance, online video games and video conferences rely on sustained speed for their successes. While increasing number of users and people are totally dependent on internet, researchers are searching and finding ways to speed up the communication speed.

Over the last several decades, wireless communication technology has grown tremendously, improving Wireless Local Area Network (WLAN) efficiency. One example is the IEEE 802.11 technology with huge popularity. The early 802.11 standards simply divide the channel into fourteen sub-channels, although only three of them are orthogonal (i.e., non-interfering or non-overlapping with each other). Nodes in the area would contend to send their data through the three sub-channels and the rest of the sub-channels are left unused. Direct-Sequence Spread Spectrum (DSSS) technique is used to carry the information in the given bandwidth. However this technique is not quite sufficient, since it allows using three channels out of fourteen to avoid overlapping and that is waste of space. While using Orthogonally Frequency Division Multiplexing (OFDM) technique that allows the channels to overlap without interfering this allows more information to be carried out through the bandwidth using more channels without interfering with each other. An interesting technique called Fine-Grained Channel Access (FICA) was introduced in 2010 [5]. FICA suggested dividing the channel into sub-channels and each sub-channel is divided into sub-carriers that would help multiple nodes send their data simultaneously and that would increase the efficiency of the network significantly.

This thesis focuses on the design of FICA. Our particular interest is to investigate the chance of having better contention nodes on specified frequency in order to increase the efficiency, throughput and speed of the network. As FICA simulation results suggest improving in efficiency ratio up to 400% compared to existing 802.11 standard [5]. Also, increasing efficiency means the network channel should use the whole bandwidth without wasting any frequency, and if so, the capacity of the channel would increase. [32] explained that increasing capacity could be applied on by working the two following points: (1) new design for the physical layer in a way that increases the data rate (2) better use for the bandwidth spectrum.

The thesis is organized as follows. Chapter II discusses some background information for the general problem of wireless communication and contention resolution. We propose the new design in Chapter III, which present each design with different scenarios and discuss each channel setup of having one AP. The details of channel setup in real world of having a network with multiple APs are presented in Chapter IV. Chapter V concludes the work and points out some future research directions.

CHAPTER II

BACKGROUND

2.1. Wireless LAN Overview

WLAN has widely expanded in the last decade. It facilitates the access for users to communicate remotely from their homes, offices and also due to the increasing bandwidth; WLAN now covers larger geographical area. It was limited to a small building, however now it is increasing to cover a group of buildings, airport, hospital or even a city. WLAN consists of two devices or more that are connected through AP using one of the wireless spectrum methods, for example spread spectrum or OFDM radio. The main advantage of such networks is that they support continuous connectivity even while users are mobile, the opposite of wired network that constrained users from moving. Most modern WLANs are based on 802.11 standards, which are a set of specifications that are held by IEEE committee that create and maintain the communication standards in order to continue the best internet connectivity [9]. Figure 1 illustrates WLAN network system components; in this network we have three small WLANs. With each AP we consider it as a separate WLAN, and each of the APs has two users that are connecting by some wireless radio spectrum (OFDM mostly used these days). Also, all of the APs are connected with Access Scanning (AC) to communicate between each other [10]. APs could be a router or switch, and user could be any computer, laptop, cell phone and/or tablets.

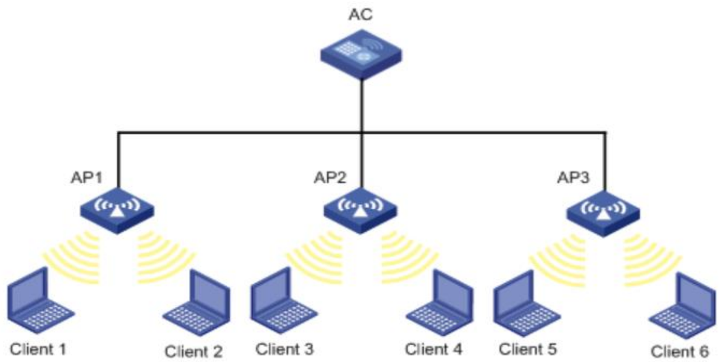


Figure 1. WLAN system components

WLAN has become more valuable and important. For instance, members of a family can use tablets with Internet connectivity while a desktop computer is downloading a document. At the same time, another member plays an online video game and a third member listens to Pandora music. All communications go through one router (AP). As demonstrated by the scenario, more clients are using the same WLAN (the same AP) at the same time. However, due to the limited amount of bandwidth, which would cause congestion in the network, it is important to know the optimum number of users for certain network, and to come up with the best design that allows more users to have the best connectivity with this limited bandwidth range. More details will be discussed in the chapter three and four.

2.2. 802.11 Technologies

IEEE 802.11 standard family has made a lot of developments and amendments throughout recent years. It started with 802.11 and developed to 802.11a, b, g, n, ac and ad. Each of these protocols has added new technologies to improve them.

Table 1 summarizes the major improvements in the protocols and the modulation type that have been used in each protocol. Modulation is one of the important things that research focus on and specifies its impact on the technology.

Table 1. IEEE 802.11 protocol generations and their properties

V • T • E 802.11 network standards [hide]

802.11 protocol	Release[6]	Freq. (GHz)	Bandwidth (MHz)	Data rate per stream (Mbit/s)[7]	Allowable MIMO streams	Modulation	Approximate indoor range[citation needed]		Approximate outdoor range[citation needed]	
							(m)	(ft)	(m)	(ft)
—	Jun 1997	2.4	20	1, 2	1	DSSS, FHSS	20	66	100	330
a	Sep 1999	5	20	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM	35	115	120	390
		3.7[A]					—	—	5,000	16,000[A]
b	Sep 1999	2.4	20	1, 2, 5.5, 11	1	DSSS	35	115	140	460
g	Jun 2003	2.4	20	6, 9, 12, 18, 24, 36, 48, 54	1	OFDM, DSSS	38	125	140	460
n	Oct 2009	2.4/5	20	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2[B]	4	OFDM	70	230	250	820[8]
			40	15, 30, 45, 60, 90, 120, 135, 150[B]			70	230	250	820[8]
ac (DRAFT)	~Dec 2012	5	20	up to 87.6[9]	8					
			40	up to 200[9]						
			80	up to 433.3[9]						
			160	up to 866.7[9]						
ad	Feb 2014	2.4/5/60		up to 7000						

Current 802.11n technology basically has one channel that all nodes contend to win the chance of sending their data. Once one node wins and starts sending its data, all other nodes have to wait until the channel is idle again. Otherwise, if more than one node sends its packet at the same time, a collision will be occurring. A collision is usually detected by missing acknowledgment (ACK) from the receiver. All nodes in the area have to wait a random time before starting to send new packets again. This waiting time is called short interface space (SIFS). To avoid collision the 802.11n uses a protocol that is used to check the idle channel, this protocol is called carrier sensing multiple access with collision detection (CSMA/CD). With this protocol, collision will be avoided [5]. In addition, the 802.11 protocol provides an optimal four-way handshaking technique, known as Request-To-Send/ Clear-To-Send (RTS/CTS) mode. This technique helps the source node to reserve the channel by sending RTS short frame. The destination node in return sends CTS frame indicating the channel is reserved for data transition (data packets). After the transmission is completed ACK response occurs [11]. However, nodes' waiting for a free channel is considered waste of time, while the whole channel is being used only for one node. Moreover the channel is sometime reserved for a node that does not have a lot of data transmission and yet cannot share the channel with other nodes and other nodes have to wait till the transmission is completed [5]. Therefore, there are two types of MAC overhead as [20] specifies them: *channel idle overhead* happens when all nodes are waiting to transmit, while the channel is idle. The other type is *collision overhead*, which occurs when a number of nodes transmit at the same time and that would cause increasing number of collisions. To control collision overhead, the protocol use Contention Window (CW). As soon as the collision increase the CW increases to help reduce number of collision in the network.

In order to send the message signal from one station to another wirelessly, we use modulation techniques. “Modulation is a process of conveying a message signal, for example a digital bit stream or an analog audio signal, inside another signal that can be physically transmitted” [13]. In early 802.11 protocols, Direct Sequence Spread Spectrum (DSSS) modulation technique was used. As with other spread spectrum technologies, the transmitted signal takes up more bandwidth than the information signal that modulates the carrier or broadcast frequency [2]. Figure 2 illustrates two sets of DSSS modulation; the first set has three non-overlapping channels that are separated with space to prevent interference between each other. While in the second set, there is an increase in the number of channels that caused half-overlapping between the channels, as a result that would cause possible interference between them, this is called “Interference concerns” [15]. The 802.11n standard uses Orthogonal Frequency Division Multiplexing (OFDM) modulation technique. This technique offers better efficiency, where OFDM is a subset of frequency division multiplexing in which a single channel utilizes multiple sub-carriers on adjacent frequencies. In addition the sub-carriers in an OFDM system are overlapping to maximize spectral efficiency. Ordinarily, overlapping adjacent channels can interfere with one another. “However, sub-carriers in an OFDM system are precisely orthogonal to one another. Thus, they are able to overlap without interfering. As a result, OFDM systems are able to maximize spectral efficiency without causing adjacent channel interference" [3]. The frequency domain of an OFDM system is represented in Figure 3.

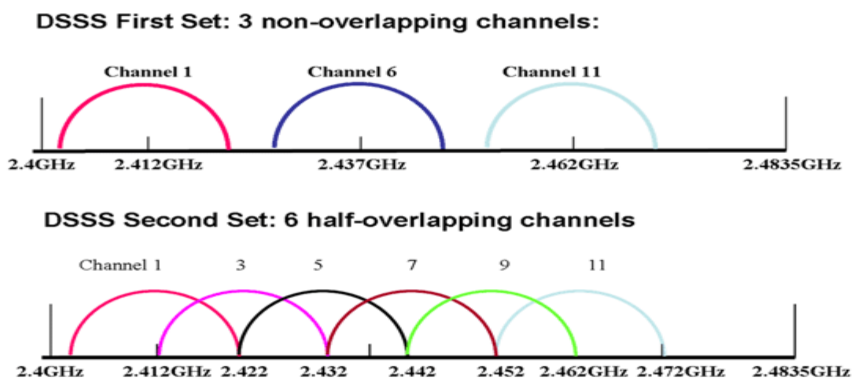


Figure 2. DSSS first set modulation has only three non-overlapping channels and when the number of channels increase to six in the second set it caused the channels to half-overlapping [14].

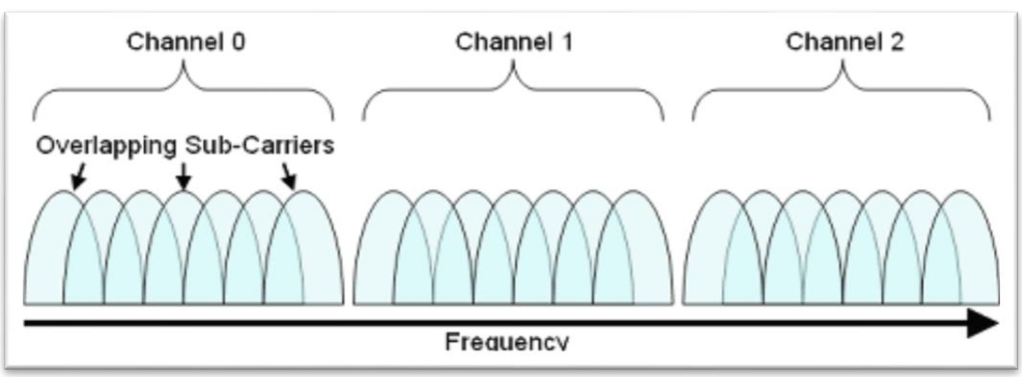


Figure 3. Illustration of a frequency band using OFDM. There are three channels on the frequency band. Each channel has several overlapping sub-carriers [3].

OFDM technique allows the channel to be divided into 14 sub-channels, and dividing the frequency among them as well. In 802.11n the use of channels is different from one country to another; it varies from 3 to 4 non adjacent sub-channels from the 14 sub-channels in order to avoid overlapping that causes interference between the sub-channels. In this case, many sub-channels left free without being used and that consider wasting of frequency space and transmission opportunities. Whenever the user chooses a sub-channel, other sub-channels would be idle and other users have to wait until it is free [4].

As we explained the mechanisms and techniques that have been used in 802.11 model, there are several impairments that we mentioned above. We list them below [11]:

1) Collision: happens on data packet transmission. CSMA/CA used to solve the problem, by making the station (node) listen to the channel to detect the channel status (whether it is busy or not). If the channel is busy, the node waits for a while and checks the channel again after a random time. However if collision is detected, the node waits a random time before its start sending again. The level of collision is an indication of a loaded or busy network. For instance, 802.11b with four saturated nodes has a collision probability of around 14%, while saturated has a collision probability of 40% [12].

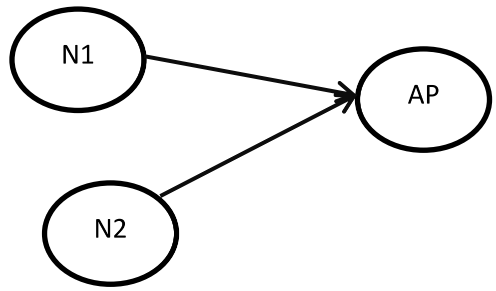


Figure 4. Collision occurs when nodes N1 and N2 send packets at the same time to the same AP.

2) Hidden nodes: “Frame corruptions due to concurrent transmissions other than collisions are referred to hidden node interference”. The probability that data transmission fails, which can be indicated by loss of ACK. For example, we have a number of transmitting nodes and a receiver. The hidden node (N2) transmits to an independent receiver (AP2). We ensure that the following conditions hold: the link from the transmitter (N1) to our receiver (AP1) is of high quality in isolation; the link from the hidden node to the hidden receiver is of high quality in isolation; a link cannot be established from the transmitter (N1) to the hidden node (N2); losses occur when the hidden node operates at the same time as the transmitter as illustrated in Figure 5.

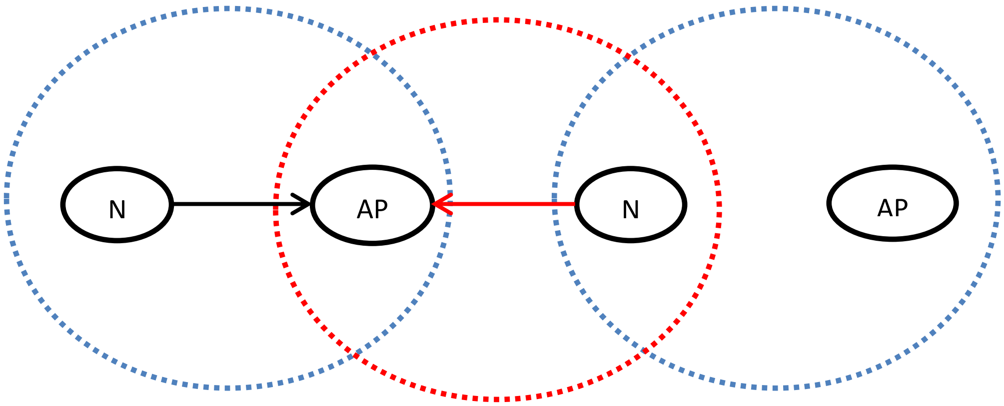


Figure 5. N2 sends to AP1 simultaneously with N1, while N2 should be transmitting to AP2. N1 cannot see N2 and that would cause hidden node problem.

3) Noise errors: Frame corruptions due to source other than transmissions by other 802.11 stations are referred to as noise losses.
4) Exposed nodes: The inability to transmit 802.11 frames is not just due to link losses. In particular, the carrier sense mechanism used in 802.11 to sense busy channel conditions may incorrectly classify the conditions. For instance, the station may detect the channel is busy when in fact a successful transmission could have been made.
5) Capture effect: The probability of successful reception of a frame when a collision occurs.

2.3. FICA Technology

Fine-grained Channel Access (FICA) in wireless LAN is a new Physical (PHY) layer architecture design that still under research presented by Tan and others. The new technology design aims to speed up the communication between users by proposing new physical architecture based on dividing the bandwidth into multi-channel. Therefore this would allow more than one user to send their data at the same time resulting more efficient WLAN.

FICA architecture uses the OFDM method, which would allow the channel to be divided into a number of sub-channels with no interference. Consequently that would allow multi-users to be assigned to these sub-channels at the same time without colliding with each other since the signals will be carried orthogonally [16]. FICA divides the channel into fourteen orthogonal sub-channels and each sub-channel into sixteen sub-carriers; while multiple nodes are able to send their data packets at the same time avoiding interference and as a result that would increase the efficiency and throughput of the network. Moreover, using OFDM would eliminate the need for guard band and that would save the bandwidth for transmission use [5].

FICA uses RTS/CTS frame packets for simultaneous transmission by using OFDM to avoid sub-channel collisions. Unlike IEEE 802.11 MAC that uses RTS/CTS to avoid collision that happen during simultaneous transmission. For each node to win a sub-carrier from the channel network, they need to contend in contention band. The contending nodes send RTS signals simultaneously to the access point (AP). The AP on its behalf determines the data transmission path by sending CTS signal randomly to destination nodes using OFDM technique as well.

FICA does not support bidirectional traffic. It separates uplink and downlink transmission from each other to avoid collision (full-duplexing). Instead, FICA assigns different Distributed Inter-Frame Sequence (DIFS) times to both uplink and downlink communications by allowing the nodes to communicate after certain DIFS time. In comparison, other MAC schemes use random backoff times to avoid collisions.

FICA suggested that the channel bandwidth is divided into fourteen sub-channels and each sub-channel is divided into sixteen sub-carriers for 20MHz bandwidth (experiment assumption). This group of sub-carriers is called *contention band*. If the node wins the sub-carriers it would receive CTS signal indicating this path is reserved for its transmission. Even if more than one node chooses the same sub-carrier, AP will decide the winner based on certain priority, like the one with highest energy.

The proposed FICA scheme while interesting leaves several critical questions unanswered:

1- What is the optimum number of sub-channels and sub-carriers? Will these optimum numbers change as network condition varies?

2- What if two nodes transmit on the same contention sub-carrier? How can we make sure the AP can differentiate them and choose one in a fair fashion?

3- What is the maximum number of frame bits that should be sent to each sub-carrier for reservation?

4- What if we have more than one AP? Do we need receiver ID? And if so, how could these IDs apply to nodes?

These are the essential questions of this thesis. By answering them, we present our attempt to address the sophisticated problem of high-speed wireless networking, making it both realistic and useful.

2.4. Related Works

Recently many studies focus on the developing and creating of new protocols, where all of them aim to increase the throughput of WLAN network. This research focuses on contention resolution since it is the key component in carrier-sense-based wireless MAC protocols. [20] divided the studies into two main groups, first group study centers on developing new MAC protocol by using part of the bandwidth for contention and the rest for the data transmission. The other group is using the directional antenna by dividing the spectrum into sub-bands that are used for data transmission. Most of the research falls into the first category, as well as this research. Following is a list of some of related work:

Han, Deng and Haas present a design using ALOHA technique [21]. The Medium Access Control (MAC) schemes controls the access of the active stations in the network. The design consists of one control sub-channel and m data sub-channels. Control sub-channel is used to control access to the data sub-channels. Also, RTS/CTS are used for reservation, and to control resolution, ALOHA technique is used. Each node keeps a list of free channels and transmits RTS in all free channels. If a winner node in the control sub-channel finds available idle data sub-channel, it will enter a queue to be sent to the available data sub-channel. If the queue has no idle data sub-channel it will wait until one sub-channel is free. But in the case where all sub-channels are busy and the queue is full, its request will be dropped and the node competes again later.

Zhou, Marshall and Lee adopted a simple contention resolution scheme called *k_Round* elimination contention based on MAC protocol [22]. MAC elimination contention protocol implements Binary Exponential Backoff (BEB) scheme, which showed a good achievement for transmitting small size packets in a wireless network. However, the BEB mechanism showed inefficient results later when the size of the network increased, that result in increasing in collision rate as the number of contending nodes increases. In the new scheme *k-round* elimination contention (*k*_EC), the number of contending nodes is gradually reduced in k-rounds mechanism, so the contention resolution is performed by elimination, each of which eliminates some of the contending nodes. The simulation showed high efficiency and robustness during the collision resolution. Also it is feasible for large size data packets. As a result, the WLAN gets few collisions and that would increase the efficiency of the network.

Abichar and Chang worked on finding a new MAC scheme with Constant-Time Contention Resolution for WLAN [23]. They presented a new scheme such that it resolves the contention in a constant number of time slots, therefore called constant time contention resolution (CCR); as a result, the collision rate is very low. The common scheme DCF in IEEE 802.11 performs well enough for a small-size network, exactly as [22] discussed. However, the scheme shows low performance when the packet size in the network is increased. The main idea of CCR scheme is running a certain number of contention slots to resolve the contention before a transmission can be initiated. This period of time is called contention resolution period (CRP). In each contention, part of the contending nodes is eliminated to reduce the number of collision. Eliminated nodes can contend again later. As a result, the collision is reduced and that would enhance the efficiency and increase the throughput of the network.

Abichar and Chang presented another scheme Constant-Time Contention (CONTI) that aims to decrease the collision rate in the channel [24]. Stations in IEEE 802.11 are using Distributed Coordination Function (DCF) for contention, which showed low performance by increasing the number of stations. CONTI resolves the number of contention by using k number of slots for n number of stations. When nodes contend they send signal 1, and if they are listening to the channel, the signal would be 0. When the node hears a collision it stops sending signals. Winner nodes win slots from the k slots, and they move to the next slot until only one node wins the channel. By this, collision is avoided and the throughput of the channel is increased.

Wu, Utgikar and Tzeng proposed new MAC protocol called SYN_MAC (which stand for SYNchronized MAC) as an alternative to IEEE 802.11 protocol for wireless communication [25]. This approach is based on binary count down. This new protocol showed low collision probability and high performance which helped to increase the efficiency of multi-hop networks using synchronizing scheme. Also, it does not use the collision detection protocols that are used in IEEE 802.11. In the scheme, when the channel is busy, the stations stop transmitting until the other stations finish transmitting. If the station is in collision domain, only one node will win to move on to the next step. In transmission nodes compete with each other, however this competition is in order. Nodes compete with nodes around themselves, but not all the nodes in the network. Therefore the transmission is synchronized and that would decrease the number of collision.

Another research proposing a new protocol that falls into finding a better mechanism that would solve the contention resolution problem, presented by Jibukumar, Datta and Biswas [20]. The research proposed a random access MAC protocol that showed increasing in throughput regardless of the number of nodes contending in the channel. The protocol called Busy Tone Contention Protocol (BTCP) that uses out-of-band signals for contention resolution in WLAN. Also, it separates the multimedia traffic from data transmission.

Other protocol design aims to increase the performance of wireless network for multi-hop network in multi-channel network called *iMAC*, presented by Maiya and Hamdaoui [26]. Although *iMAC* is not part of 802.11 protocols, it uses the same mechanism for data transmission over the wireless channel. In *iMAC* control packets on a channel enable a three-way hand-shake communication between two stations. The research shows gains in throughput of the channel in medium contention rate.

Many researchers now are focusing on the use of OFDM. Rahul, Edalat, Katabi and Sodini used OFDM on their research of their scheme Frequency-Aware Rate

Adaption (FARA) for dividing the channel bandwidth into multiple distinct channels that avoid interference which showed increasing in the throughput [27]. Dutta et al in their research SMACK - A SMart ACKnowledgment Scheme for Broadcast Messages in Wireless Networks, they are implementing a reliable, faster broadcast for infrastructure and peer-to-peer network that aims to resolve group communication by using OFDM mechanism [28]. Also, Ahmed, Mohammed and Alnuweiri have used OFDM in their survey on the fairness of resource allocation in wireless mesh network (WMN) [29]. Moreover, Guo, Dang and Liao used OFDM for their research on distributed resource allocation with fairness for cognitive radios in wireless mobile ad hoc networks [31]. Their results excel comparing to other models they used in their research in terms of throughput and fairness allocation. They worked on multiuser distributed resource allocation over frequency channels based on OFDM that helped to get better results.

Others focused on the *contention unfairness problem* that rose in CSMA protocol. Kolar et al present in their paper how important fairness is in communication and how it is a challenging problem that needs more attention [30]. The paper shows that unfairness contention is caused by the interaction between nodes and the fact that they all share the same channel network, and that what happens when a number of stations try to communicate, some of the nodes wait for the channel to be idle. This waiting time is unfair especially when it is caused by other hidden terminals. Therefore, for higher throughput of Multi-Hop Wireless Network (MHWN), model should be developed in a way that present fairness in node contention. Another study about Multi-Channel Multi-Radio (MCMR) is trying to solve the interference problem between the network channels lowering throughput. In their paper, Vallam, Kanagasapathy and Murthy [34] emphasize the importance of the channel assignment in a way that it guarantees the use of all the available bandwidth.

CHAPTER III

NEW DESIGN

Our new design is developed on top of the FICA design; it is working on finding a better design to supply many users efficient WLAN in real world. This new design assumes the network channel is divided into a number of sub-channels, m, and each sub-channel is divided into a number of sub-carriers, k; FICA made similar assumptions.

The new design has proven that the more sub-carriers the channel has it gives better efficiency, η, while in the FICA design it presented a limited number of sub-carriers (sixteen sub-carriers in each of the fourteen sub-channels and that equals 224 sub-carriers as total in the whole channel). FICA is depending on using OFDM technique to the whole channel to prevent interference between the sub-channels and avoid wasting bandwidth on guard band; as a result the channel can use the bandwidth for having more sub-channels and sub-carriers. *Guard band* is a band that current protocols are using to separate the sub-channels between each other hoping to prevent interference. This band takes part of the bandwidth, while FICA uses OFDM to avoid using guard band and use this amount of bandwidth for actual transmission.

In the next sub-sections, we present the different scenarios of different network sets of our design.

3.1 Single Channel, Single AP

In this experiment the network consists of one receiver, access point (AP), and a number of transmitters/users, nodes (N). These nodes will contend on several sub-carriers to win the right to send on the channel. We will consider having only one channel by dividing it into k sub-carriers. In contrast of 802.11 standards that allow the nodes to contend to reserve the channel and only one node will win, more nodes can win in our design. Collisions could happen if two or more nodes choose the same sub-carrier at the same time. However, the number of collisions would be much lower than in FICA design regarding increasing number of sub-carriers in the new design and allowing more nodes to win. What happens is increasing number of sub-carriers in the channel would allow increasing the contention band, therefore bigger chance for more than one node to contend and win at the same time. This means better network efficiency.

There are two major important factors that affect the efficiency of the WLAN, number of sub-carriers (nsc) and number of nodes (N). *Efficiency* of a network is the fundamental key of the network study because there is a limited amount of spectrum to transmit data packets such as voice, text, and other internet services, like streaming video and music [7]. Therefore, enhancing the network to become more efficient is the essential key in this study. By definition *efficiency* is a quality that characterizes the correspondence between the consumed resource and the attained utility [8]. That is to say, the network needs to use the bandwidth spectrum more effectively such that more data bits can be transmitted and received successfully in each unit time on each unit spectrum. In this thesis, we define *efficiency* (η) as the number of successful contentions in each unit time on the entire bandwidth.

Our investigation is mainly through MATLAB simulations (Check Appendix A, B, C and D). First, we test the relation between number of sub-carriers that the channel has and its impact on the network efficiency. Therefore, the number of nodes is kept as a constant number. Figure 6 illustrates the impact of number of sub-carriers on the channel, nsc, on efficiency (with N=100 contending nodes in the network). From Figure 6, it can be seen that η increases with nsc until it reaches a saturation point. After this point, η decreases as nsc increases further.

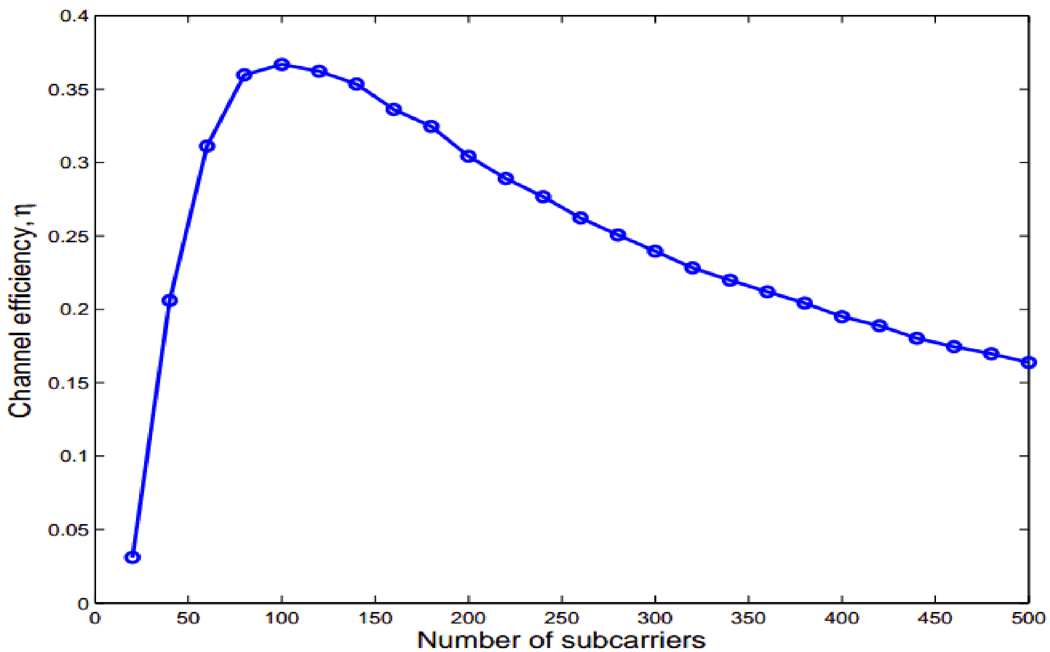


Figure 6. Increasing η while increasing number of sub-carrier (nsc), indicating that it is possible to divide the channel into number of sub-carriers and get a better η. N=100 in this set of experiments.

From Figure 6, it is easy to conclude that it is better not to use a small limited number of sub-carriers. The more sub-carriers the channel has, more users it will serve. As a result, that would speed up the network communication avoiding the time that the user has to wait until it gets free channel to send their data packets. Also, it gives the network high performance and better efficiency. In spite of the conclusion of increasing η while increasing nsc, there is still an optimum number of nsc to obtain the best η because of the limited amount of bandwidth.

Table 2 has the values from Figure 6 showing the different η while increasing number of sub-carriers. For example, when nsc = 100, η = 0.36, which is the optimum number in this experiment. While η= 0.2 for both nsc = 400 and nsc = 50, showing that η goes down while increasing nsc to reach the same one when nsc=50.

Table 2. Increasing η values while increasing nsc indicating the network that have more nsc would have better throughput and as a result serving more users. N=100 in this experiment.

η	Number of Sub-carrier(nsc)
0.05	25
0.2	50
0.38	100
0.2	400

However, Figure 6 presents η in general without taking the bandwidth of the channel into consideration and how much bandwidth each sub-carrier needs for transmission. That is to say, we consider each sub-carrier the same whatever number of sub-carriers a system has. In reality, splitting the frequency band into an increased number of sub-carriers would reduce the data rate of each sub-carrier. In fact, the data rate of each sub-carrier is proportional to the inverse of the number of sub-carriers. Therefore, we define *effective efficiency*, η_e (η^*), which shows the effective successful data transmission/reception in each unit time on each unit spectrum on the channel. Figure 7 shows the results. From Figure 7, it can be seen that it is good to know the approximate number of competing nodes in a network. Such information would help to estimate the number of sub-carriers required to serve that network and give a high efficiency in a certain bandwidth spectrum value.

Table 3 lists the optimum nsc, nsc*, and its corresponding efficiency, η*.

Table 3. For each number of competing nodes in the network, there is an optimum nsc, nsc*, that can result in the best efficiency, η*.

Number of Competing Nodes (N)	Number of sub-carrier, nsc*	Efficiency, η*
100	70	0.34
300	200	0.27
500	350	0.22

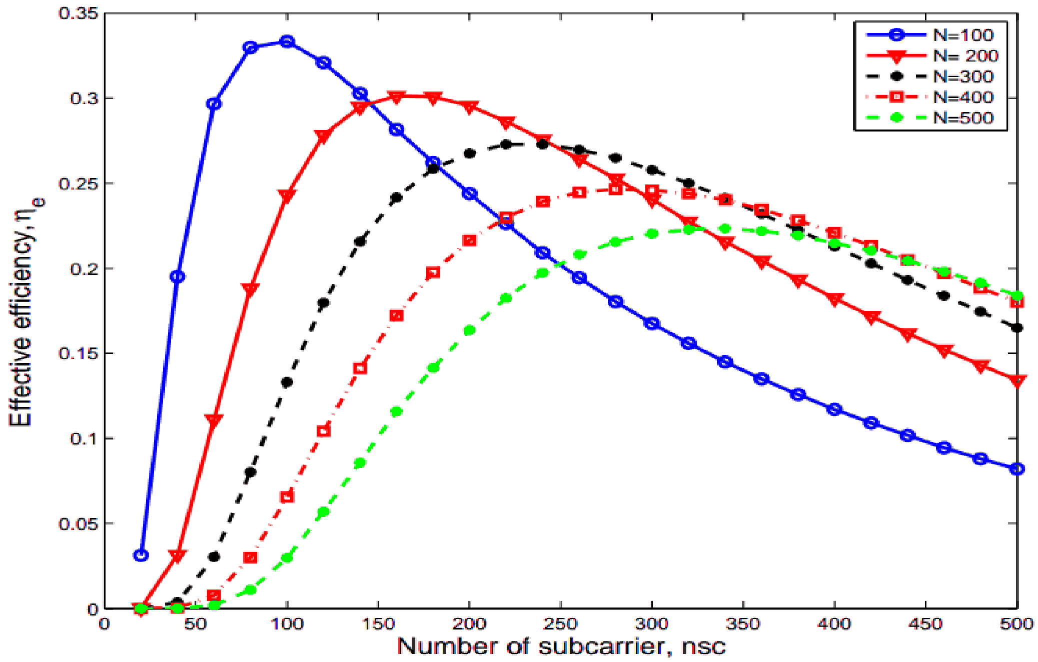


Figure 7. Effective efficiency, η_e, of different competing nodes. In each curve, η_e increases with nsc at the beginning until it reaches a saturation point. Then it comes down as nsc increases further. The optimum nsc for each different N scenario is obvious.

As we see in Figure 7 and Table 3, η^* column, efficiency has varying values depending on nsc and the number of competing nodes in a specific spectrum. As a conclusion, increasing number of sub-carriers in the channel alone is not enough to have a better efficiency regarding to other factors that play a role in the efficiency of the network. Factors include bandwidth, since there is a limited amount of bandwidth, and number of stations (N). Increasing N too much could cause the network to over load and that would reduce the efficiency of the network. Again from Figure 7 and

Table 3. For each number of competing nodes in the network, there is an optimum nsc, nsc*, that can result in the best efficiency, η^*. When nsc=70, the effective efficiency= 0.34 and when the nsc is increased to 350, the effective efficiency is lowered to 0.22. We can summarize from Figure 7 the following:

1- The optimum nsc, nsc*, increases with N. Therefore, as the number of competing nodes in the network increases, there should be more sub-carriers to share among competing nodes. From

2- Table 3 we can see that there is almost a linear relationship between nsc* and N (nsc*=0.7N).

2- With regard to the optimum effective efficiency, it decreases with N. Such a decrease can be explained by the higher contention with more competing nodes.

Based on the conclusions from Figure 7, we draw Figure 8. The more competing nodes the network has, the more sub-carriers it needs, as we can see when the network has 200 nodes the nsc* is 180, and while the number of competing nodes increases to 400, nsc* value increased to 280.

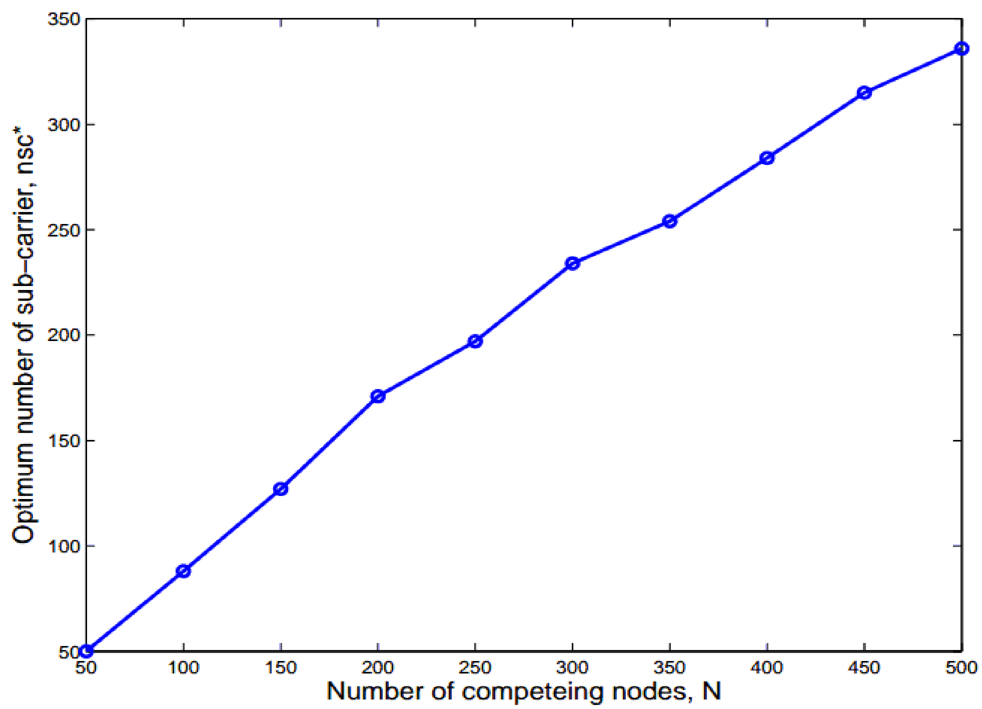


Figure 8. Increasing the optimum nsc, nsc*, while increasing the competing number of nodes, N. Showing that increasing number competing nodes in the network needs more sub-carriers to compete for better transmission.

In all the scenarios that have been discussed previously, we focused on a network communication between numbers of competing nodes (N) and one access point (AP). There is one channel that connects N and AP and this channel is the bandwidth for that network (w) and the channel is divided into sub-carriers (nsc). Therefore, the competing nodes compete to win a sub-carrier from the channel and reserve it from contention band (nsc*f) where f is the bandwidth per sub-carrier. Whenever the node wins the sub-carrier from the contention band, it will start sending its data through the channel. Figure 9 demonstrates the channel and its variables that have been used for simulations for the different scenarios. In addition, the equation that is used to calculate the effective efficiency, η_e, of the network in Figure 9 is $\frac{w-nsc*f}{w}$, and it's easy to see where this equation came from.

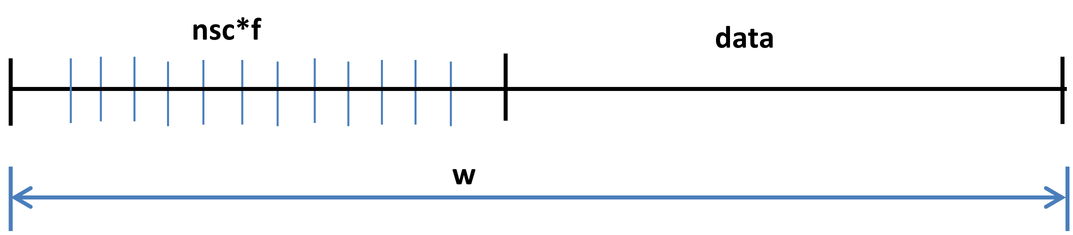


Figure 9. Illustration of the channel and the equation (w-nsc*f)/w. Where w is the total bandwidth of the channel, f is the bandwidth per sub-carrier, nsc*f is the contention band and data is the band that winner nodes will use to send their data to the AP.

Figure 10 illustrates further the second point that was concluded from Figure 7: decreasing the effective efficiency, η_e, while increasing number of competing nodes in a network. For competing nodes N, the effective efficiency is almost 0.33 and when N increases to 350 the, η_e, decreases to 0.26. We can conclude from that each network have a certain number of nodes that can serve with high data rates and throughput. Otherwise, after a saturated point of nodes, efficiency and data rate will decrease, presenting low network efficiency.

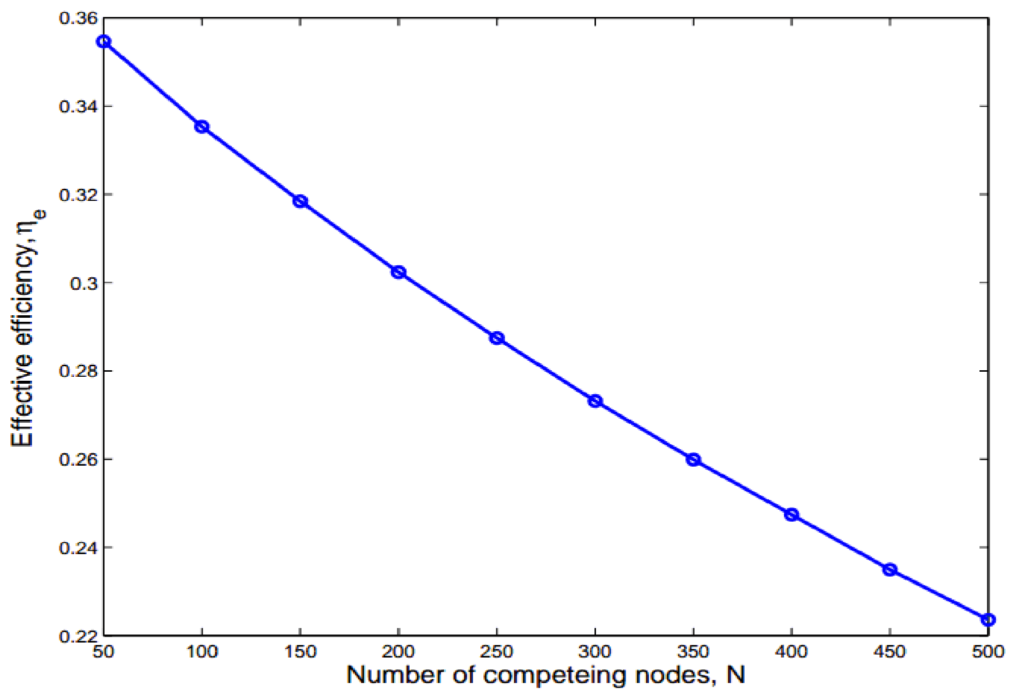


Figure 10. Decreasing the effective efficiency, η_e, while increasing number of competing nodes, N.

We have been focusing on the selection of number of sub-carriers in this subsection. In the real network, multiple sub-channels may be chosen. Therefore, the study on how to select sub-channels and sub-carriers is in order.

3.2. Multiple Channel, Single AP

3.2.1. First Model

In previous network experiment, the competing nodes, N, were competing to use one channel that is divided into a number of sub-carriers through one Access point (AP). In this subsection, we investigate the multiple channel scenarios. The current network setup is the following: one AP serving as the common receiver, N nodes competing for the use of the shared channel (or sub-channels), and multiple channels, moreover each sub-channel is divided to number of sub-carrier. There are two phases in each cycle of the transmission: reservation phase and transmission phase. In the reservation phase, nodes compete on the sub-carriers within the same sub-channel to reserve for the use of the (sub) channel. However in the case, only one node is supposed to win sub-channel, but more than one node wins different sub-channels and is able to transmit its data packets. In the transmission phase, successful nodes send packets on the reserved (sub) channel. Figure 11 illustrates the first model and how the channel is divided into m sub-channels. The two phases occur at each sub-channel; first nodes contend to win a sub-carrier (reservation phase) then start sending its data packets (transmission phase). We are interested in finding out the best arrangement to maximize the overall throughput in specific bandwidth (W).

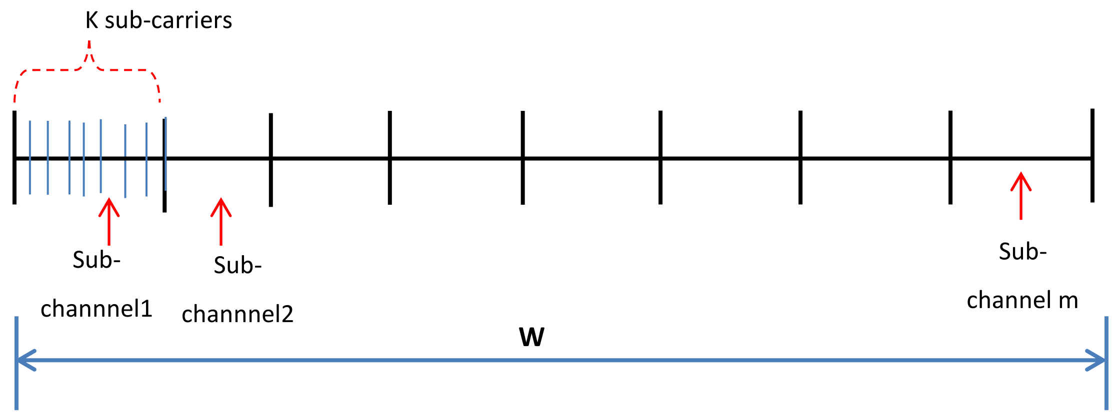


Figure 11. Illustration of the channel when it's divided into m sub-channels, each sub-channel has k sub-carriers. Red arrow indicates the winner sub-carrier for node reservation. Where W is the bandwidth of the channel.

In our study, we tried to identify the optimum number of sub-carriers for each known number of active nodes, N, in the network. Further investigations include the following assumptions:

1- There are usually m sub-channels and in each sub-channel there are k sub-carriers for contention purposes (therefore, there are altogether m*k sub-carriers for contention). See Figure 11 for more details.

2- Each competing node selects j sub-channel for contention, j<m. In each sub-channel, it sends on L of the sub-carriers. In essence, this is an extended case of the previous subsection, in which j=m=L=1.

3- If two nodes choose the same sub-carrier, collisions will occur on the sub-carrier. The result of the collisions is that the receiver, the single AP, receives a failed contention on the sub-carrier. In the contention sub-carriers on the same sub-channel, the node winning the left-most (in sub-carrier number) sub-carrier wins the right to transmit on the corresponding data channel.

From these assumptions, the experiment continues to investigate the following directions for real network setup:

1- Assuming that each of the N contending nodes is allowed to contend for only one sub-channel by indicating on one sub-carrier, i.e., j=L=1, what is the optimum m and k?
2- Assuming that each of the N contending nodes is allowed to contend for only one sub-channel by indicating on L sub-carriers, i.e., j=1, what is the optimum m and k as a function of L?
3- Assuming that each of the N contending nodes is allowed to contend for j sub-channels by indicating on L sub-carriers, i.e., arbitrary j and L, what is the optimum m and k as a function of j and L?

3.2.1.1. j=1 and L=1

In the research on a single channel (section 2.1), all sub-carriers belong to the same channel (there was no sub-channels). In fact, this new design suggested dividing the channel bandwidth into m sub-channels and in each sub-channel there are *k* sub-carriers (therefore, there are altogether *m*k* sub-carriers) in order to make the channel more efficient by allowing more nodes to use the channel, or part of it, at the same time. Each user competes to win one sub-carrier which enables the winner to reserve the sub-channel then use it for transmitting its data.

The goal is to find the optimum number of sub-channels, m*, for a network, in the case that the competing node has the chance to win only one sub-channel by using only one sub-carrier (j=1 and L=1).

Based on the assumption of j=1 and L=1, each node can only compete on one sub-channel and can only select one sub-carrier to do so. Assuming that there are *k* sub-carriers on each sub-channel, we can analyze the network throughput based on successful reservation probability as follows:

Since there are *m* sub-channels and each of them has *k* sub-carriers, the probability of each node choosing a particular sub-carrier is simply:

$$p = \frac{1}{(km)}$$

In the following, we assume the probability of each node choosing any sub-carrier to be independent and compute the following two probabilities: the probability of being idle, P_i, and the probability of successful reservation, P_s. For each sub-carrier, the chance of successful reservation is when only one of the N nodes chooses the sub-carrier but all others do not:

$$P_s \approx \binom{N}{1} p \, (1 - p)^{(N-1)}$$

For each sub-channel, we only need to check whether there is any sub-carrier that has been successfully reserved. We find the chance of all *k* sub-carriers with failed reservation or being idle first:

$$Prob(subchannel\ not\ successful) \approx (1 - P_s)^k$$

The probability of a sub-channel having at least one successful sub-carrier reservation is then:

$$\Gamma = Prob(subchannel\ successful) = 1 - (1 - P_s)^k$$

In order to find the optimum *m* as a function of other parameters, we should take a partial derivative of Γ based on *m* and find the value of m that gives us the maximum Γ. However, a more careful look revealed that we can simply maximize P_s:

$$\frac{\partial Ps}{\partial m} = \frac{\partial}{\partial m}\left[N\frac{1}{km}\left(1 - \frac{1}{km}\right)^{N-1}\right] = 0$$

Eliminating N/k from the term above, we have:

$$\frac{-1}{m^2}\left(1 - \frac{1}{km}\right)^{N-1} + \frac{1}{m}(N-1)\left(1 - \frac{1}{km}\right)^{N-2}\frac{1}{km^2} = 0$$

Which is:

$$\frac{1}{m^2}\left(1 - \frac{1}{km}\right) = \frac{1}{m}(N-1)\frac{1}{km^2}$$

$$km - 1 = N - 1$$

$$m = \frac{N}{k}$$

The expression above shows that the optimum number of sub-channels (m*) in a network depends on the number of nodes, N, and the number of sub-carriers (k). The relationship between m* and N is positive correlation (Direct relationship), for example: m*= 200/40=5, m*=400/40=10, meaning that as the number of nodes increase in a certain network number of required sub-channels increases as well. While the relationship between m* and k is a negative correlation (Inverse relationship), as it shows in the following example: m*=200/10=20, m*=200/40=5, m*=200/100=2. As putting N constant and changing the values of k, it is clear that whenever k increases the optimum number required for that network decreases, making it an inverse relationship.

However, simulating the previous scenario did not give the predictable results, actually the result pointed out a serious problem that might arise. The result shows that whatever number of k was in the whole channel, the total number of sub-channels would be no more than one. Actually increasing k would decrease successful m sub-channels. This outcome contradicts our assumption of dividing the k sub-carriers into m sub-channels to increase the throughput of the channel and that would allow group of nodes to win the different sub-channels and send their data at the same time. Meaning that, the idea of N nodes contends on the k-sub-carriers on the whole channel was not helping to fasten the transmission. Also, allowing the number of nodes to compete to win a sub-carrier in the whole channel would increase the overhead of the channel (m/k), making the entire channel busy for competing and transmitting. Figure 12 shows the result of the simulation and how the model behaves. In this scenario, each node is allowed to contend to win only one sub-carrier (L=1) and as a result winning only one sub-channel(c=1) indicating that the maximum number of active sub-channel would be one sub-channel and increasing k actually decreases the chance of having m successful sub-channels.

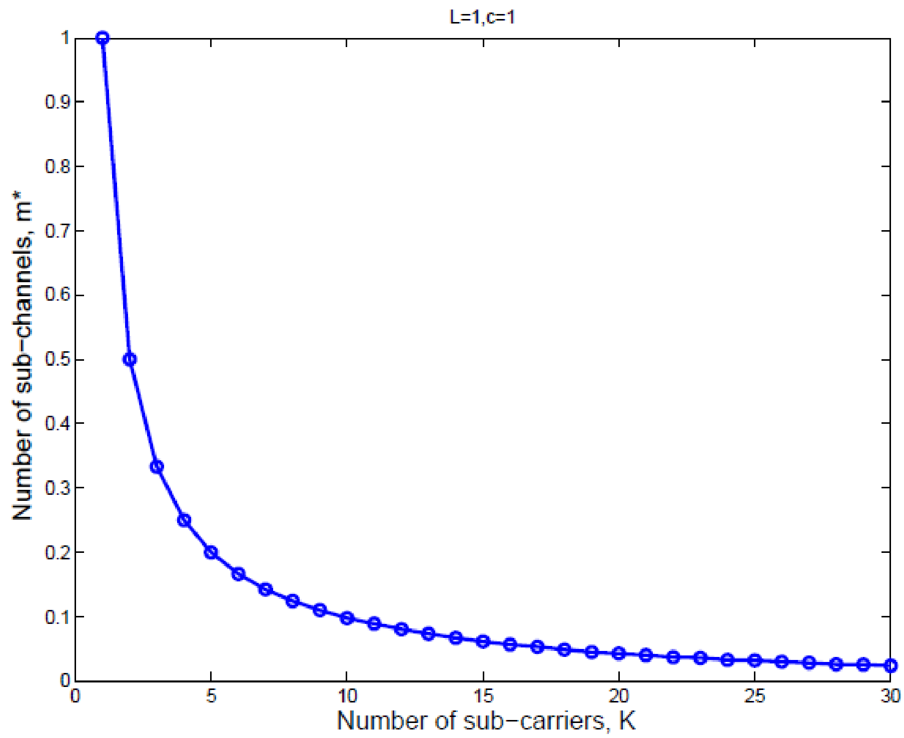


Figure 12. One is the optimum number of sub-channels in Model 1, when each node has the chance to win only one sub-channel(c=1).

3.2.2. Second Model

We then investigated our second model. Modifying the first model in a way that would consist of two phases: reservation phase and transmission phase. However, in this model both phase cycles take place separately. The reservation phase consists of *m* sub-carriers which is exactly the same number of sub-channels in the transmission phase. In reservation phase nodes would compete to win a sub-carrier first, and as a result the winner would be allowed to transmit its data through the corresponding sub-channel.

Making nodes compete on part of the channel (contention band) would help decreasing overhead that result from nodes contending and competing to win a sub-carrier in the whole channel, and this is the case in the first model and FICA design. While in transmission phase, it contains *k* sub-carriers that is divided on *m* sub-channels (m/k), therefore each sub-channel consist of same number of sub-carriers for winning nodes to send data packets to the destination (Access point). Figure 13 illustrates the new second model arrangement of the channel. The new arrangement aims to maximize the overall throughput in the specific bandwidth (W).

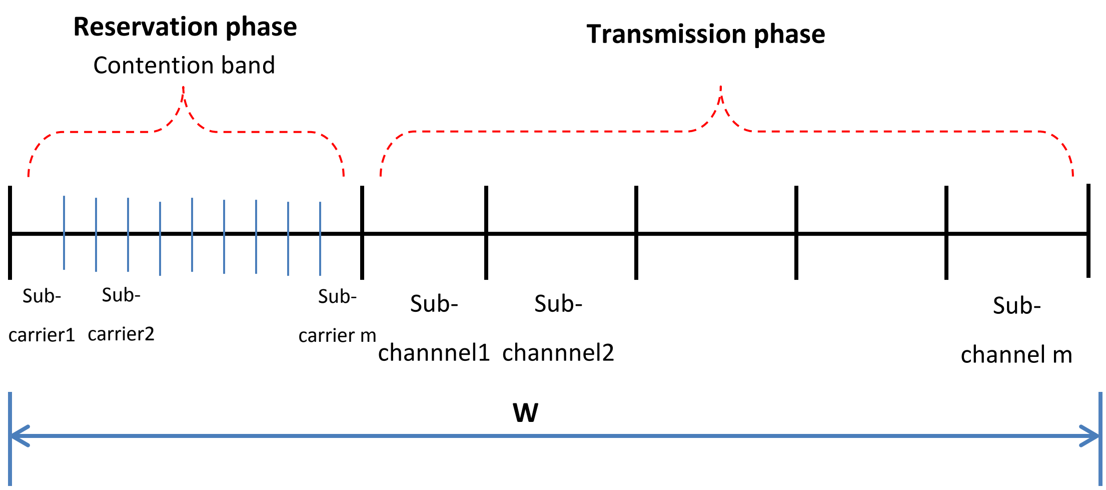


Figure 13. Second Model, consist of two phases: Reservation phase (Contention band) and Transmission phase. Also, number of sub-carriers in contention band equals to the number of sub-channels in the transmission phase.

The mechanism for the second model is as follows: when a node N_i contends and wins a sub-carrier 2 from the contention band, the node would win the correspondent sub-channel 2 from the transition band, and then start sending its data packets to the access point using all the sub-carriers in sub-channel 2.

The investigation for the second model goes under almost the same assumptions of the first model. These assumptions include the following:

1- There are m sub-carriers for reservation phase that are used for contention purposes. See Figure 13

2- There are m sub-channels and each sub-channel contains (m/k) sub-carriers that are used for transmission purposes. See Figure 13.

3- Each competing node selects j sub-carrier for contention (j<m), nodes will send L sub-carriers to win the reservation (Different scenarios depends on the value of L, will discuss later independently in details).

4- If two nodes choose the same sub-carrier from the reservation band, collision will occur on that sub-carrier. The result of the collision no node would win, resulting in failed connection to the AP.

From these assumptions for the second model, the experiment continues to investigate the following directions for real network setup:

1- Assuming that each of the N contending nodes is allowed to contend for only one sub-channel by indicating on one sub-carrier, i.e. j=L=1, what is the optimum m and k?

2- Assuming that each of the N contending nodes is allowed to contend for only one sub-channel by indicating on L sub-carriers, i.e., j=1, what is the optimum m and k as a function of L?

3- Assuming that each of the N contending nodes is allowed to contend for j sub-channels by indicating on L sub-carriers, i.e., arbitrary j and L, what is the optimum m and k as a function of j and L?

From the direction of the experiment, the investigation carries on to study each point separately in the following order:

3.2.2.1. L=1

Within the second model design, the first scenario allows each node to contend and win only one sub-carrier from the contention band, we denote it by (L = 1). Each sub-carrier is related to one corresponding sub-channel, for example winner node on sub-carrier 4 would be able to send its data to sub-channel 4 and winner node on sub-carrier 9 would be able to send its data to sub-channel 9 and so on (see Figure 13).

The channel contains k-sub-carriers; m-sub-carriers are used for reservation phase and the rest of the sub-carriers (k-m) are divided by on the number of sub-channel (m) for transition phase. And for calculating the overhead of the channel, we divide the effective sub-carriers that are used for transmission by the number of sub-channel $\frac{k-m}{m}$. Figure

14 is the resulted figure from simulation of the previous scenario when (L=1) and we can conclude the following:

a. Optimum throughput that the network can get when the node has the chance to win only one sub-carrier (L=1) is influenced by number of sub-carriers in the channel.
b. The figure plotted three lines for three different values of k, and the maximum throughput between these three lines in 0.34 is for the biggest k (k= 500). And that confirms our assumption of increasing number of sub-carriers in the channel could increase the throughput of the channel, and as a result make the network faster by making more sub-carriers used for transmitting the data.
c. Also, the figure shows the number of sub-channel m needed can vary for different k, for instance when k=500 number of sub-cannels needed is almost 40 while when k=100 m is between 30 and 33 the line degrades after peak point of the throughput proving that there are an optimum number of sub-carriers and sub-channels.

To sum up, dividing the channel into m number of sub-carriers in contention band and m number of sub-channels in transmission band gives different results depending on the number of sub-carriers and channels. Whereas, increasing m in both bands can give higher throughput and that proves our theory. For this experiment number of nodes used is N= 50 and the selection for each node is L=1.

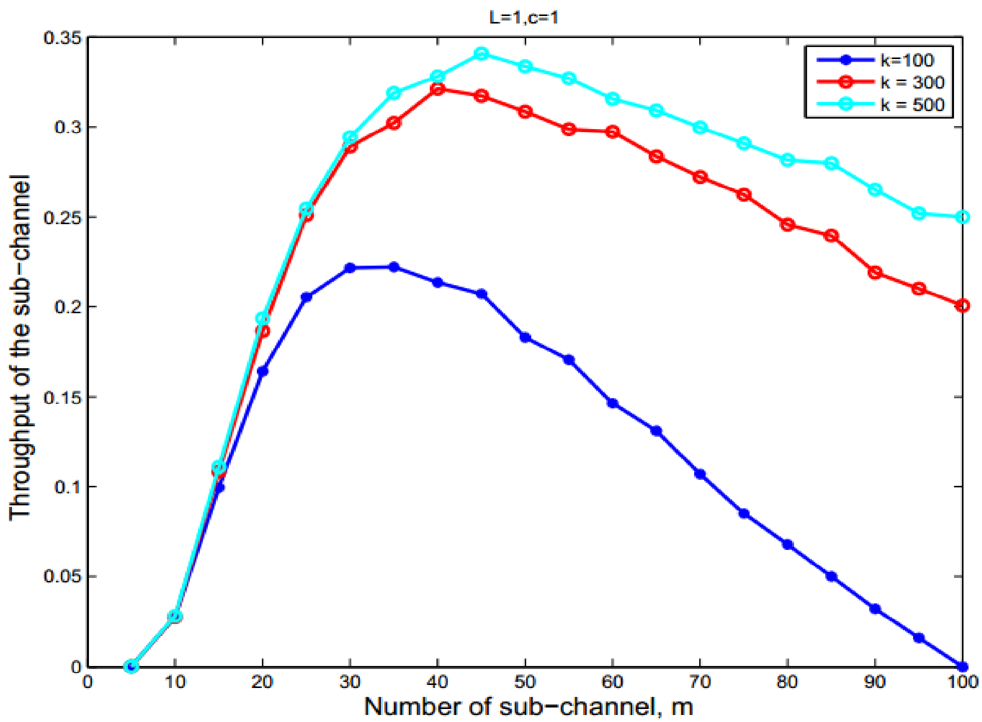


Figure 14. Throughput for model 2 when (L = 1) and different (k). Maximum throughput is when (k=500) indicating increasing k would increase the throughput of the channel. Also, can find the number of m required for that network, in this example (N=50).

In real wireless network, it is hard to know the numbers of active users, but it is important to estimate the number of users to offer better network connectivity that satisfies the users' needs. For this matter, the investigation continued to find out the optimum number of sub-channels with existence of different number of users (nodes, N) for different number of sub-carriers (k). The result in Figure 15 helps to understand the fact that more users using the network more sub-channels are needed for efficient network. And it is logically correct, because when each node had the chance to use one sub-channel, after m nodes (since we have m sub-channels, so m would be the maximum number of winners) the throughput of the network will decrease indicating the need for more sub-channels to serve the users N, in addition to the possibility of collision that might happen if two nodes or more sends at the same time. See Figure 14 that illustrates k effect on the throughput by increasing it while increasing k. Whereas Figure 15 shows the influence of nodes N on finding the optimum sub-channels m*. The figure has three values of k (200, 400, 600), and the more k is it will serve more sub-channels. For instance, when k=200 and N=80, the m*= 65, while when k=600 for the same N, the m*=75. These values indicate that increasing k would increase the number of the sub-channels provided to that channel meaning higher m* and better throughput. The total number of sub-channels that used in the simulation is 200. From this we can see how N affects the number of sub-channels needed; hence the maximum value of sub-channels needed did not exceed 90.

Table 4 is comparing two k sets of values (200, 600) from Figure 15 and how increasing k would provide higher m*, moreover, increasing N would increase the need for m*. Consequently, both k and N will affect the optimum number of sub-channels needed for certain wireless networks.

Table 4. The optimum number of sub-channels (m*) needed with two different (k) values and four (N) values obtained from Figure 15.

Number of sub-carriers (k)	Number of nodes (N)	Optimum number of sub-channel(m*)
200	40	30
200	60	42
200	80	65
200	100	70
600	40	40
600	60	50
600	80	75
600	100	88

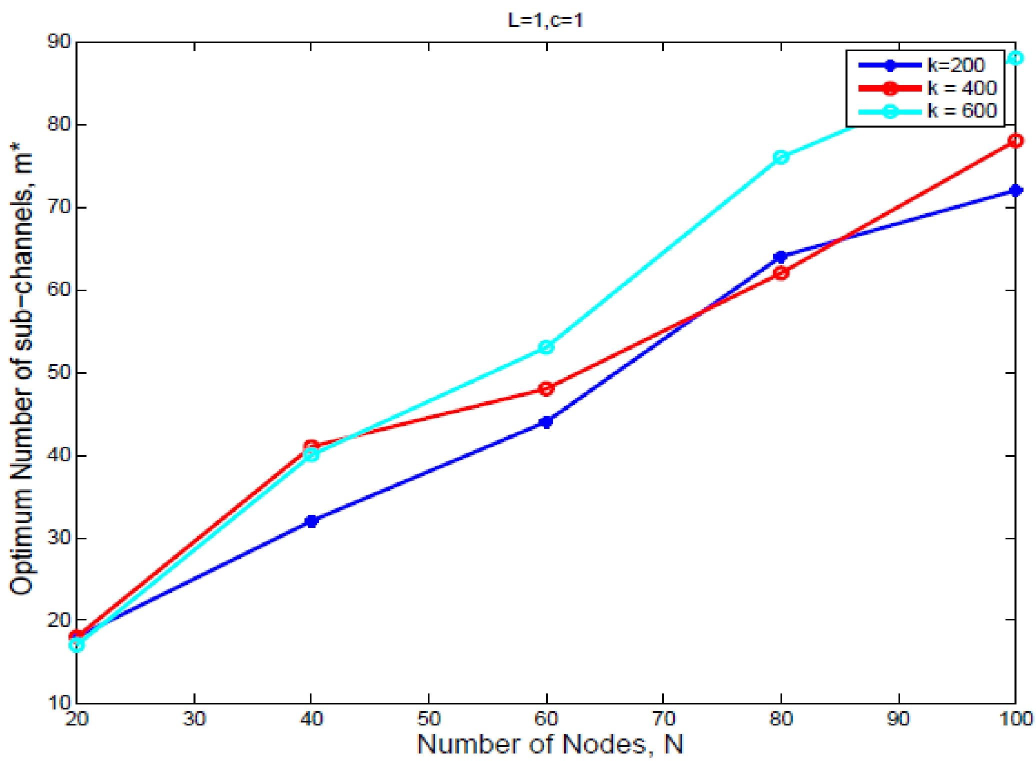


Figure 15. Finding the optimum number of sub-channels (m*) when nodes (N) range is [20:20:100] with different (k) values.

The investigation continues to simulate different rang of N (100, 200, 300) for the same range of k (200, 400, 600) and the total number of sub-channels in the simulation is 200 as well. But in this simulation, regarding the increasing number of N, the maximum number of sub-channel almost reached 180.

Table 5. The optimum number of sub-channels (m*) needed with two different (k) values and three (N) values obtained from Figure 16.

Number of sub-carriers (k)	Number of nodes (N)	Optimum number of sub-channel(m*)
200	100	50
200	200	90
200	300	120
600	100	90
600	200	150
600	300	180

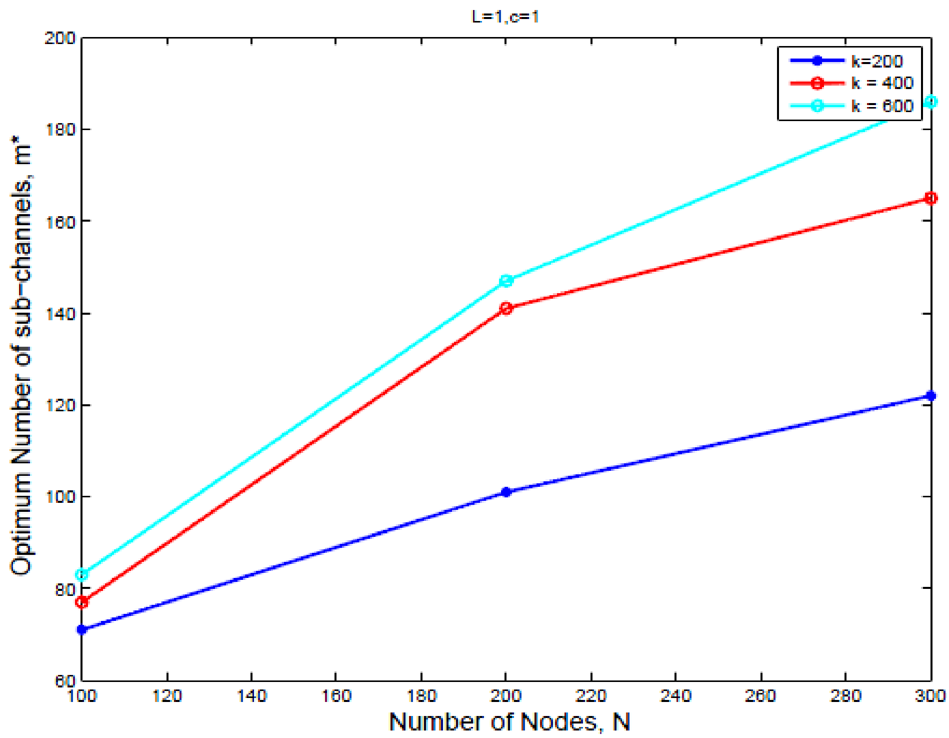


Figure 16. Finding the optimum number of sub-channels (m*) when the N range is [100:100:300], with different k values.

Both figures, Figure 15 and Figure 16 have the same trend. They are both showing that increasing N in the network demands increasing m.

3.2.2.2. L>1

In the previous section, the research was focusing on finding the optimum number of sub-channels (m*) for different number of nodes, N, and sub-carriers, k, and see how changing them affects the output of the network and its efficiency. However in all the cases in the previous section, the nodes had the chance to win only one sub-channel

(L=1). The investigation continues to check the results if the node has the chance to win more than one sub-channel (L>1) and how it impacts the efficiency of the network.

As for model two, the channel is divided into *m* sub-carriers in the reservation phase and *m* sub-channels on the transmission phase. When (L=1) the node wins one sub-carrier from the reservation phase, which means the node wins only the equivalent sub-channel in the transmission phase. Though, the new network model showed more efficiency than 802.11 that allow one node to transmit its data at a time, there is a possibility to make the new model more efficient and with higher output. In the case the network was not so busy, meaning that not a lot of users are using the channel, that would result in leaving some sub-channels idle and that would make the network inefficient because is considered wasting time and resources. For making the network more efficient, which is the goal of this study, the research carries on by giving a chance for the node to win more than one sub-channel (L>1) and that would allow each node to transmit its data through these sub-channels. As a result that would in increasing the speed of the network, making it more efficient and get higher throughput. Also, if the node failed to win a sub-channel, it may get a chance to win another. Thus, the research continues to examine this assumption.

By allowing each node to win L sub-channels, the simulation result shows increasing in the throughput of the network while increasing m, see Figure 17, and this would prove our assumption.

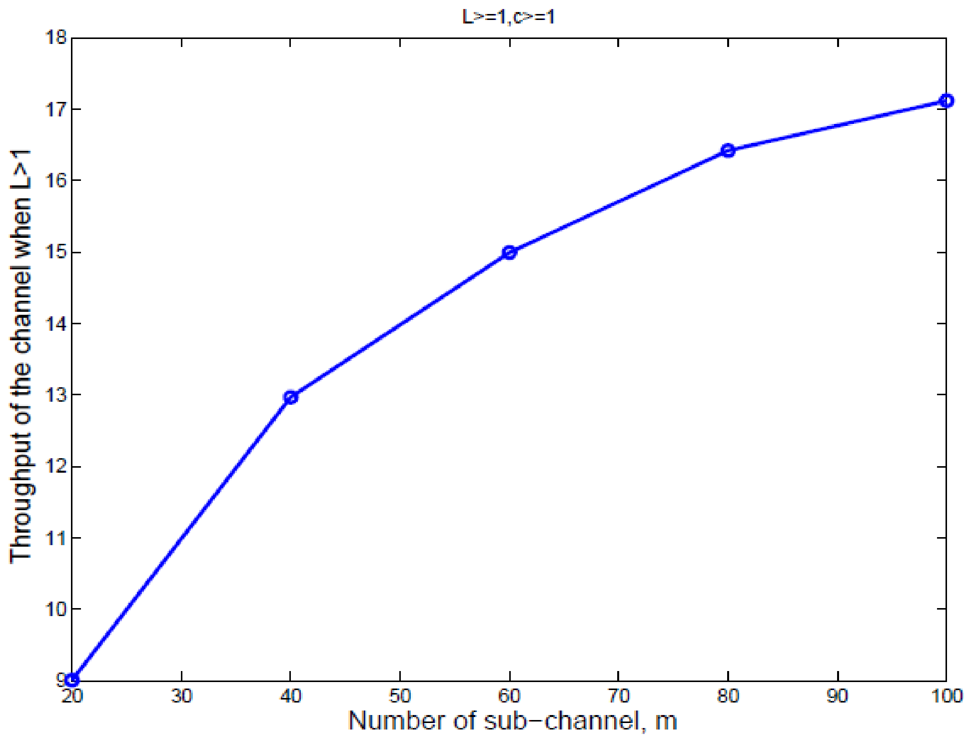


Figure 17. Throughput of a network when the nodes have the chance to win more than one sub-channel. Increasing the throughput while increasing number of sub-channels (m) when (L>1) indicates the idea the assumption was correct.

CHAPTER IV

MULTIPLE_CHANNEL MULTIPLE_AP MULTI_HOP NETWORK

Multi-hop wireless networks can provide a large coverage area, by transmitting data packets from one source node to a destination node going through a number of nodes and hopping/carrying the data packets along the way to the destination. Figure 18 shows an example of how the data hops from one node to another until it reaches its destination. Recently many researches have been performed on multi-hop networks. This is because of two reasons: a) *scalability:* where one node relies on other nodes to send data from one source node to another destination node [18]; and b) *usability*: where multi-hop is being used for different application, e.g. small wireless sensor network devices equipped with a radio transmitter and a battery are deployed in a geographic area for monitoring or measuring some desired properties like temperature, pressure, and others [18]. Researchers also analyze the performance of the network while data hopping from one node to another [19], as well as energy-efficiency, routing algorithms that find the shortest path to reach the destination node, load-balancing, and simulations of multi-hop network. Also adding multiple hops in a network shows improvement in the wireless network system capacity[1] [32]. As recent technologies and earlier investigation had proven that multi-channel networks increase the speed of information delivery and network throughput, we use a multi-hop network on a multi-channel, aiming to increase the speed of the network and also to add more scalability and usability to the wireless network.

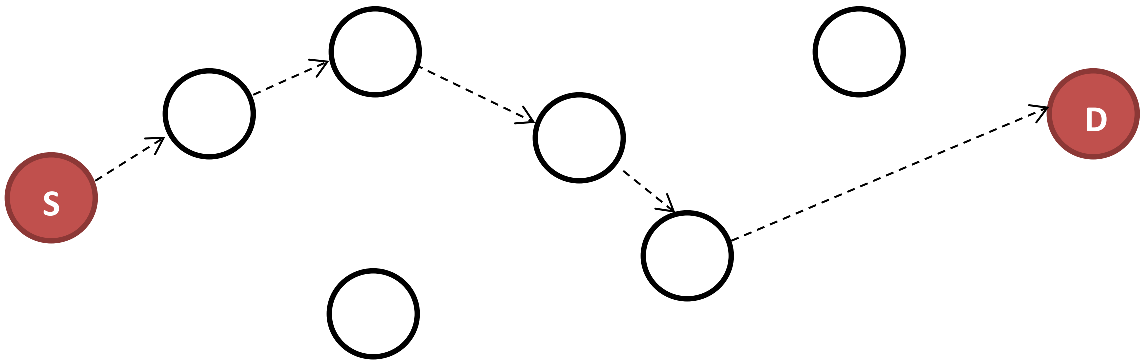


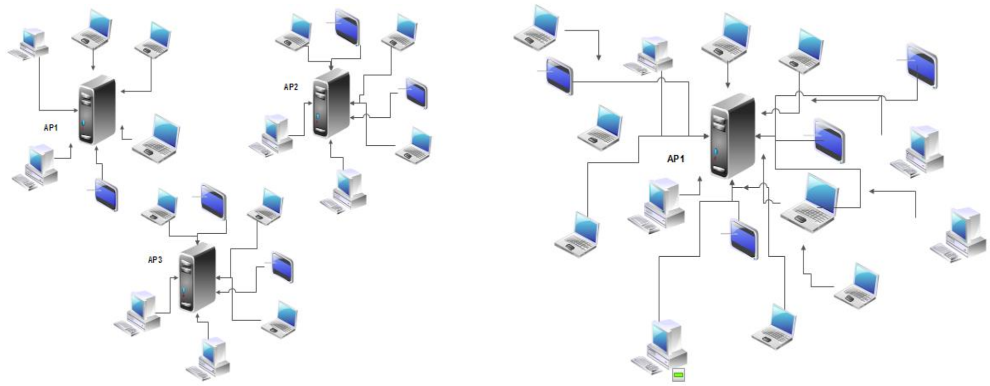
Figure 18. Multi-hop wireless network. The source node (S) goes through multi-hops until it reaches the destination node (D).

More specifically, in this research, we are interested in optimizing the frequency domain in a network channel by having *m* sub-channels that serve multiple APs for bigger network setup, aiming for better throughput and higher efficiency. We first illustrate the setup of multiple APs.

Due to the increasing number of users in wireless LAN, dividing the channel into a number of sub-channels is not quite sufficient in this case. For instance, multiple users in a conference room, hotel, airport etc. are sharing the sub-channels for one AP, but due to

[1] Capacity is: "defined as the cumulative number of bits received by all destination nodes from all traffic flows." [33].

the increasing number of those users, dividing the channel alone is not enough to improve throughput, because having all the nodes contending on one AP will overload the AP and that would decrease the throughput of the channel, since the AP can serve limited number of users. Consequently, the network is provided with more than one AP to reduce the overhead that users cause. One other way to help to increase the throughput is to increase the number of APs [17]. Adding multiple APs would allow a sub-group of users to focus on one AP, while other sub-groups contend on other APs. Instead of forcing all users in the network to contend on one AP, users have the chance to choose different APs distributed over the network and that would normally reduce contention level, reduce the overhead and collisions, and provide more efficient and reliable network. Figure 19 illustrates the two WLAN settings; network (A) consists of three APs that nodes are divided among, while in network (B) all the nodes are contending on one AP. It is easily seen how much overhead AP in network (B) would experience comparing to each AP in network (A). For that reason, having multi-hop multiple AP network with multi-channels would help increasing the efficiency of the network. Therefore, we continue our investigation by focusing on multi-channel with multi-hop and multi-AP network and what is the best arrangement for such a network.



Network (A): Consist of three APs and each number of nodes contends on one AP.

Network (B): Consist of one AP and all the nodes contend on the same AP.

Figure 19. Illustration of two different network settings, network (A) with three APs and network (B) with one AP.

Here we assume that the channel is divided into *m* sub-channels and the entire channel has k sub-carriers altogether that are divided among these sub-channels. Similar to the previous section of multiple channels, the channel was divided into two bands: contention band and transmission band. We further assume that the number of sub-channels equals the number of sub-carriers in the contention band. Yet, the case for multiple AP is that all the APs in the network will share the same channel, meaning that they will share the same contention band and reservation band. The multiple APs complicate the situation as the APs need to know the exact target, among all APs, of each contending node. Therefore, it is important to add an ID to each AP to distinguish among these APs. The questions here now are: How does the system work after adding these IDs to the AP? Where should the ID be set?

In FICA, each AP is assumed to have an ID although it did not specify how the ID can be set. FICA has reserved 40 bits to distinguish the IDs, and each bit is set for one AP, so when a certain bit is set from the 40 bit, a corresponding sub-carrier will carry this one bit to the node. The design uses RTS/CTS for that matter. Station (node) sends RTS to the receiver AP and other node might send RTS to a different receiver at the same time. Before transmitting RTS, a node will hash one bit receiver's ID from the 40 reserved bits. The node will check the corresponding sub-carrier if its ID has been set. If it is true, the receiver will send CTS back. However this mechanism is not quite accurate and "non-trivial" as FICA paper said, since multiple nodes may transmit M_RTSs simultaneously to different receivers and the receivers' information may be mixed. The next step is to find a best arrangement and algorithm for setting AP's ID and how the nodes can specify them.

Assuming the network has three APs (AP1, AP2, AP3) with a three sub-channel network, stations will contend to win a sub-channel and start communicating with the destination through one of the APs. While this scenario seems quite easy and feasible, it is unfortunately impractical. In real networks, there is no fixed number of APs; also it is hard to know how many nodes are active. Real networks are dynamic, meaning that there are an unpredictable number of APs and users. Therefore we need to set a dynamic design that satisfies the dynamic needs for users, using AP's ID to make a distinction between the APs. Therefore, we design the following scheme:

Figure 20 shows the channel layout in a wireless network, and it is the same as the second model, although this time, the design will hash AP ID to the winner node so that it can distinguish different APs.

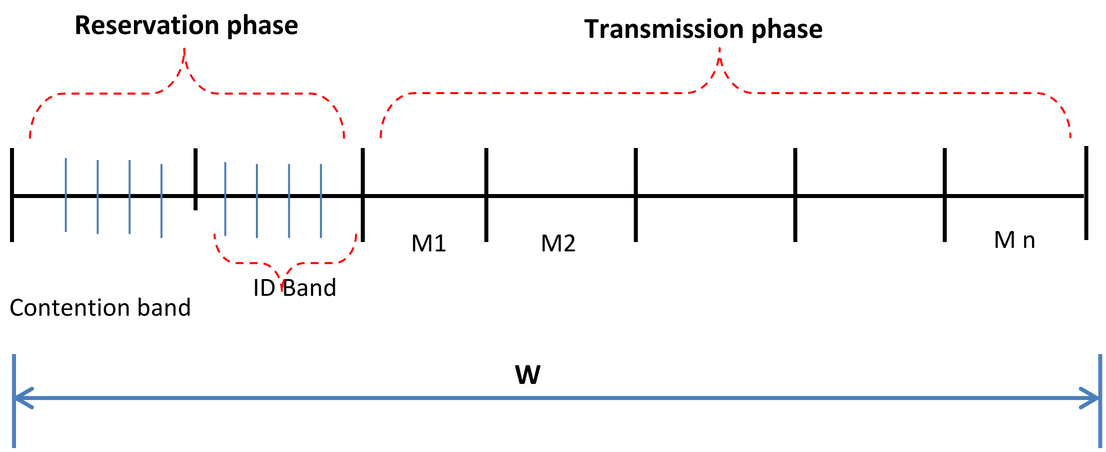


Figure 20. Multi-channel multi-AP layout. Contention band has an ID band used to hash AP ID to the winner node.

This new setup assumes that the number of sub-channels *m* and sub-carriers *k* are fixed and equal to each other, while the numbers of APs are dynamic. Each AP has a unique ID. ID band is part of the contention band and is used to hash the ID of the available and free APs; also it set 40 bit for now (as FICA did).

The multi-AP multi-hop scenario is presented in Figure 21 and it can be described as following:

1- Each sub-channel is assigned to a corresponding sub-carrier. When sub-channel is available, its corresponding sub-carrier would be free waiting for a winner node.

2- Nodes contend to win one sub-carrier or more from the contention band, meaning that each node selects L sub-carriers ($L \leq m$).

3- Winner node waits for a response from one of the APs. Nodes win ($j \leq m$) sub-carriers.

4- Available APs check ID-band and hash its ID, indicating its willingness to serve an active user.

5- If the node finds the desired AP, the AP hashes its ID to the requested node and the sub-channel will be reserved for that node (each AP has different unique ID).

6- A message (flag bit) will be sent to the winner node indicating it winning a sub-channel or more and can start communicating.

7- APs check the ID-band after random time span, hoping to find more idle sub-channels. If it finds one or more, it will use it for its communication and that would increase the speed of the channel.

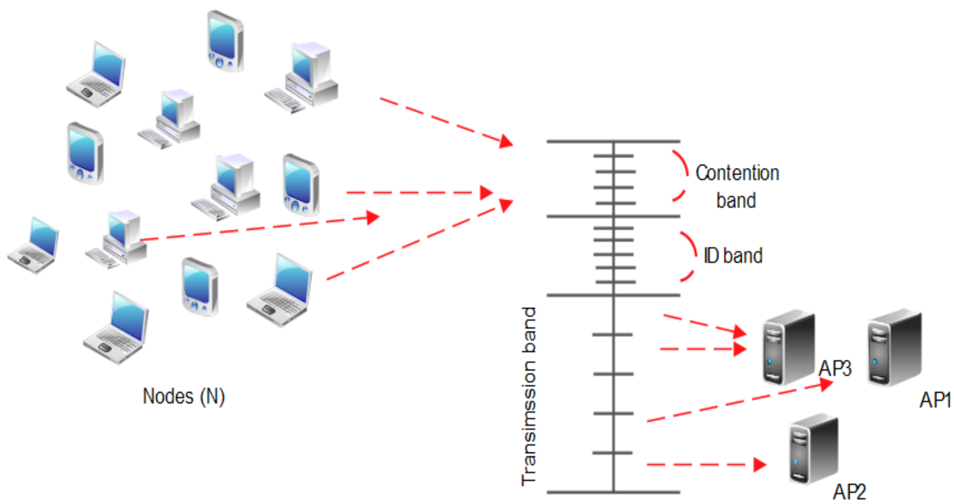


Figure 21. Multi-AP multi-hop set up and scenario.

Allowing the nodes to win more than one sub-channel, likewise allowing the APs to win more than one sub-channel, gives the model more flexibility to serve more users. Also, adding AP ID helps solving the problem of distinguishing different contending nodes, and giving the AP responsibility of checking for idle sub-channels and then hashing its ID. As a result, that would reduce the contention overhead, increasing the speed of the channel and the reliability of the communication. The assumptions for the model include the following:

1- Nodes should be able to check for channel status: if it is overloading or not by checking the contention band.
2- The contention band will show the sub-channel status. Thus if the node detects that one of sub-carriers is idle, then it would reserve the sub-carrier

that is corresponding to its sub-channel. Then the node checks for the desired AP if it is available by hashing its ID in the ID band and sends it to the node. Consequently the nodes start its communication through the reserved AP.

3- Nodes contend for L sub-carriers on the contention band. But to make the model more dynamic, the model checks the status of the channel by checking the collision rate, as following:

Higher rate of collision ⟶ Channel is busy ⟶ Decrease L (L--)

Lower rate of collision ⟶ Channel is not busy ⟶ Increase L (L++)

4- The design adds a timer that allows the node to check the channel from time to time for checking collision rates. For example, if the node checked the first time and found higher rate of collision, it either waits or decreases L value. Using the timer, node will check again after certain amount of time. If the collision rate decreased, it will check the contention band and would increase L value for contention purposes.

5- In the case of non-overloaded channel, if the node finds more than one sub-channel idle, it is allowed to use them, and that would assure no waste of idle sub-channels and time.

By adding the timer, the design became more flexible to ensure a better, faster and dynamic network. This dynamic design helps the network to embrace more APs and more nodes assuring more efficient WLAN.

Simulating the scenario to find the throughput of the channel when number of sub-carriers in the contention band (k) equals the number of sub-channels in the transmission band, m, showed a higher amount of collision in the contention band. Therefore, we increased number of (k) in the contention band to the double (k = 2m), and it showed increasing throughput while increasing number of APs, as Figure 22 illustrates. In this simulation, the result tested the throughput of the channel for multiple APs, and 40 bits AP's IDs in the ID band were used as FICA suggested.

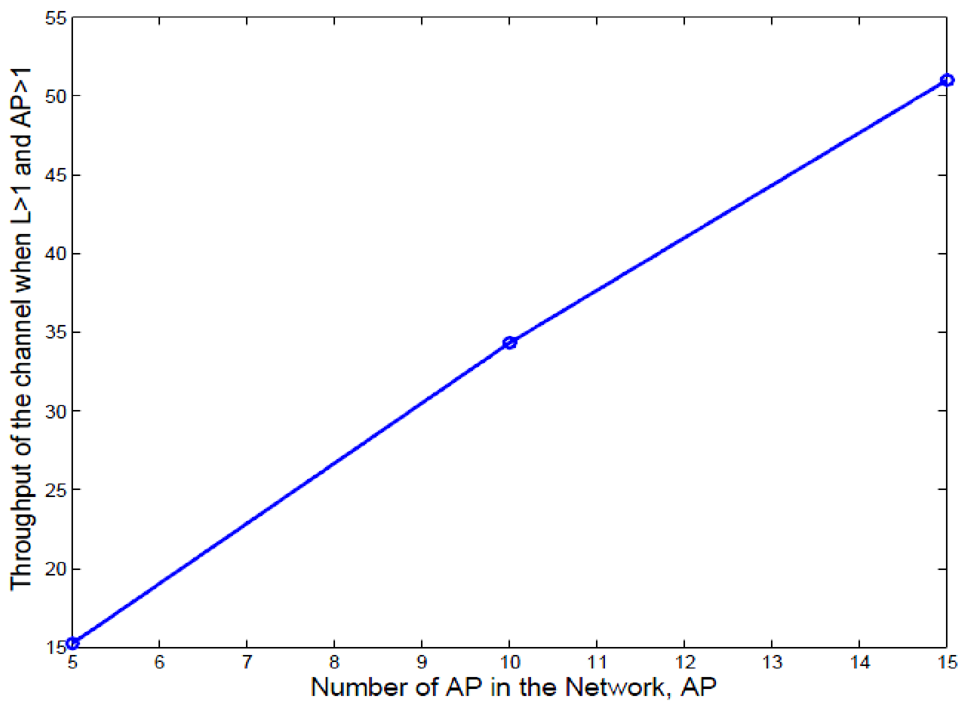


Figure 22. Throughput of the channel for multiple APs, when number of sub-carriers of the contention band is doubled (k = 2m).

However, we want to investigate the ID value. The question being: is 40 bit is the idle number? Or is it possible to reduce ID range to less than 40 bits and save this amount of bandwidth for data transmission?

Figure 23 shows that increasing the ID band range do not necessarily increase the throughput of the channel. The channel needs certain number of bits for hashing the AP's ID. However, the result shows that the throughput of the channel is quite good with ID range of 20 bits and even 30 bits and they are not big difference comparing to the ID range of 40 bits. From this we conclude; we can use less than 40 bits to assign to the AP ID and still get good throughput.

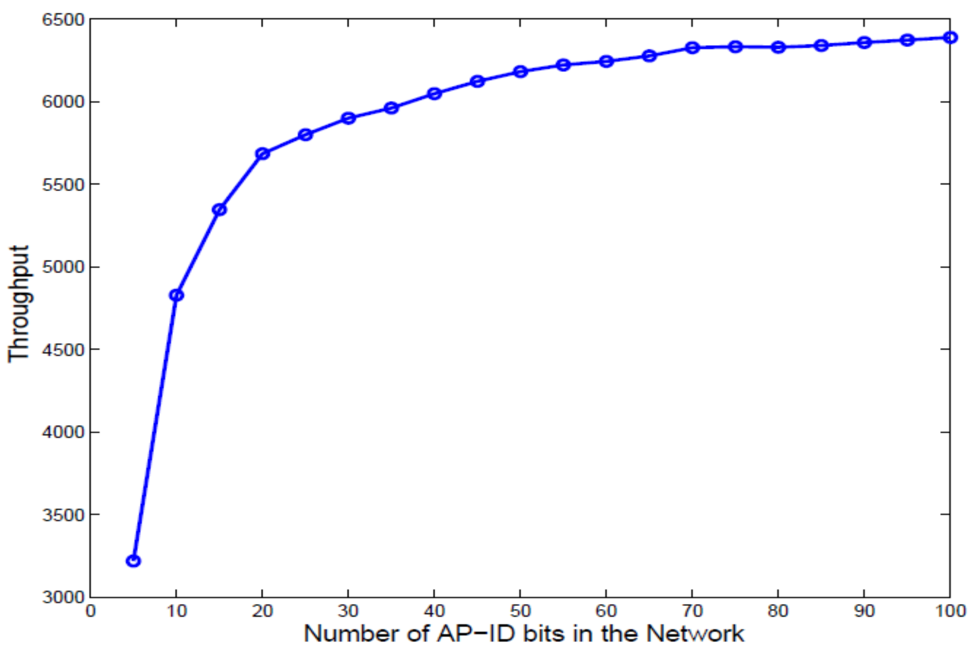


Figure 23. Throughput of the channel for multi-AP in the ID range [0:10:100] and (k=2m). Throughput increases till it reaches certain point, and then the throughput almost settles.

Also to check the effect of the size of sub-carriers in the contention band on the throughput for the same range of AP ID [0:10:100] bit, we simulate the code again by increasing (k=4m). Figure 24 presented a higher throughput for multi-AP for different ID range sizes [0:10:100]. The difference between the 20 bit ID and the 40bit ID is quite larger in the case of (k=4m) than when (k=2m).

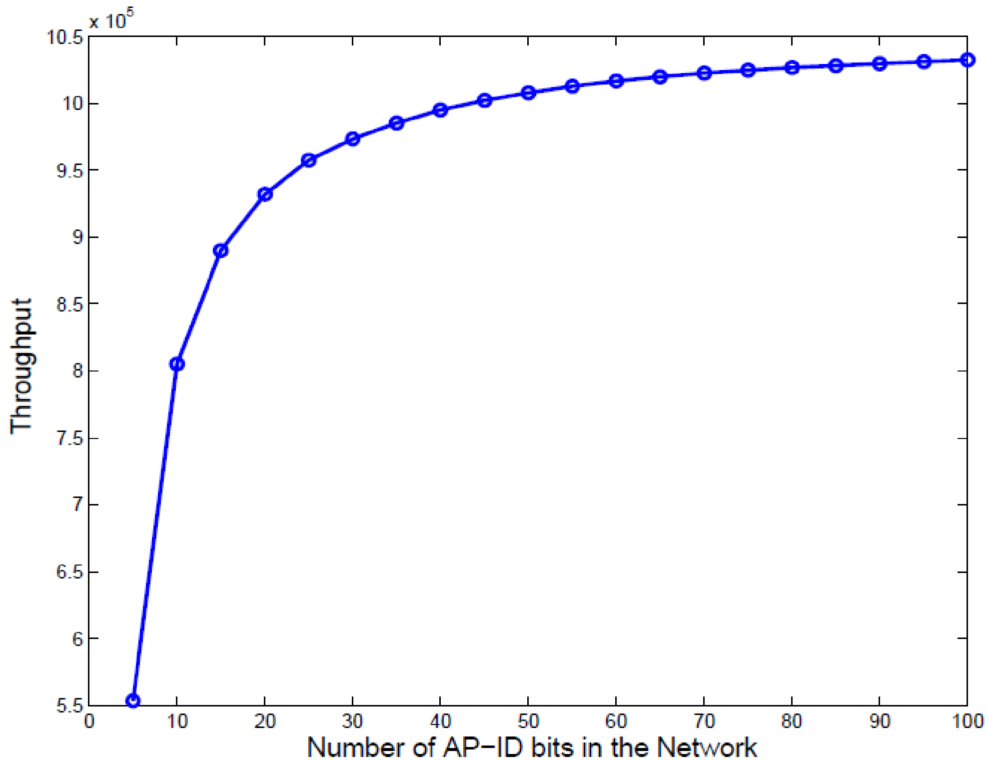


Figure 24. Throughput of the channel for multi-AP with range of ID size [0:10:100] bit for (k=4m). Throughput increases till it reaches certain point, and then the throughput almost settles.

Table 6 shows comparison between the two channel arrangements for investigating number of sub-carriers effects on the throughput. From the table we can easily notice the big difference in the throughput between the two arrangements. For example, (k=2m) when ID =20bit is (5700) and it equals (9.5*105) when (k=4m), and the difference is noticeable. The same thing applies for the rest of the AP ID sizes. However the difference of the throughput among the arrangement itself is not that big for different ID size. Table 6 is comparing Figure 23 and Figure 24.

Table 6. Comparison between the two channel arrangements regarding number of sub-carrier in the contention band

Channel arrangement	Throughput when AP ID = 20bit	Throughput when AP ID = 30bit	Throughput when AP ID = 40bit
k = 2m	5700	5800	6000
k = 4m	$9.4 * 10^5$	$9.7 * 10^5$	$10 * 10^5$

From above we can conclude the following:

1- Number of sub-carriers (k) in the contention band has a big effect on the throughput of the channel.

2- The size of AP's ID (40 bit) can be reduced to 30 or even 20 bit and still get a high throughput and use this bandwidth for actual data transmission.

CHAPTER V

CONCLUSION

The research investigated many points all trying to find the best design for a wireless channel in order to have higher throughput and solve problems in the current design. The results of the new design are based on the FICA design. This research relied on using OFDM technique that would allow dividing the channel into a number of sub-channels and also dividing each sub-channel into a number of sub-carriers without interfering with each other. Based on that, the research shows it is possible to divide the channel into number of sub-carriers and it showed increasing in the throughput of the channel. The first model, having multi-channel-single AP, is dividing the channel into a number of sub-channels and each sub-channel is divided into number of sub-carriers, while allows the nodes to contend on the whole channel trying to win a sub-carrier, which shows decreasing in the throughput which brings the second model. In the second model, the channel is divided into two bands: contention band where the nodes contend to win a chance to transmit its data through the second band, the transmission band. However, the research tested the behavior of the channel when the nodes have the chance to win only one sub-carrier (win one sub-channel). Also the throughput when the nodes have the chance to win more than one sub-carrier (win more than one sub-channel).

Both showed increasing number of throughput, indicating the channel design was correct. Moreover, the research continues to investigate the idea behind having multi-channel multi-AP. Since we have multi-AP, it is necessary to use ID to distinguish between the groups of AP in the network. However, the contention band should be at least doubled in order to provide good throughput.

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APPENDIX A

CALCULATING ETA (EFFICIENCY)

```
 % Sending a flag between N nodes and detecting collision
 clear; close all;

N = 350;          % number of nodes
SuccessfulT =0;   % Number of successful reserved subcarrier
Noofcollision=0;  %Number of Collision

   % Simulate the whole process for k times
          N_ind =1;
          N_array =[100:100:1000];
   for N= N_array;

          for sub_channel =1:50

        for nsc = 50:50:500

  SuccessfulT =0;   % Number of successful reserved subcarrier
  Noofcollision=0;  %Number of Collision
  Max_eff = 0;      % Maximum number of efficency for each number of nodes N
  successful_Trans =0;

                    total_runs = 5000;
          for k=1: total_runs;
```

APPENDIX B

OPTIMUM NUMBER OF SUB-CHANNEL

```
   % Choose a subcarrier randomly
selection = ceil(nsc*rand (1,N));
%disp (selection);
%if (N< 16)
 %   nsc= N;
%end

  % To check if there is a collision by comparing the sc_selection results
  % The total rounds = nsc* k
 for sc= 1:nsc

     result= sum (sc == selection);
     if (result>1)
         Noofcollision= Noofcollision+1;

     elseif ( result == 1)
        SuccessfulT= SuccessfulT+1;
     end
end
          end  % for k
  end % for nsc

eta = (SuccessfulT)/ sub_channel /total_runs;  % 100 is the number of runs (k)
 dlmwrite ('sub_ch.txt', [N,sub_channel,nsc,k,eta, SuccessfulT],'delimiter','\t','precision',6,'-
append' );

      end % for sub-channel

    M(N_ind)= eta;     % M(nsc/50) create an array to store the efficiency
    N_ind =N_ind+1;

        end % for N

plot(N_array,M,'o-r', 'LineWidth',2);
xlabel ('Number of Nodes (N)', 'FontSize', 14)
ylabel ('Optimum number of sub_channel (m)', 'FontSize', 14)
```

```
print -depsc2 a.eps
!ps2pdf a.eps a.pdf
```

APPENDIX C

THROUGHPUT OF THE CHANNEL

```
% Throughput of the channel
close all; clear
style= char ('-*', 'o-r','o-c', 's-.r','v-m');
N_ind=1;
N = 50; % Number of Nodes
kk=100; %number of subcarriers in contention band
kk_array=[100:200:500]; %number of subcarriers in reservation phase
   for kk= kk_array;
        mm_array = [5:5:100];
        for mm = mm_array
          % contintion band and it's k equal to the number of sub-channels in the channel
           total_success=0;
           total_run=10000;

                    for run=1:total_run
             %L=1, it's just simple subcarrier selection
              subcarrier_selection = floor(mm*rand(1, N))+1;
                 %we look for any node choosing the subcarrier for subchannel 1
                 if  sum(subcarrier_selection==1)==1
                               %success if only one node claims that sc
                       total_success=total_success+1;
                end % if sum
       end % for run
  S(mm/5)=  total_success/total_run * (1 - mm/kk);
% dlmwrite ('new6.txt', [S], 'delimiter', '\t', 'precision',6,'-append');
  end % for mm

plot (mm_array, S,style(N_ind, :), 'LineWidth',2);
 N_ind= N_ind+1;
 hold on;
 end % kk

xlabel (' Number of sub-channel, m','FontSize',14);
ylabel (' Throughput of the sub-channel','FontSize',14);
title ( 'L=1,c=1')
legend ('k=100','k = 300', 'k = 500')
```

```
print -depsc2 a.eps
!ps2pdf a.eps a.pdf
```

APPENDIX D

THROUGHPUT OF THE CHANNEL WHEN L>1 AND AP>1

```
 %Multi-channel - Multiple AP. Calculating the best AP ID number of bits
clear; close all;
% Number of sub-carrier in the contention band equals= mm *2
N = 20;        % number of nodes
style=char('o-', 'v-r', '*--k', 's-.r','o-y','v-m','*--g','s-.b','o-c','v-r');
N_ind= 1;
AP_N= 15;      % number of AP in the network
AP_ID = 40; Av =0;   T_AP_success=0;
mm = 20;    L =mm;
for round= 1:20

AP_ID_array= [5:5:100];
for AP_ID = AP_ID_array
%Selecting and Hashing AP ID randomely

for AP= 1: AP_N
                AP_selection = randperm (AP_N, 1);
                AP_S{1}= [ 'A' num2str(AP_selection)];
                          AP_ID_selection = randperm (AP_ID,1 );
                 HashAP = containers.Map ( AP_S{1} , AP_ID_selection);
                          A(AP) = AP_ID_selection;
end % for AP
        A;
        values_AP= unique(A);
     result_AP = histc (A(:), values_AP);
     v_AP= (result_AP ==1);
     S_AP_selection = sum (v_AP);


%% Node contention
     AP_sel=0;     S=0;
     total_runs = 2000;              AP_success=0;
     for run = 1: total_runs

     % Node Contending on the contention band
      subcarrier_selection = floor(mm*2 *rand(L,N))+1;

      % find the nodes that win successful reservation
```

```
        values= unique(subcarrier_selection);
        result = histc (subcarrier_selection(:), values);
             v= (result ==1);
             S_selection = sum (v);

              % Hashing AP ID to the winner nodes
         for i=1:S_selection
                        N_selection =  result (randi(numel(result)));
                                    HashAP_N = containers.Map ( values_AP(randi(numel(values_AP))) ,
N_selection);
                                     AP_success= AP_success+1;
         end % for i
T_AP_success=T_AP_success + AP_success;
S = T_AP_success/run;

end % for run
M (AP_ID/5) = S;
SUM_M = sum (M);

end % for AP_ID
Av(round) =  SUM_M/round;

end % roumd

plot (AP_ID_array, Av ,style(N_ind, :), 'LineWidth',2)
N_ind= N_ind+1;
hold on;

xlabel (' Number of AP_ID bits in the Network','FontSize',14);
ylabel (' Throughput of the channel when L>1 and AP>1','FontSize',14);
title ( '1<=L<=AP , c>=1, AP=10')
print -depsc2 a.eps
!ps2pdf a.eps a.pdf
```