A Framework For Coping With Intra-Node Adjacent Channel Interference In Multi- Channel Multi-Radio Mesh Networks

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A Framework For Coping With Intra-Node Adjacent Channel Interference In Multi- Channel Multi-Radio Mesh Networks

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ABSTRACT

Typically, in a wireless data network, all devices use the same channel (i.e. the same frequency) so that they can easily communicate with each other. For example, in a home wireless network, the access point connected to the Internet communicates with all wireless enabled computers using the same frequency. This approach allows devices to discover each other easily and ensures maximum connectivity. However, as node density increases, the throughput share of each device decreases due to contention of the wireless medium. It seems that the capacity problem in wireless mesh networks can be alleviated by equipping the nodes with multiple radios tuned to non-overlapping channels. The usage of multiple radios and channels can be a double-edged sword. Whereas on one hand, it reduces contention and interference between the different transmitters, it can possibly break the connectivity.

In theory it should be possible to have simultaneous reliable transmissions on orthogonal non-overlapping channels. In practice though, due to signal leakage from one channel to another, transmissions on these non overlapping channels interfere with each other. The majority of research simply neglect any inter-channel effects.

In this work, we claim that the assumption of perfect independence between non-overlapping operating channels does not always hold in general. If two transceivers are in close proximity to each other, as is the default setup for multi-radio systems, the assumption that multiple independent transmissions over non-overlapping channels can coexist without mutual interference does not work anymore. One of the contributions of this work is to demonstrate the presence of interference effects between "non-overlapping" channels by means of specific experiments with multi-radio nodes.

This dissertation explores whether it is possible to exploit the existence of multiple channels and the ability of radios to work simultaneously to increase network throughput with existence of adjacent channel interference (ACI). During this thesis some practical measurements have been done about adjacent channel interference, taking into consideration various factors such as antenna separation, number of channels and radios, transmit-power and packet size. The interference effects in different channels have been compared. Furthermore, the causes and effects of adjacent channel interference have been evaluated and studied via analysis, experiments and simulation. As a result, our experiments suggest that current off-the-shelf IEEE802.11 chipsets without any special mechanism might not be ready to be integrated in a single box with few centimeters of antenna separation. Appropriate solutions to achieve robust multi-radio wireless systems are needed.

As the IEEE 802.11 MAC protocol is designed for a single channel and does not work well in a multi-channel environment. Therefore the focus of our research is to mitigate the negative effects of ACI in multi-channel multi-radio wireless networks. So the possible solutions which are feasible have been classified, and by adopting the concept of reservation, a solution called MRR (Multi-Radio Reservation) is proposed. Finally the proposed solution has been evaluated to consider the amount of improvement which can be achieved. MRR is compared with single radio single channel case and while this solution has the potential of mitigating the negative effects of ACI and it improves the performance by applying multi channel in the network, challenges are still present to investigate for further improvements.

بسم الله الرحمن الرحيم

To HIM

Mother, Father

&

Behzad

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Finally I thank dear GOD, with whom all things are possible.

TI-WMC COMPANY

Twente Institute for Mobile and Wireless Communications (TI-WMC) is an innovative company with room for open-minded people. WMC provides an environment of cooperation, commitment, confidence, and involvement in the field of wireless and mobile communications. They are doing a lot of research and new challenges in wireless and mobile communications. As part of their team you connect the frontiers of technology with today's communications needs.

Being as **the House of Ad-hoc Radio Networks** they ensure rapid and robust radio communications.

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LIST OF ACRONYMS

ACI	Adjacent Channel Interference
ACK	Acknowledgment
AP	Access Point
BS	Base Station
BSS	Basic Service Set
CCA	Clear Channel Assessment
CF	Coordination Functions
CFTR	Confirm To Reserve
CHMA	Channel Hoping Multiple Access
CS	Carrier Sense
CHAT	Channel Hopping multiple Access with packet Trains
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
DCA	Dynamic Channel Allocation
DCA-PC	Dynamic Channel Allocation with Power Control
DCF	Distributed Coordination Function
DIFS	Distributed Inter Frame Space
DPC	Dynamic Private Channel
DS	Distribution System
ED	Energy Detection
EIRP	Equivalent Isotropically Radiated Power
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
HRMA	Hop-Reservation Multiple Access
IBSS	Independent Basic Service Set
LBT	Listen Before Talk
MAC	Medium Access Control
MAP	Multi-channel Access Protocol
MSDU	MAC Service Data Unit
MRR	Multi-Radio Reservation
McMAC	Multi-channel MAC
NAV	Network Allocation Vector
NIC	Network Interface Card
OFDM	Orthogonal Frequency Division Multiplexing

PIFS	Priority Inter Frame Space
PLL	Phase Locked Loop
PMD	Physical Medium Dependent
PLCP	Physical Layer Convergence Protocol
P-CS	Physical Carrier Sense
RTS	Request to Send
RSSI	Receive Signal Strength Indicator
RTT	Round Trip Time
RQTR	Request To Reserve
RPTR	Reply To Reserve
RSS	Radio State Schedule
RTT	Round Trip Time
SIFS	Short Inter Frame Space
SSCH	Slotted Seeded Channel Hopping
TCP	Transmission Control Protocol
VCO	Voltage Control Oscillator
V-CS	Virtual Carrier Sense
WMN	Wireless Mesh Network
WM	Wireless Medium

CHAPTER 1

INTRODUCTION

1.1 Overview

Wireless Mesh Networks (WMNs) are emerging as a wireless broadband solution for metropolitan areas, campus environments and last mile access. WMNs promise to achieve cost-effectiveness by means of dynamic self-organization, self-configuration and self-healing. While standardization efforts are devoted to define new standards (e.g. IEEE 802.11n, 802.11s) for WMNs, most of the research so far has focused on the optimization of existing standards (IEEE 802.11a/b/g) to achieve higher throughput, better security, easy maintenance, high scalability and reliable services. In this context the research community has explored the potential of multi-channel communication within existing IEEE 802.11 standards. Building upon the concept of “non-overlapping channels”, it has become a general practice in the wireless networking community to assume that any pair of channels with at least 20MHz spacing can be used simultaneously without mutual interference. This assumption is at the basis of several researches published in top level conferences.

Due to their self-configuring and self-healing capabilities, as well as their low equipment and deployment cost, Wireless Mesh Networks based on commodity hardware present a promising technology for a wide range of applications. Currently, one of the key challenges that WMN technology faces is the limited capacity and scalability due to high levels of interference, which is typical for multi-hop wireless networks. A simple and relatively low-cost approach to address this problem that has recently been proposed is the use of multiple wireless network interfaces (radios) per node. It seems that operating the radios of each node on different, non-overlapping channels allows making more efficient use of the radio spectrum and thereby reducing interference and contention.

Decreasing the cost of wireless hardware devices today presents an opportunity to equip wireless nodes with multiple wireless radio interfaces. The presence of orthogonal channels in the spectrum defined by the wireless technology standards (such as IEEE 802.11) enables the simultaneous usage of multiple interfaces at a node. In theory it should be possible to have simultaneous reliable transmissions on these channels. In practice though, due to signal leakage from one channel to another, transmissions on these non overlapping channels may interfere with one another. The majority of works in this area simply neglect any intra-node effects. We claim that the assumption of perfect independence between non-overlapping operating channels does not hold in general. If interfaces are in close proximity to each other, as it is the default setup for multi-radio devices, there is a detrimental interference effects between “non-overlapping” channels.

This dissertation explores whether it is possible to exploit the existence of multiple interfaces and the ability of radios to work simultaneously to increase network throughput with existence of adjacent channel interference (ACI). Furthermore we are going to evaluate and study the causes and effects of adjacent channel interference via measurements, analysis, calculations and simulation in order to investigate the possible solutions to cope with adjacent channel interference issue.

1.2 Motivation

1.2.1 Motivating Scenario

Wireless communication is a very valuable tool in disaster relief scenarios. After a disaster strikes, existing wired infrastructure and even cellular phone networks are often destroyed due to power generator failures and cable cuts. To effectively coordinate different agencies in a disaster relief scenario, it is very important to quickly restore communications to the affected area such that damages can be assessed and resources can be directed to people needing the most help.

In these situations, multi-channel multi-radio wireless mesh networks are a promising technology. In contrast to wired networks, it can self-organize the wireless relay nodes within the network to find quickly a path from any source to any destination without human supervision. Moreover due to multi-radio concept they can reach to higher capacity and using different channels allow the network to coexist with less interference.

1.2.2 Inefficiencies of Single Channel MACs

Today, commodity wireless local area network equipments operate at speeds ranging from 11 Mbps to 54 Mbps per channel. In a multi-hop wireless network, the achievable throughput is much lower than the speed of the radio because the indicated speed does not take into account the medium sharing effects of a multi-hop wireless network. First, nodes cannot transmit and receive at the same time. Second, when a node transmits, all of its neighbors cannot receive from another node. Fortunately, quite often, several channels are available. One can increase network throughput by allowing adjacent nodes to transmit on different channels simultaneously. Consider the disaster relief scenario mentioned earlier; to setup a temporary wireless network to carry information to an area that has been cut off from the Internet or phone network, a number of wireless relay devices are placed linearly along a road to form a chain network as shown in figure 1.1. Each node in the network has one radio tunable to one of the two available channels. The leftmost device has a direct high speed wired connection to the Internet. Consider the case in which the rightmost node of the network needs to download a large document via the Internet connection. For simplicity, we model it as a unidirectional flow of packets being forwarded from the leftmost node to the right. The goal is to maximize the throughput of the flow. We assume that due to interference, transmission and sensing ranges, for a node to receive a packet from its left neighbor correctly, it cannot be within 2 hops of another sender.

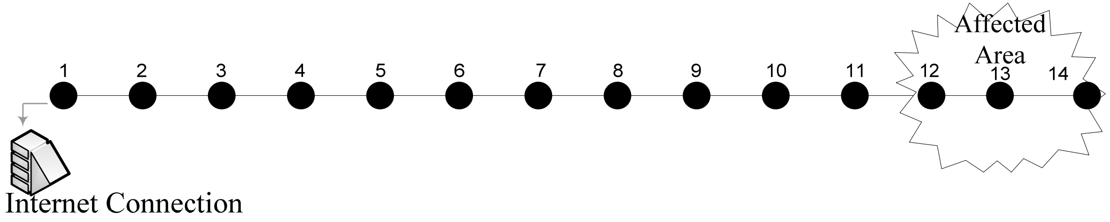


Figure 1.1: Using temporary relay routers in order to connect the disaster affected area to Internet.

For simplicity, assume that time is slotted, all the packets are of equal length, and the nodes are synchronized. In this situation, if only 1 channel can be used, nodes 1, 5, 9, 13 can transmit at the same time while the other nodes must remain quiet (figure 1.2). In the next time slot, nodes 2, 6, 10 can transmit. During each time slot, the fraction of nodes transmitting is 1⁄4, and hence the throughput should be approximately 1⁄4 of the link speed.

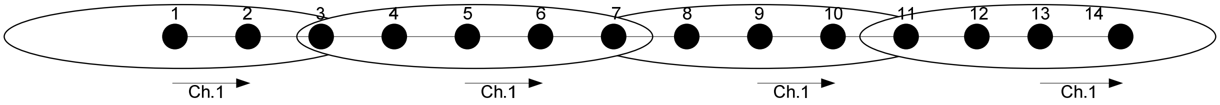


Figure 1.2: Discussed scenario while just 1 channel is available.

Consider the case where 2 channels are available per node, so with using various channels, nodes which are in interference range of each other can send and receive the data in different channels (as an example instead Ch.1 using Ch.1 and Ch.2); this example shows that there is a huge potential for network throughput to increase significantly when multi-channel multi-radio are available.

1.3 Problem Definition

A Medium Access Control (MAC) protocol is a set of rules that nodes follow when accessing the medium. The design of a MAC protocol balances the need for high throughput and low medium access delay with fairness among different nodes. Traditionally, all nodes that communicate with each other use the same channel. In general, wireless networks have been designed for single radio networks, but as the number of node increases, due to higher contention and collision, network performance will degrade quickly. One approach to relieving the problem is to utilize multiple radios per node working on different non-overlapping channels. The IEEE 802.11 standard allows for the use of multiple channels available at the physical layer, but its MAC protocol is designed only for a single channel. A single channel MAC protocol does not work well in a multi-channel environment.

In theory it should be possible to have simultaneous reliable transmissions on non-overlapping channels. In practice though, due to signal leakage from one channel to another, transmissions on these non overlapping channels interfere with one another. The interference level is affected by many factors such as the hardware used, distance between transmitters, antennas pattern, transmit power, etc. There is a detrimental interference effect between non-overlapping channels when interfaces are in close proximity to each other. The majority of works in this area simply neglect this effect. As we know, there has been much work in the simulation of multi-channel multi-radio networks but less work on the analysis of physical implementations.

But during this thesis, we have evaluated and studied the causes and effects of adjacent channel interference via measurements, analysis, calculation and simulation in order to investigate the possible solutions to cope with adjacent channel interference issue.

1.4 Organization of Dissertation

This thesis provides the following contributions towards a better understanding of ACI in 802.11-based multi-channel multi-radio wireless mesh networks.

It consists of three different parts. The first part provides the background knowledge which is useful in understanding the chapters to follow. The main concepts of IEEE 802.11 and wireless mesh networks are mentioned in Ch.2. The capacity issues of single and multi channel networks are discussed in Ch.3 We summarize the various related research in Ch.4 and classify known approaches of multi-channel protocols into 4 categories, discuss the pros and cons of each and evaluate shortcomings of any existing solutions. Part two is the analysis part which consists of three chapters. In Ch.5, we directly address the adjacent channel interference issue and consider the causes and effects of ACI. The analysis of different metrics, existed experiments in this field and link budget calculations have been done and mentioned in this chapter. We have done different scenarios of experimental measurements; the results and analysis of them are discussed in Ch.6 and we simulate various multi-interface multi-channel testbeds using a *Java* simulator in Ch.7. The conclusion of analysis part is discussed in Ch.8. Having understood the advantages of different approaches in this area, we investigate part3 which is the solution part. Different possible solutions and our main proposal to cope with adjacent channel interference problem are suggested and evaluated in Ch.9. Finally, Ch.10 summarizes achievements of our research and note open problems that have not been addressed so far. In addition, it will list some ideas and areas for future work.

1.5 Figo Nodes

During this thesis and mostly in our measurements we use Figo nodes as mesh nodes. Figo nodes are next technical product of the TI-WMC Company for multi-channel multi-radio communications which are still in progress. Figo nodes guarantee both local and global communication. They integrate a variety of radio communication techniques. This ensures that communication always continues. When Figo nodes meet, they automatically form among one another a robust network, enabling WiFi Connectivity to any device within its range. Nodes see each other and can communicate directly with one another.

The network of these nodes could be temporal for e.g. events. The network can select from multiple paths to reach other nodes. Figo's patented FLAME (Meshing algorithm) investigates each of the paths and chooses the most attractive one. Besides connecting the local network Figo provides access to the infrastructure through multiple paths. Figo nodes have multiple radio techniques, each providing access to the infrastructure via a different path. Also wired access to the infrastructure is among the possibilities. This enhances the redundancy even further, and creates continuity of services under very changing circumstances.

Figo nodes can make use of each other's access to the infrastructure. Each node is a gateway for the other nodes. Being in the shadow of a building no longer blocks communication.

PART I BACKGROUND

CHAPTER 2

IEEE 802.11 AND WIRELESS MESH NETWORKS

In this chapter we review the basics of wireless data networks with an emphasis on the IEEE 802.11 standard and multi-channel transmission protocols. We also briefly describe some variants of mesh networks proposed to meet some real-world application requirements.

2.1 Wireless Networks

Wireless networks consist of stations that are not connected with wires or fiber, but communicate through other media such as radio signals or infra-red light. These networks can generally be classified into two broad categories: infrastructure-based and *ad-hoc*.

A wireless network with infrastructure consists of fixed base-stations at specified locations that provide wireless connectivity to devices within their coverage area. Examples include cellular networks such as the Global System for Mobile Communication (GSM) and IEEE 802.11 WLAN. Infrastructure includes equipment needed for communicating with end-users, the backbone to interconnect base-stations, hardware to bridge with other networks, etc.

In contrast, *ad-hoc* networks are wireless networks without pre-established infrastructure. Such networks are instantaneously formed when nodes come within each other’s communication range. Ad-hoc networks can be very useful in situations where there is no infrastructure or where its creation would be too costly. Applications of these networks include providing connectivity in a disaster-relief situation, (e.g. for keeping contact between rescue-team members), for communication between soldiers in battlefields, for sharing traffic-related information along congested roads, etc.

Many different standards and technologies for wireless communication are available. For data-intensive traffic, specifications such as IEEE 802.11 and Bluetooth have been developed. While IEEE 802.11b/g and Bluetooth operate on the 2.4 GHz band, IEEE 802.11a uses the 5 GHz band. Today, the IEEE 802.11 standard is the most popular standard that draws support from major players in the wireless networking industry. We briefly describe some of IEEE 802.11 specification.

2.2 IEEE 802.11

In this section we provide an overview of essential topics in the IEEE 802.11 standard that are subsequently referred to in this thesis. A more detailed description is available in the actual IEEE 802.11 specification [1].

2.2.1 IEEE 802.11 Architecture

The IEEE 802.11 standard specifies three primary setups and two operational modes. A station is a component that connects to the wireless medium. The simplest setup is a Basic Service Set (BSS), which comprises of a number of stations that communicate with each other. When these stations are not connected to a wired network, they are referred to as an Independent Basic Service Set (IBSS). They operate in the *ad-hoc* mode such that each station is able to directly communicate with another within its reach.

In comparison, an Infrastructure Basic Service Set is a BSS, which has a base-station (BS). When a BSS works in the infrastructure mode, each station in the BSS goes through the BS for any communication with other stations. A BS is an access point (AP) if it is connected to a wired network.

When different BSS are connected via their BSs using a network backbone (also called distribution system (DS)), an extended service set (ESS) is formed. An ESS acts as one MAC-layer network. The specification does not mandate any particular technology for the DS.

In the infrastructure mode, a station needs to join a BSS to communicate. It obtains synchronization information from periodic beacons from the base station. It can either obtain this information by requesting it from the BS (active probing), or else it can wait for the periodic beacon from the BS. Before being able to send and receive data, the station has to go through an authentication and association process. The roaming function is not defined in the standard, but logical services have been described for this purpose.

The IEEE 802.11 standard not only defines a Medium Access Protocol (MAC), but also the related management protocols and services, and the physical layer. In this work, we will deal with the OFDM operating on the 5 GHz band. Standard organization has defined 11 non-overlapping Channels for IEEE 802.11a (ETSI).

Before introducing the medium-access mechanism, we describe some important timing intervals prescribed by the standard.

- *Short inter-frame space (SIFS)*: It is the shortest time interval. It is used between a frame and its acknowledgment.
- *Slot time (Slot)*: a little longer than SIFS, it is the basic time unit for the binary exponential back-off algorithm spelled out in the standard.
- *Priority inter-frame space (PIFS)*: it is equal to SIFS + one Slot. It is used by the Point Coordinator to get higher priority in accessing the medium.
- *Distributed inter-frame space (DIFS)*: It is used before starting a new transmission.

2.2.2 Distributed Coordination Function (DCF)

The IEEE 802.11 MAC protocol is a carrier-sense multiple-access scheme with collision avoidance (CSMA/CA). The standard refers to this scheme as the distributed coordination function (DCF). The goal of the MAC protocol is to allow multiple competing senders to share the radio medium without interfering with each other. The DCF protocol allows stations to access the medium in a distributed manner. There is no central entity mediating the use of the shared channel. Two access mechanisms are spelled out for DCF, the Basic Access and RTS/CTS mechanism.

2.2.3 Basic Access Mechanism

The Basic Access scheme is carrier sense multiple access with collision avoidance (CSMA/CA). When the MAC layer needs to transmit a frame, it physically senses the medium to check its status. If the medium is free, the station waits for an interval of DIFS to check that the medium remains free. If it is still free, the station sends its frame. Otherwise, the MAC selects a random back-off value from the contention window. This scheme is depicted in figure 2.1. The back-off value is decremented each time the medium is free for one time slot. If a collision happens, the contention window will set to twice its size and a back-off value will be chosen from the new interval. After a successful transmission, the contention window is reset to a pre-set minimum value. The random back-off is also called after each successful transmission and each retransmission to reduce probability of collisions. The IEEE 802.11 MAC uses a positive acknowledgment scheme to detect collisions. Each unicast frame sent by the MAC has to be acknowledged by the receiver. If an acknowledgment is not received, the frame is retransmitted by the MAC layer. Broadcast packets are not acknowledged. Also, retransmissions are limited to a maximum number of retries.

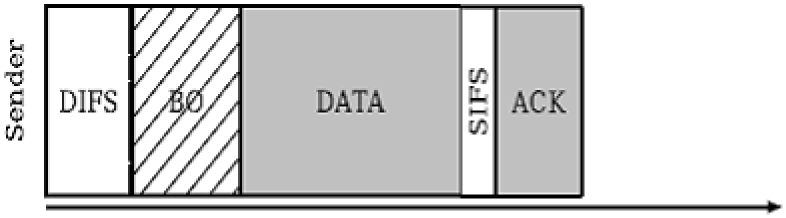


Figure 2.1: 802.11 DCF Basic Access Mechanisms.

2.2.4 The RTS/CTS Access Mechanism

In a wireless medium, the sender is not able to detect a collision because it occurs at the receiver. If a packet collides at the receiver, the whole packet still needs to be transmitted and then re-transmitted when an acknowledgment is not received. In addition, stations in the receiver’s surrounding may not sense a transmission from the sender. If any of these stations transmits, there will be a collision at the receiver. This is referred to as the Hidden Node Terminal problem which will be explained in next part. To circumvent this problem and enable faster collision detection, the IEEE 802.11 MAC specifies a prior hand-shake. Whenever a station has data to sent, it first sends a Request to Send (RTS) frame. The destination replies with a Clear to Send frame (CTS). These two frames contain duration information of the forthcoming data frame. All neighboring stations hearing these frames set a variable called Network Allocation Vector (NAV) to keep track of the availability of the medium. Checking the NAV before a transmission is also called a Virtual Carrier Sense mechanism. This protocol is shown in figure 2.2.

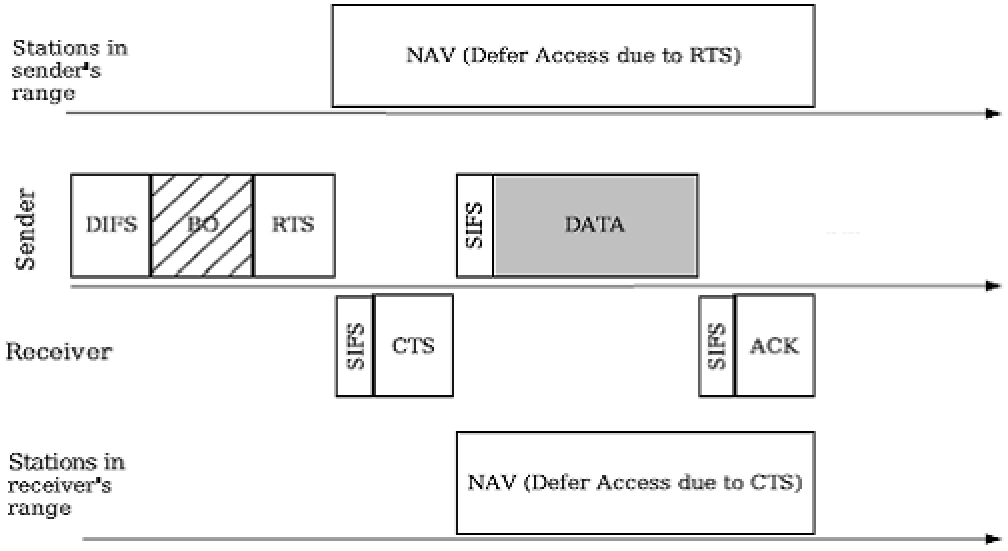
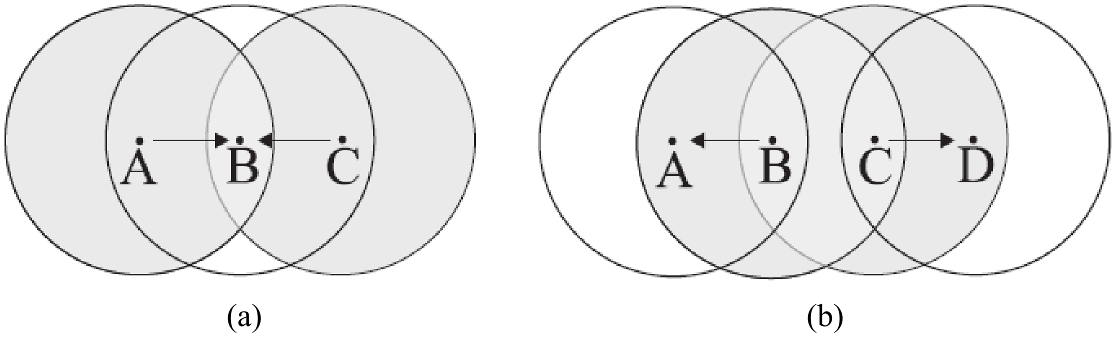


Figure 2.2: 802.11 DCF RTS/CTS Access Mechanism.

The 802.11 standard specifies RTS/CTS protocol as an optional protocol which can reduce radio contention in some scenarios.

2.2.5 The Medium Access Control Problems in Wireless Mobile Networks

In wireless networks, a MAC protocol has to contend with the hidden terminal and the exposed terminal problems. To see the first problem, consider the scenario of three nodes in figure 2.3 (a). Node *A* and *B* are within each other's transmission range, and so do node *B* and *C*. However, *A* and *C* can not hear each other. When *A* is transmitting to *B*, since node *C* cannot sense *A*'s transmission, it may falsely conclude that the medium is free and transmit, thus destroying A's ongoing packets. The problem that a station can not detect a potential competitor because the competitor is too far away is called the hidden terminal problem. In figure 2.3 (b), when *B* is transmitting to *A*, node *C* can sense the medium and thus will conclude that it can not transmit. However, if *C*'s intended recipient is *D*, then such transmission can actually be granted. Such inefficiency in channel use is called the exposed terminal problem.



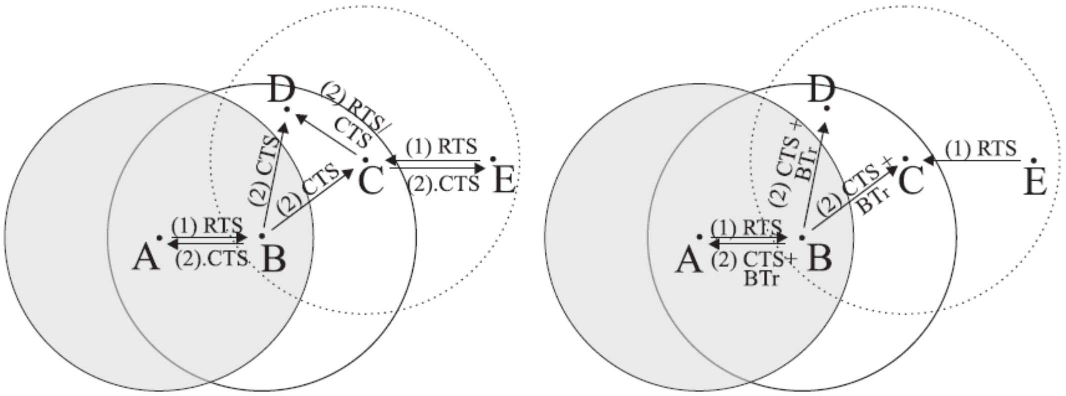
(a) (b)

Figure 2.3: Scenarios to show (a) the hidden terminal problem, and (b) the exposed terminal problem.

To alleviate these problems, a number of protocols have been proposed based on sending RTS/CTS packets before the data transmission is actually taken place [2, 3, 4, 5, 6]. When a node wishes to transmit a packet to a neighbor, it first transmits a RTS packet. The receiver then consents to the communication by replying a CTS packet. On hearing the CTS, the sender can go on transmitting its data packet. The hidden terminal problem in figure 2.3(a) will be eliminated when C hears the CTS packet, and the exposed terminal problem in figure 2.3(b) will be eliminated if we grant C to transmit if it can hear B's RTS but not A's CTS. Such an approach has been accepted by the IEEE 802.11 standard [1]. In IEEE 802.11, a field called NAV is added in the RTS/CTS packets to indicate the expected transmit/receive time of the data packet.

2.2.6 RTS/CTS Dialogue Enhanced with Busy Tones

Although the RTS/CTS dialogue can alleviate some hidden and exposed terminal problems, as observed in [7], when propagation and transmission delays are long, the CTS packets can easily be destroyed. This will result in destroy of data packets when traffic load is heavy. Consider the scenario in figure 2.4 (a). Node *A* sends a RTS to *B*, which in return replies a CTS to *A*. In the meanwhile, as host *C* can not hear *A*'s RTS, it may send a RTS (to start a transmission with *D*) or a CTS (to respond to *E*'s RTS). In either case, *D* can hear neither *C*'s nor *B*'s RTS/CTS, but the transmission from *A* and *B* will continue as normal. If later *D* decides to send any packet while *A* is transmitting to *B*, the packet will be destroyed at *B*. As analyzed in [7], the probability of data packets experiencing collision will be as high as 60% when traffic load is high.
To resolve the aforementioned problem, a protocol called DBTMA (Dual Busy Tone Multiple Access) is proposed [7, 8]. The single common channel is split into two sub-channels, a data channel and a control channel. The control channel is to transmit RTS/CTS dialogues. Also, two narrow-band busy tones, called transmit busy tone (BT_t) and receive busy tone (BT_r), are placed on the spectrum at different frequencies with enough separation. Figure 2.5 shows a possible spectrum allocation.



(a) (b)

Figure 2.4: (a) A scenario that *B*'s CTS is destroyed at *D* by *C*'s RTS/CTS. (b)Using busy tones to resolve the CTS destroyed problem.

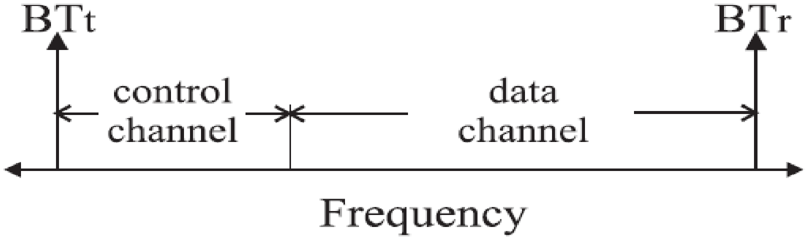


Figure 2.5: Frequency chart of the DBTMA protocol.

The purpose of busy tones is to add a capability similar to carrier sense to transceivers; BT_t is to indicate that a node is transmitting, while BT_r is to indicate that a node is receiving. A sending node must turn its BT*t* on when transmitting a data packet and a receiving host must turn its BT_r on when it replies the sender a CTS. When a node wants to send a RTS, it has to make sure that there is no BT_r around it. Conversely, to reply a CTS, a node must make sure that there is no BT_t around. So in the scenario of figure 2.4 (a), node *D* will be aware of, through B's BT*r*, B's receiving actively. Figure 2.4 (b) illustrates this scenario; *B*'s BT_r will prohibit *C*'s RTS/CTS.

In summary, a simple rule is used in DBTMA; a host should not send if it hears any BT_r, and should not consent to send if it hears any BT_t. As a final comment, it is also possible to use busy tones to save power [9], but this is out of the scope of this dissertation.

2.3 Wireless Mesh Networks

The IEEE 802.11 standard and related technologies have been successfully used to provide connectivity between wireless devices. The IEEE 802.11 ad-hoc mode provides for setting up wireless network between a group of nodes. Wireless mesh networks are such ad-hoc mode based networks which are easily deployable and offer flexible and cost efficient solution to providing network connectivity. Wireless mesh networks require high data rate support for good performance, therefore the mesh nodes should use the available communication bandwidth as efficiently as possible. The IEEE 802.11 wireless technology standard divides the available bandwidth into multiple channels. Further, the commercially available wireless radio interfaces can transmit and receive on one channel at a time. One of the key challenges of WMNs is the limited capacity and scalability. Equipping nodes with multiple wireless radio interfaces has not much implementation cost, since the cost of wireless interfaces are reducing day by day. The use of multiple channels in the network with the help of multiple interfaces at a node offers an opportunity to significantly improve the capacity of the network as opposed to using a single channel in the network.

Wireless Mesh Networks (WMNs) have recently gained considerable popularity due to their low cost, and self configuring and rapid deployment capabilities. Application scenarios for WMNs that have been proposed include building automation, intelligent transportation systems, metropolitan area networks and public safety applications. It has shown in [10, 11], that using multiple radio-interfaces per node, operating on orthogonal channels, can greatly increase the capacity of wireless mesh networks.

WMN is a promising broadband access technology where mesh clients, that are potentially mobile, connect to a relatively stationary core of mesh routers using multi hop wireless links [12]. The stationary mesh nodes form a multi-hop wireless overlay such that an individual mesh node acts as both a forwarding relay between WMN nodes and an access point to mobile and consumer devices in its vicinity. Since WMNs are dynamically self-organized and self-configured, they promise easy network maintenance, robustness, and reliable service coverage [12]. WMNs, especially when built from commodity wireless cards that operate over unregulated spectrum, are increasingly being recognized as a cost effective, viable broadband solution for urban [13], rural [14], campus and office [15] environments.

In this thesis we look in detail at such a multi-channel multi-interface wireless mesh network implementation. There are two lines of research for multi-channel wireless mesh network. A line of researches has focused on exploiting multiple channels by switching channels on the same radio interface which require modifying on MAC layer of the current IEEE 802.11. Another line of researches is to use multiple radio interfaces cards on each node and assign different channels to these interfaces.

During this work we analyze the various aspects of the multi-channel multi-interface network testbed and we take into account the adjacent channel interference which is neglected in majority of researches in multi-radio area. We describe the different issues that come up during the analysis and we draw attention to related points about the usage of multi-radio in the network. The issues we report during our discussions are the ones we believe would be faced by other similar multi-radio wireless networks.

CHAPTER 3

CAPACITY

3.1 Capacity Issues in Single-Channel Networks

Many researchers have studied the performance of single channel networks and have reported their poor scaling, theoretically and experimentally. As the number of nodes in single-channel network increases, due to higher contention and collision, the network performance will degrade quickly. For better understanding the performance implication of IEEE 802.11 MAC protocol, we need to differentiate between transmission, carrier-sense, and interference range. The Transmission Range (R_t) is the maximum distance within which a packet can be correctly exchanged between two nodes, assuming there is no interference. It is determined by the transmission power and the radio propagation characteristics of the environment. The Carrier Sense Range (R_{cs}) is the maximum distance at which a signal can be sensed by a receiving node. This value depends on the antenna sensitivity. Finally, the Interference Range (R_i) is the distance between a receiver and arbitrary node whose transmission will corrupt the packet being heard at the receiver. A packet is successfully captured if its signal to noise ratio (SNR) exceeds a certain threshold. A large interference range decreases performance of the network. A large carrier sense range reduces the network performance by preventing channel reuse, because some nodes in the R_{cs} range will defer transmission despite the fact that their transmission would not cause any interference. Not only throughput decrease caused by collision, but it happens when nodes waste too much time in back-off. As we can see, several factors contribute to the poor performance of single-channel networks. As the channel is a shared medium, throughput per node decreases when there are more users per area-unit. In addition, the CSMA protocol and the exponential back-off algorithm can lead to under-utilization of the medium, which results in high variability in throughput. Multi-channel protocols can be used in order to increase the capacity of wireless networks.

3.2 Multi-Channel Design

A key challenge in multi-hop wireless mesh network is to provision for sufficient network capacity to meet user requirements. Several approaches have been proposed to improve the network capacity in multi-channel networks, ranging from approaches that improve the efficiency of existing protocols, to approaches that use additional resources.
In this dissertation, we are going to evaluate whether it is possible to exploit the existence of multiple channels and the ability of radios to work simultaneously to increase the network capacity. It seems that the capacity problem in wireless mesh networks can be alleviated by equipping the mesh nodes with multiple radios tuned to non-overlapping channels. However, signal leakage presents a challenge because when the interfaces are in a close proximity to each other the amount of adjacent channel interference can not be neglected. The resultant increment in interference can adversely affects on the

performance. It should be noted that the results of theoretical and practical achievable throughput-gain, using multi-channel multi radio nodes, are different. We identify that the problems arising from the usage of multiple channels for concurrent transmissions when interfaces do not have considerable separation. We should mention that, at shorter distances, the interfaces experience more interference.

3.2.1 Related Work

Commercially available wireless networks can typically make use of a single radio interface on a fixed channel to communicate with neighboring nodes. Single-radio mesh networks can suffer from serious capacity degradation due to the half duplex nature of the wireless medium [16] and interference between multiple simultaneous transmissions. Previous studies have shown that overall network capacity decreases rapidly as node density and the number of hops increases [17, 18, 19].

Several researchers have proposed the use of multiple wireless channels for enhancing network capacity. Multiple channels have been exploited in infrastructure based networks by assigning different channels to adjacent access points, thereby minimizing interference between access points. However, nodes can exchange data only if they have a radio interface tuned to a common channel. Currently more available off-the-shelf interfaces can operate only on any one channel at a time, though over time, an interface can be switched across different channels. Typically, nodes are equipped with one or a small number of radio interfaces. Due to cost and complexity constraints, the total number of interfaces at each node is expected to be fewer than the total number of channels available in the network. However, by exploiting their ability to switch between channels over time, nodes can communicate over all possible channels, leading to increased network capacity. One protocol design approach when nodes have fewer interfaces than channels is to assign the interfaces of different nodes in a neighborhood to different channels [20,21], in this approach, interfaces do not switch channels, but collectively the interfaces of all the nodes in a region are distributed across the available channels. An alternate approach that is more flexible is to allow each node to potentially access all the channels by switching some of its interfaces among the available channels [22, 23]. This interface switching approach allows dynamic channel assignment based on node density, traffic, channel conditions, etc.; it has shown to be a good choice in theory [24, 25]. However, from practical point of view, frequently switching interfaces introduces extra implementation complexity. Moreover, the delay in switching channels tends to be on the order of a hundred milliseconds, which causes a significant decrease in performance. Also, it is possible that the node misses an RTS/CTS exchange on one channel when switching between channels.

Most of multi-channel wireless protocols assume that wireless transmissions by radio interfaces on different channels do not interfere. Though this is true when the interfaces have considerable separation, at shorter distances they experience some interference, especially when the channels are adjacent. This thesis addresses the problem of intra-node adjacent channel interference in multi-channel multi-radio mesh networks. The IEEE 802.11 PHY specification permits the simultaneous operation of multiple non-overlapping channels but its MAC protocol is designed for sharing a single channel between nodes and it dose not work well in multi-channel environment The IEEE

802.11a specification allows up to 11 non-overlapping channels in the 5.0 GHz band. In theory, by utilizing two orthogonal channels per node, the capacity improves significantly; however practically the performance of wireless network interface cards (NICs) within one node are constrained and can not operate as expected. A theoretical example will be discussed in the next parts. Actually, the extent of the interference between radios appears to be dependent on the various parameters such as hardware used, distance between transmitters, antennas pattern, receiver sensitivity, transmit power, etc.

3.2.2 A Theoretical Example

Multi-radio nodes are effectively full duplex; i.e., they can receive on channel C_1 on one interface while simultaneously transmitting on channel C_2 on the other interface, thereby immediately doubling the node throughput. As an example, consider the path 1→2→3 in figure 3.1. Let R denote the maximum possible transmit rate over one hop (i.e. from 1→2). With one radio, node 2 spends roughly half the time receiving from node 1 and the other half transmitting to node 3. Consequently, if the source (node 1) rate is R bps, the average receive rate at node 3 is approximately R/2 bps. With two radios at node 2 and two orthogonal channels, radio 1 can be tuned to channel 1 and radio 2 can be tuned to channel 2, in this case the receive rate at node 3 will be theoretically equal to R bps. Now, consider the case when there is a concurrent transmission on the route 4→2→5. In this case, node 2 has to spend a quarter of its time receiving from nodes 1 and 4 and transmitting to nodes 3 and 5. The average receive rate at nodes 3 and 5 in this case is R/4 bps. Consider the case when node 2 is equipped with two radios and there are 2 available orthogonal channels. In this case, radios 1 and 2 can be tuned to channels 1 and 2 respectively. If radios 1, 2 are used on a half-duplex mode to support the routes 1→2→3, 4→2→5 respectively, the average receiver throughput for each flow doubles to R/2 bps.

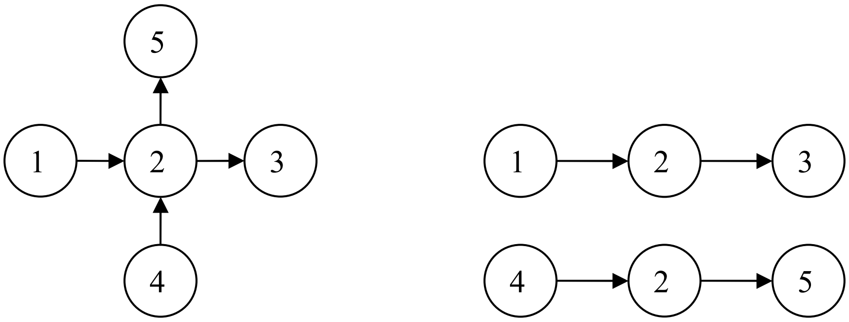


Figure 3.1: A Theoretical example motivating the improvement in throughput that can be obtained with multi-channel multi-radio.

3.3 Capacity Issues

In this part we consider how the capacity of a static multi-channel network scales as the number of nodes, *n*, increases. Gupta and Kumar [18] have determined the capacity of single channel networks, and theoretically those bounds are applicable to multi-channel networks as well, provided each node in the network has a dedicated interface per channel. In [10], Kyasanur and Vaidya established the capacity of general multi-channel networks wherein the number of interfaces, m, may be smaller than the number of channels, c. They showed that the capacity of multi-channel networks exhibits different bounds that are dependent on the ratio between c and m. Previous research [18, 26] has characterized the capacity of wireless networks.

3.3.1 Modeling Multi-Channel Multi-Interface Networks

We consider a static wireless network containing n nodes. There are c channels, and we assume that every node is equipped with m interfaces, $1 \leq m \leq c$. We assume that an interface is capable of transmitting or receiving data on one channel at a given time. We use the notation (m, c)-network to refer to a network with m interfaces per node, and c channels. We define two channel models to represent the data rate supported by each channel:

Channel Model 1: In model 1, we assume that the total data rate possible by using all channels is W. The total data rate is divided equally among the channels, and therefore the data rate supported by any one of the c channels is W/c. This was the channel model used by Gupta and Kumar [18]. In this model, as the number of channels increases, each channel supports a smaller data rate. This model is applicable to the scenario where the total available bandwidth is fixed, and new channels are created by partitioning existing channels.

Channel Model 2: In model 2 [10], we assume that each channel can support a fixed data rate of W, independent of the number of channels. Therefore, the possible aggregate data rate by using all c channels is Wc. This model is applicable to the scenario where new channels are created by utilizing additional frequency spectrum.

3.3.2 Definitions

We study the capacity of static multi-channel wireless networks under the two settings introduced by Gupta and Kumar [18].

Arbitrary Networks: In the arbitrary network setting, the location of nodes and traffic patterns can be controlled. Since any suitable traffic pattern and node placement can be used, the bounds for this scenario are applicable to any network. The arbitrary network bounds may be viewed as the *best case* bounds on network capacity. The network capacity is measured in terms of “bit-meters/sec” (originally introduced by Gupta and Kumar [18]). The network is said to transport one “bit-meter/ sec” when one bit has been transported across a distance of one meter in one second.

Random Networks: In the random network setting, node locations are randomly chosen, and each node sets up one flow to a randomly chosen destination. The network capacity is defined to be the aggregate throughput over all the flows in the network, and is measured in terms of bits/sec. We use the following notation to represent bounds:

1) $f(n) = O(g(n))$ implies there exists some constant d and integer N such that $f(n) \leq dg(n)$ for $n > N$.

2) $f(n) = o(g(n))$ implies that $\lim_{n \to \infty} f(n)/g(n) = 0$.

3) $f(n) = \Omega(g(n))$ implies $g(n) = O(f(n))$.

4) $f(n) = \omega(g(n))$ implies $g(n) = o(f(n))$.

5) *f(n)* = θ *(g(n))* implies *f(n) = O(g(n))* and *g(n) = O(f(n))*.
6) MIN$_O$ (f(n), g(n)) is equal to *f(n)*, if *f(n) = O(g(n))*, else, is equal to *g(n)*.
The bounds for random networks hold *with high probability (whp)*. Here *whp* implies with "probability 1 when $n \to \infty$."

3.4 Main Results

Gupta and Kumar [18] have shown that in an arbitrary network, the network capacity scales as $\Theta(W\sqrt{n})$ bit-meters/sec, and in a random network, the network capacity scales as $\Theta(W\sqrt{\frac{n}{\log n}})$ bits/sec.

The goal of this part is to study the impact of the number of channels *c*, and the number of interfaces per node *m*, on the capacity of arbitrary and random networks. In [10] results show that the capacity is dependent on the ratio $\frac{c}{m}$, and not on the exact values of either *c* or *m* (as shown in Lemma 2, Appendix A). We now state the main results of Kyasanur and Vaidya under channel model 1.

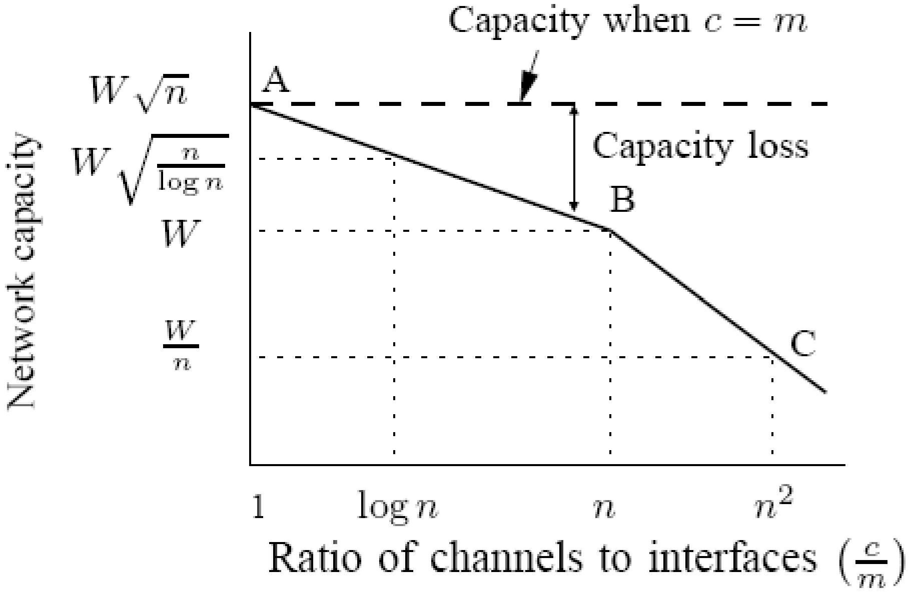


Figure 3.2: Impact of number of channels on capacity scaling in arbitrary networks (figure is not to scale)

1. Results for arbitrary network: The network capacity of (*m, c*)-network has two regions (see figure 3.2) as follows (from Theorem 1 and Theorem 2, Appendix A):

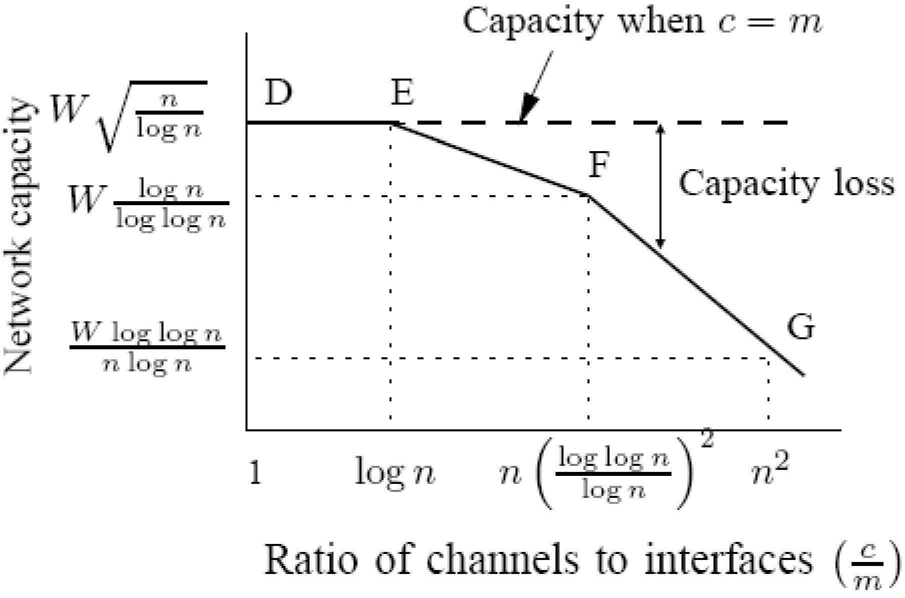


Figure 3.3: Impact of number of channels on capacity scaling in random networks (figure is not to scale)

1) When $\frac{c}{m}$ is *O(n)*, the network capacity is $\Theta(W\sqrt{\frac{nm}{c}})$ bit-meters/sec (segment A-B in figure 3.2). Compared to a *(c, c)*-network, there is a capacity loss by a factor of $1-\sqrt{\frac{m}{c}}$.

2) When $\frac{c}{m}$ is Ω*(n)*, the network capacity is $\Theta(W\frac{nm}{c})$ bit-meters/sec (line B-C in figure 3.2). In this case, there is larger capacity degradation than case 1, as $\frac{nm}{c} \le \sqrt{\frac{nm}{c}}$ when $\frac{c}{m} \ge n$.

Therefore, there is always a capacity loss in arbitrary networks whenever the number of interfaces per node is fewer than the number of channels.

2. Results for random network: The network capacity of a (*m, c*)-network has three regions (see figure 3.3) as follows (Theorem 3 and Theorem 4, Appendix A):

1) When $\frac{c}{m}$ is *O(log n)*, the network capacity is $\Theta(W\sqrt{\frac{n}{\log n}})$ bits/sec (segment D-E in figure 3.3). In this case, there *is no loss* compared to a (*c, c*)-network. Hence, in many practical scenarios where *c* may be constant or small, a single interface per node suffices.

2) When $\frac{c}{m}$ is Ω *(log n)* and also $O(n(\frac{\log\log n}{\log n})^2)$, the network capacity is $\Theta(W\sqrt{\frac{nm}{c}})$ bits/sec (segment E-F in figure 3.3). In this case, there is some capacity loss.

Furthermore, in this region, the capacity of a (*m, c*)-random network *is the same* as that of a (*m, c*) - arbitrary network (segment E-F in figure 3.3 overlaps part of segment A-B in figure 3.2); implying “randomness” does not incur a capacity penalty.

3) When $\frac{c}{m}$ is $\Omega(n(\frac{\log\log n}{\log n})^2)$, the network capacity is $\Theta(\frac{Wnm\log\log n}{c\log n})$ bits/sec (line F-G in figure 3.3). In this case, there is larger capacity degradation than case 2. Furthermore, in this region, the capacity of a (*m, c*)-random network is smaller than that of a (*m, c*)-arbitrary network, in contrast to case 2.

3.5 Upper Bound on Capacity

3.5.1 Arbitrary Networks

The capacity of multi-channel arbitrary networks is limited by two constraints (described below), and each of them is used to obtain a bound on the network capacity. The minimum of the two bounds (the bounds depend on ratio between the number of channels c and the number of interfaces m) is an upper bound on the network capacity. The bounds under channel model 1, and state the results under channel model 2 as well are derived.

Constraint 1 – Interference constraint: The capacity of arbitrary networks is constrained by interference. Using the proof techniques presented in [18] with some modifications to account for multiple interfaces and channels, a bound on the network capacity is $O(W\sqrt{\frac{nm}{c}})$ bit-meters/sec. (Theorem 5, Appendix A)

Constraint 2 – Interface constraint: The capacity of arbitrary networks is also constrained by the maximum number of bits that can be transmitted simultaneously over all interfaces in the network. Since each node has *m* interfaces, there are a total of *mn* interfaces in the (*m, c*)-network. Each interface can transmit at a rate of $\frac{W}{c}$ bits/sec. Also, the maximum distance a bit can travel in the network is *O(1)* meters. Hence, the total network capacity is at most $O(W\frac{nm}{c})$ bit-meters/sec. This bound is tight when $\frac{c}{m}$ is Ω *(n).*

Combining the two constraints, the network capacity is $O(MIN_O(W\sqrt{\frac{nm}{c}}, W\frac{nm}{c}))$ bit-meters /sec, under channel model 1.

3.5.2 Random Networks

The capacity of multi-channel random networks is limited by three constraints, and each of them is used to obtain a bound on the network capacity. The minimum of the three bounds (the bounds depend on ratio between the number of channels *c* and the number of interfaces *m*) is an upper bound on the network capacity. The bounds under channel model 1, and state the results under channel model 2 are derived.

Constraint 1 – Connectivity constraint: The capacity of random networks is constrained by the need to ensure the network is connected, so that every source-destination pair can successfully communicate. Gupta and Kumar [18] have presented a bound on the network capacity of $O(W\sqrt{\frac{n}{\log n}})$ bits/sec based on this requirement. This bound is applicable to multi-channel networks as well.

Constraint 2 – Interference constraint: The capacity of multi-channel random networks is also constrained by interference (this is same as constraint 1 listed for arbitrary networks). This constraint was already captured in the upper bound for arbitrary networks, and a bound of $O(W\sqrt{\frac{nm}{c}})$ bit-meters/sec is obtained. In a random network, each of the n source-destination pairs are separated by an average distance of $\Theta(1)$ meter. Consequently, the network capacity of random networks is at most $O(W\sqrt{\frac{nm}{c}})$ bits/sec.

Constraint 3 – Destination bottleneck constraint: The capacity of a multi-channel network is constrained by the data that can be received by a destination node. Consider a node X which is the destination of the maximum number (that is *D(n)*) of flows. Recall that in a (*m, c*)-network, each channel supports a data rate of $\frac{W}{c}$ bits/sec. Therefore, the total data rate at which X can receive data over *m* interfaces is $\frac{Wm}{c}$ bits/sec. Since X has *D(n)* incoming flows, the data rate of the minimum rate flow is at most $\frac{Wm}{cD(n)}$ bits/sec. Therefore, by definition of λ(n), $\lambda(n) \le \frac{Wm}{cD(n)}$, implying that network capacity (which by definition is $n\lambda(n)$) is at most $O(\frac{Wmn}{cD(n)})$ bits/sec. Substituting for *D(n)* from Lemma 3 (Appendix A), the network capacity is at most $O(\frac{Wmn\log\log n}{c\log n})$ bits/sec.

Lemmas and Theorems which are used in chapter 7 are available in appendix. If you are interested for more information and proofs you can refer to [10].

It should be noted that in reality, interfaces of one node are in close proximity to each other so there is a detrimental interference effects between non-overlapping channels due to the signal leakage of radios. As a result the wireless network interface cards within one node cannot operate as theoretically expected. The amount of adjacent channel interference between radios depend on the various parameters such as hardware used, distance between transmitters, antennas pattern, transmit power, receiver sensitivity, etc.

CHAPTER 4

MULTI-CHANNEL PROTOCOLS

4.1 Introduction

In this chapter, we review the literature relevant to multi-channel wireless networks. Initially, we will survey existing multi-channel techniques, and categorize them based on common features. We follow this discussion with comparison of existing protocols that have been proposed for multi-channel WMNs. Although these protocols and related works do not take into account the adjacent channel interference issues but understanding the principles of their operation gives us useful insights in order to propose better solutions which considering ACI issues.

4.2 Multi-Channel Protocols

IEEE 802.11 defines a contention based MAC protocol that adopts techniques including CSMA/CA, RTS/CTS and random back-off to avoid transmission collision. However, IEEE 802.11 MAC protocol is designed for single channel environment. Decreasing cost of wireless hardware devices presents an opportunity to equip wireless nodes with multiple wireless radio interfaces. It is expected that using multi channel protocols, which allow multiple communication pairs to transmit data simultaneously, can alleviate the performance degradation and increase the throughput. Many researchers have focused on multi-channel MAC protocols.

4.2.1 Comparison of Multi-Channel MAC Approaches

Protocols are different regarding how devices agree on the channel to be used for transmission and how they resolve potential contention for a channel. These choices affect the delay and throughput characteristics of the protocol.

4.2.2 Description of Protocols

There are many variations on multi-channel protocols. We are going to classify them based on their general principles of operation. We then describe representative protocols of the different classes. We also comment on variations that have been proposed for such protocols.

4.2.3 Principles of Operation

The idea of using multiple wireless radio interfaces at a node raises new challenges and leaves several questions to be answered. The commercially available 802.11 wireless radio interfaces at one time can communicate on one channel. Assuming a distributed system without any central controller, the nodes using multiple interfaces and multiple channels in a wireless network may need to be synchronized or they should use some control messages in order to be able to communicate with each other. The wireless nodes need to come up with a channel assignment schedule which specifies at what time a node would be listening on what channel. A good channel assignment coupled with an intelligent routing protocol is important for better performance of the system and it may increase the possibility of having more concurrent transmissions in the network.

4.3 Classification

There were many works [27-39] utilizing multiple channels with one interface because they consider that it is expensive to equip each node with multiple interfaces. Many evaluations of wireless protocols and testbed implementations such as MIT Roofnet [40-42], Uppsala University wireless network testbed [43] and others [14, 44, 45] have been done in the past. They all have single-channel single interface network testbeds. Chandra and Bahl [34] have developed an interface switching architecture called "Multinet". Multinet is also designed for nodes with a single interface.

However, with the trend of reduced hardware costs [46] and in order to utilize multiple channels efficiently, there have been many proposed MAC protocols [11, 34-36, 38, 47-52] using multiple interfaces.

The protocols proposed for the scenario where nodes have fewer interfaces than channels [11, 14, 28, 30, 53, 54] have mostly been evaluated in a simulation environment. The hybrid multi-channel protocol [51, 54, 55] proposed by Kyasanur and Vaidya aims to provide connectivity between nodes using multiple interfaces and multiple channels. The hybrid multi-channel protocol requires multiple wireless interfaces at each node and assumes that frequent channel switching is possible on at least one of the interfaces.

Devices using a multi-channel MAC protocol exchange control information in order to agree on the channel for transmitting data. In *single rendezvous* protocols, the exchange of control information occurs on only one channel at any time. *Multiple rendezvous* protocols allow multiple devices to use several channels in parallel to exchange control information and make new agreements. This approach alleviates the rendezvous channel congestion problem but raises the challenge of ensuring the idle transmitter and receiver visit the same rendezvous channel.

Multi-channel MAC protocols can be divided into those using a single or multiple transceivers (radios) per node. Another way of categorization is by the mechanism sender-receiver pairs use to agree on a data transfer channel. In such way, multi-channel MAC protocols can be classified into 4 categories:

. Dedicated Control Channel (single rendezvous): devices use one radio to constantly monitor the control channel. Examples are DCA (Dynamic Channel Allocation) [56], DCA-PC (Dynamic Channel Allocation with Power Control) [57] and DPC (Dynamic Private Channel) [58].

. Split-Phase (single rendezvous): devices periodically tune to the control channel together. Both MMAC [59] and MAP (Multi-channel Access Protocol) [60] are examples.

. Common Hopping (single rendezvous): devices hop together quickly and stop upon agreement for transmission. Examples include CHMA (channel hoping multiple access) [61], CHAT (Channel Hopping multiple Access with packet Trains) [62], and Hop-Reservation Multiple Access (HRMA) [63].

. Parallel Rendezvous (multiple rendezvous): transmitter jumps to receiver's hopping sequence. Examples of this approach include SSCH (Slotted Seeded Channel Hopping) [30] and McMAC [64].

There have been only limited studies comparing these protocols. In this part, we compare several existing MAC Protocols. As may be expected, different protocols are preferable depending on the operating conditions. The intent of these protocols is to increase capacity by enabling maximal spatial re-use of available channels in a distributed manner. Our objective is to figure out the relative merits of different designs.

4.4 Understanding Existing Approaches

There has been a large number of existing protocols proposed to date. It is therefore necessary to understand the fundamental differences of various approaches, pros and cons of them.

For split phase protocol, nodes only have one network interface. Time is divided into the channel negotiation phase and data exchange phase. In the channel negotiation phase, all nodes must listen to the common channel. Nodes that want to transmit frames negotiate a data channel during the channel negotiation phase, after that, nodes switch to the selected channel and exchange data/Ack frames. The advantage of this approach is that it requires only one radio per device. However, it requires time synchronization among all devices, though the synchronization can be looser than in common hopping because devices hop less frequently. Examples of this approach are MMAC [59] and MAP (Multi-channel Access Protocol) [60]. Their main difference is that the duration of the data phase is fixed in MMAC whereas it is variable in MAP and depends on the agreements made during the control phase.

For common hopping protocols, only one network interface is needed. All nodes follow a common channel hopping sequence. A pair of nodes stops hopping, and exchanges data/Ack frames on the negotiated channel and rejoin the common hopping pattern subsequently after transmission ends.

The Common Hopping protocol improves on Dedicated Control Channel in two respects: 1) It uses all the channels for data exchange; 2) it requires only one transceiver per device. As shown in figure 4.1 (b), the hopping pattern cycles through channels 0, 1, 2 and 3. When node *A* wants to send to node *B*, it sends an RTS to *B* on the current common channel. If *B* receives the RTS properly, it returns a CTS on the same channel. Node *A* and *B* then pause hopping and remain on the same channel during data transfer while the other idle devices continue hopping. When they are finished, nodes *A* and *B* rejoin the common hopping sequence with all the other idle nodes. It is possible that the common hopping sequence wraps around and visits the channel *A* and *B* are using before they finish data exchange. Idle nodes sense the carrier and refrain from transmitting if it is busy. It should be noted that while *A* and *B* are exchanging data, they are unaware of the busy status of the other nodes. Hence, it is possible that a sender sends an RTS to a node that is currently busy on a different channel. Another issue with this approach is that nodes hop more frequently.

Recent work in solid state electronics reduces the settling time of the Voltage Control Oscillator (VCO) [65]. Switching the channel of a wireless card requires changing the input voltage of the VCO which operates in a Phase Locked Loop (PLL) to achieve the desired output frequency. The delay in channel switching is due to this settling time. The specification of Maxim IEEE 802.11b Transceivers [66] shows this delay to be 150 μs.

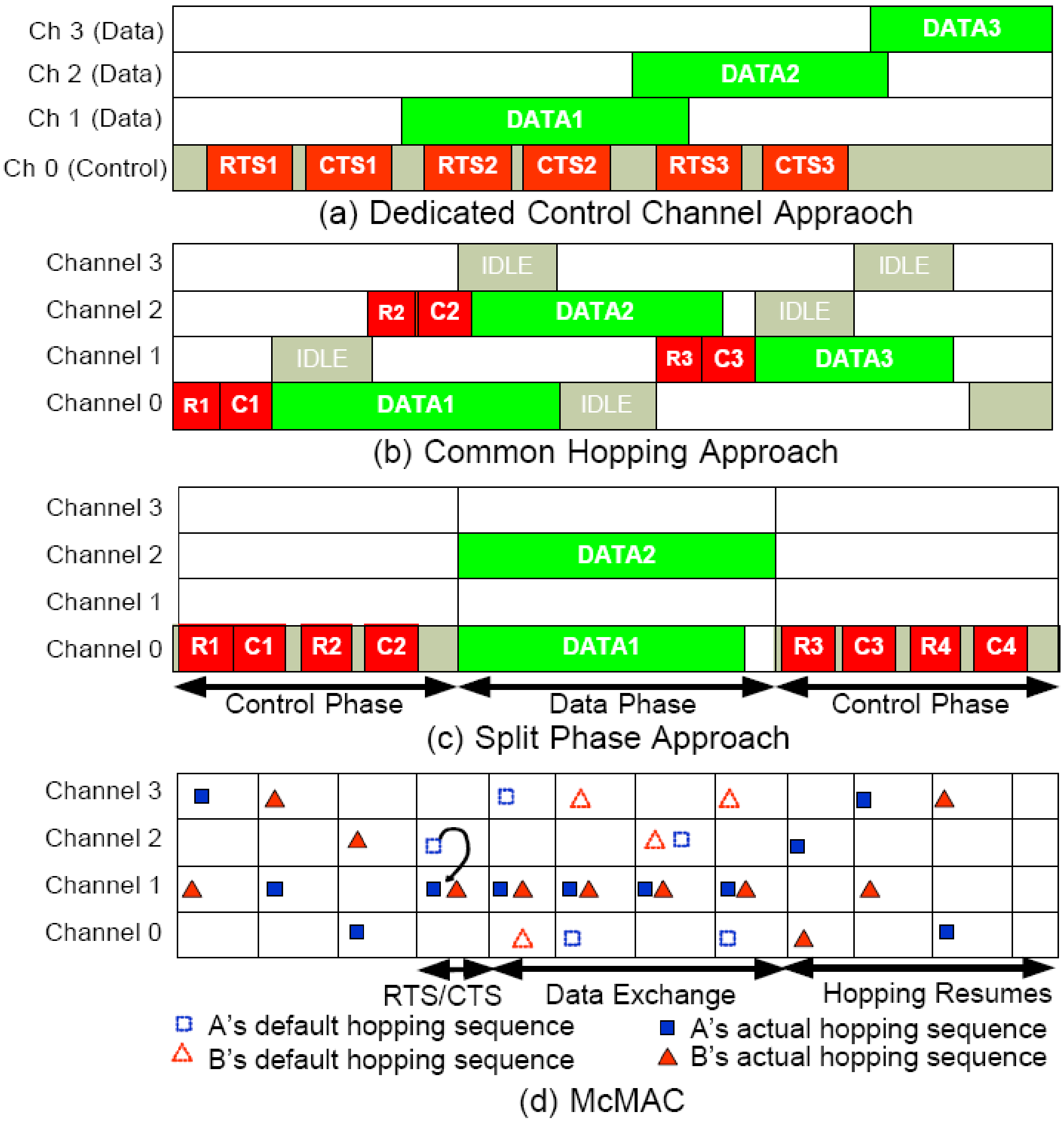


Figure 4.1: Basic operations of different MAC approaches.

A more recent work [67] shows that this delay can be reduced to 40-80 μs for IEEE 802.11a cards. Considering the time that an RTS takes, the hopping time penalty is not negligible. The approach also requires devices to have tight synchronization. Examples of this design approach include CHMA (channel hoping multiple access) [61] and CHAT (Channel Hopping multiple Access with packet Trains) [62].

Multiple rendezvous protocols differ from the other in that multiple device pairs can make agreements simultaneously on distinct channels. However, since there are multiple rendezvous channels, special coordination is required so that two nodes can rendezvous on the same channel. One solution is to follow a "home" hopping sequence; sending device should find the hopping sequence of intended receiver. Examples of this approach include SSCH (Slotted Seeded Channel Hopping) [30] and McMAC [64].

In SSCH there are as many hopping sequences that each device can follow. Each sequence is uniquely determined by the seed of a pseudo-random generator. Each node picks multiple (e.g., 4) sequences and follows them in a time multiplexed manner. When node *A* wants to talk to *B*, *A* waits until it is on the same channel as *B*. If *A* frequently wants to talk to *B*, *A* adopts one or more of *B*'s sequences, thereby increasing the time they spend on the same channel. For this mechanism to work, the sender learns the receiver's current sequences via a seed broadcast mechanism. In McMAC, each node picks a seed to generate an independent pseudo-random hopping sequence. When a node is idle, it follows its default hopping sequence as shown in figure 4.1(d). Each node puts its seed in every packet it sends, so its neighbors eventually learn its hopping sequence. For simplicity, nodes are assumed to hop synchronously. The hopping can be made less frequent than Common Hopping to reduce the channel switching and synchronization overhead. When node *A* has data to send to *B*, *A* flips a coin and transmits with some probability *p* during each time slot. If it decides to transmit, it tunes to the current channel of *B* (e.g., channel 1) and sends an RTS. If *B* does not reply with a CTS, either due to an error or because *B* is busy, then *A* tries again later by coin flips. If *B* replies with a CTS, both *A* and *B* stop hopping to exchange data. Data exchange normally takes several time slots. After the data exchange is over, *A* and *B* return to their original hopping sequence as if there was no pause in hopping.

SSCH and McMAC allow devices to rendezvous simultaneously on different channels. The above three categories protocols either need time synchronization or do not fully support frame broadcasting. However, both of these two issues are important for wireless mesh networks.

A multi-channel MAC protocol which requires only one network interface may increase the complexity and cost of frames broadcasting. A node which has a broadcast frame has to broadcast the frame on each channel. The split phase protocols enable frames broadcasting; however it needs time synchronization between nodes. Time synchronization is difficult and costly in multi-hop wireless networks.

For dedicated control channel [56, 57], nodes equipped with two (or more) network interfaces: common network interface and data network interface(s). The common network interface always stays on the specific common channel; the data network interface can be dynamically switched to any other data channels. The common channel is used to perform channel negotiation when a node has data to transmit. Figure 4.1(a) illustrates the operations of Dedicated Control Channel. In the figure, channel 0 is the control channel and channels 1, 2, and 3 are for data transmission. When node *A* wants to send to node *B*, it transmits a RTS packet on the control channel. Upon receiving the RTS, *B* responds with a CTS packet on the control channel, confirming the data channel suggested by *A*. The RTS and CTS packets also contain a Network Allocation Vector (NAV) field, as in IEEE 802.11, to inform other devices of the duration for which the sender, the receiver, and the chosen data channel are busy. Since all devices listen to the control channel at all times, they can keep track of the busy status of other devices and channels even during data exchange. Devices avoid busy channels when selecting a data channel. Examples of this approach include DCA (Dynamic Channel Allocation) [56], DCA-PC (Dynamic Channel Allocation with Power Control) [57] and DPC (Dynamic Private Channel) [58].

The major advantage of Dedicated Control Channel is that it does not require time synchronization because channel negotiation procedures are performed on common channel and since nodes always listen to the common channel, they can keep updating the channel status and broadcast frames on common channel. All approaches apart from Parallel Rendezvous suffer from control channel congestion when channels are numerous and communication tends to be short.

The problem of dedicated control channel protocols is that the control channel may become the bottleneck of the data channel utilization, since all channel negotiation procedures have to be performed in the control channel. To alleviate this problem, adopting an adaptive initial window size can significantly avoid too much cost of collisions.

However, the data frame is transmitted in the data channel in the dedicated control channel protocol, but collisions in control channel clearly affect the network throughput. Thus it is necessary to reduce the probability of collisions in the control channel.

We finish this part with some suggestions, for Dedicated Control Channel it is possible to use the control channel for data transfer when all other channels are busy. For Split Phase, adaptation of the duration of data and control phases was proposed by [59], [60] suggests advertising the number of packets for each destination in the rendezvous message to achieve better load balancing across channels. It should be noted that allowing a sender to transmit multiple back-to-back packets to the same destination after the rendezvous is highly beneficial.

These protocols and related works do not take into account the adjacent channel interference issues. In next chapter, we will review literature relevant to multi-channel wireless networks which discuss this kind of issues.

PART II ANALYSIS

CHAPTER 5

ADJACENT CHANNEL INTERFERENCE

5.1 Introduction

In this chapter, we directly address the problem of adjacent channel interference (ACI). We present the related work to the problem of Intra-node adjacent channel interference in multi-channel multi-radio WMNs. We also discuss the limited research that has been proposed in this area. We believe that multi-radio research for WMNs has primarily focused on theoretical concepts, with very little work done on practical implementation. We discuss some of these multi-radio experiments to gain general insights into the problem. The Intra-node adjacent channel interference problem, apart from its theoretical significance, is an important practical problem in WMNs. Since WMNs are generally composed of stationary routers and nodes which are powered from mains, the performance of WMNs is generally benchmarked by high-performance metrics such as throughput and latency and not by metrics conventionally used for wireless networks such as energy-efficiency or the total number of transmissions. Several scientific works have considered the possibility to build Wireless Mesh Networks (WMN) using multi-channel IEEE 802.11 architectures. At the basis of these works is the notion of “non-overlapping” channels, i.e. with a frequency separation equal or greater than 20MHz. It is now a common assumption that multiple independent transmissions over these channels can coexist without mutual interference. In this work we demonstrate that this assumption does not hold in general. If two transceivers are in close proximity to each other, as it is the default setup for multi-radio systems, and the antenna separation is limited then the assumption that multiple independent transmissions over non-overlapping channels can coexist without mutual interference does not work anymore. With extensive set of experiments we illustrate the presence of adjacent channel interference between non-overlapping channels at relay nodes. We analyze in what manner the MAC layer reacts to such interference and how this problem has detrimental effects on the global throughput. The central problem is that adjacent channel interference is not handled adequately by the MAC layer, and due to amount of interference and collisions in some cases single-channel multi-hop settings perform better than multi-channel. Our results highlight a serious mismatch between some routing and channel assignment schemes proposed recently by the research community, assuming full separation between non-overlapping channels, and what is achievable in practice. More generally, as the presence of adjacent channel interference can not be neglected at relay nodes, our findings point to a fundamental problem in building multi-channel multi-radio WMN based on IEEE 802.11 technology. Obviously, multi-radio systems were not the main focus during the standardization process of IEEE 802.11b/g/a.

5.2 Overview

The IEEE 802.11a specification provides for 11 non-overlapping channels (ETSI). In theory it should be possible to have simultaneous reliable transmissions on these channels. In practice though, due to signal leakage from one channel to another, transmissions on these non overlapping channels may still interfere with one another. The interference level is affected by many factors such as the hardware used, distance between transmitters, antennas pattern, etc. The other issue we noticed is board crosstalk. *Board crosstalk* is defined as noise caused by the usage of a common bus by several WiFi cards. On the other hand, *radiation leakage* of the wireless cards refers to over-the-air interference due to imperfect shielding of the WiFi cards.

A multi-channel architecture was proposed in [11] that uses a distributed channel assignment algorithm and considers non-overlapping channels as part of independent interference domains. The same assumption is considered by Alicherry et al. [68] who mathematically formulate a joint channel assignment and routing problem. In [10] a study of the capacity of multi-channel wireless networks is presented by assuming that multiple interfaces on a single node are capable to transmit and receive data simultaneously on non-overlapping channels. Raman [69] focuses on the problem of channel allocation in IEEE 802.11- based mesh networks. He uses multiple channels to divide the network into subgraphs that are considered fully decoupled as far as the medium contention and transmission scheduling are concerned. Burton [70] mathematically evaluates the channel overlapping in infrastructured IEEE 802.11 networks. He claims that a higher efficiency can be achieved by reducing the minimal channel separation. However, he only considers the interference between access-points without taking into account the interference caused by clients. A similar line of argument is presented in [71]. Further studies [28, 30, 47, 54, 72] have proposed dynamic channel assignment schemes in the context of self-organizing networks. The majority of them simply neglect any inter-channel effect. As we know, there has been much work in the simulation of these types of networks but less work on the analysis of a physical implementation. Simulations cannot always accurately account for many physical layer issues such as ground effect, antenna proximity, and variations in interference and delay. In the process of performing experiments, unexpected physical layer issues often arise that are not addressed in the simulated environment.

In contrast with these works we claim that the assumption of perfect independence between non-overlapping operating channels does not always hold in practice. In coming parts, we demonstrate the presence of detrimental interference effects also between non-overlapping channels by means of specific experiments with commercially available hardware. We find that the level of interference varies with many parameters, including physical distance, concurrent link-load, frame size, transmission power, receiver sensitivity and antenna patterns. The central problem is that adjacent channel interference is neither tackled by the standards nor handled adequately by the MAC layer. As a consequence its deleterious effects can be more severe than intra-channel interference between different transmitters. This is particularly critical in multi-hop topologies, where relay nodes act as transmitter and receiver simultaneously. Our findings call for a revision of some past research results in the area of multi-channel multi-radio networks based on IEEE 802.11.

5.3 Related Work

The problem of interference between non-overlapping channels in IEEE 802.11 has rarely been addressed in the research community. Although one would not expect any interference between non-overlapping channels, experiments showed that there is interference when the transceivers are in close proximity. The non-overlapping nature of the channels is true when the antennas are beyond a certain distance from each other. In [73] the authors performed some measurements on IEEE 802.11b long distance point-to-point link. They noticed mutual interference between channel 1 and 11 and attributed this effect to the leakage in the near field of the antenna from the pigtail RF connector. Draves et al. [38] propose a new metric for routing in multi-channel networks based on the loss rate and the link bandwidth. By experimenting with TCP they found that two flows interact with each other, resulting in a considerable reduction of the total throughput. There are very few studies that have experimentally measured the interference in multi-channel wireless networks. One such is the work by Liese et al wherein they study the relative performances of single and multiple channels in both single hop and multi hop wireless mesh networks [74]. In one of their experiments, they study the effect of antenna placement and determine the impact on performance. Observing unfavorable results even when the two nodes were communicating on non-overlapping channels, they attached external antennas to the PC cards and varied the antenna proximity. They concluded that goodput varies significantly with antenna proximity. The authors of [74] performed experiments of multiple channel usage in 802.11b wireless mesh backbone. They noticed that antenna proximity has a strong impact on overall performance. In [75] the authors analyze the impact of antenna separation on channel orthogonality and demonstrate that, when the antennas are in close proximity, there is no interference-free channel pair. Furthermore they find that the internal electronic circuitry itself represents an additional source of crosstalk between the interfaces on the same motherboard.

Multi-channel wireless networks are being studied as a means to increase wireless network capacity. The implicit assumption is that network throughput increases in direct proportion with the number of non-overlapping channels used. In [76], the experiments are conducted on a sample topology consisting of 1-2-3 flows on non-overlapping channels. They expected the combined throughput of the two flows to double. However, their results showed that the expected increase in throughput is seen only when the separation between the antennas of the radio devices is above a threshold value (approximately 3 feet). In their experimental setup, they observed a reduction of 25-40% in the expected total throughput value of the two flows.

All the above mentioned papers have incidentally noticed the effect of adjacent channel interference during their experiments but none of them provided any detailed investigation for analysis and solving this problem. In this thesis we directly address this problem and provide a comprehensive analysis of its causes and effects. Based on experiments we investigate the impact of several factors such as physical distance, channel separation, carrier sensing and type of traffic. In order to be able to analysis the main problem, in next part we will explain some specifications about physical and MAC layer mechanism such as clear channel assessment.

5.4 Overview of IEEE 802.11 Specifications

The IEEE 802.11 specifications include a detailed description of PHY/MAC operational requirements. While there is only a single MAC specification, several amendments for new physical layers have been standardized during the last years (e.g. IEEE 802.11a/b/g) with different modulation schemes and data rates. The PHY layer embeds two components: the Physical Medium Dependent (PMD) system which defines the transmitting and receiving schemes through the medium, and the Physical Layer Convergence Protocol (PLCP) which represents an interface between MAC protocol and different physical media. The PLCP maps the IEEE 802.11 MAC frames into a suitable format for the specific medium. It adds to each MAC-PDU a preamble and a header. The preamble is used to synchronize the transmitter and the receiver, while the header contains some physical parameters used by the PLCP. The medium is reported to be busy or idle according to the so-called Clear Channel Assessment (CCA) mode. The PLCP informs the MAC layer about the status of the channel through the primitive PHY CCA. The IEEE 802.11-1999 standard defines three CCA operation modes:

- CCA Mode 1: Energy above threshold. The medium is considered busy when the received energy exceeds the Energy Detection (ED) threshold;
- CCA Mode 2: Carrier Sense only. The medium is considered busy if a valid DSSS signal is detected, even if below the ED threshold;
- CCA Mode 3: Carrier Sense with energy above threshold. The medium is considered busy if a DSSS signal is detected and the energy is above the ED threshold.

The received energy in the channel is measured during the header transmission and is mapped by the microcode into a nonnegative integer value, namely the Receive Signal Strength Indicator (RSSI). The maximum value of the RSSI is denoted by RSSI MAX (with RSSI MAX$\leq$255). Note that the RSSI granularity, the value of RSSI MAX and the mapping relation between the measured energy and the RSSI are not specified by the standard and therefore remain vendor specific options.

In order to gain access to the channel and transmit data, an IEEE 802.11 interface senses the channel and performs a Clear Channel Assessment. In IEEE 802.11a a channel is considered busy if a preamble can be decoded at -82dBm. If the preamble cannot be correctly decoded or missed altogether, but the power detected is above -62dBm then again the medium is considered busy. Since there is significant power leakage from the nearby channels, in both IEEE 802.11g and IEEE 802.11a, it will be possible for interfaces transmitting near a sensing interface to cause the CCA of the latter to report a false negative on the clear channel assessment mechanism. This false negative of the CCA mechanism can be caused on an interface either by downlink traffic from the other interfaces of the node, or by the clients sending uplink traffic to one of the other interfaces, even when using directional antennas. Adjacent IEEE 802.11a channels have such an overlap that produces significant interference, whose impact will be noticeable when antennas are closely co-located on a node. All IEEE 802.l1 Coordination Functions (CFs) base on Listen Before Talk (LBT) that is known as Carrier Sense Multiple Access (CSMA). In IEEE 802.11, the CCA combines the input of two Carrier Sense (CS) mechanisms:

- Physical Carrier Sense (P-CS)
- Virtual Carrier Sense (V-CS)

Physical Carrier Sensing

As mentioned above, with P-CS every station senses the Wireless Medium (WM) for energy. Energy exceeding one or more thresholds is interpreted as busy channel condition. Thus, the station will not try to initiate a frame exchange. The concrete threshold value depends on the IEEE 802.11 Physical Layer (PHY) layer.

Virtual Carrier Sensing

V-CS informs stations about planned transmissions. All stations that are not in power-save mode constantly monitor the WM. Stations retrieve reservation information from any frame they decode. IEEE 802.11 frames provide the reservation information in their *Duration field*. If present, stations set their Network Allocation Vector (NAV) to the according value. The NAV works as a count-down timer. As long as the timer has a value different than zero, P-CS indicates a busy WM. The value of the NAV may be updated at any time. Thus, NAV duration may be prolonged or foreshortened.

5.5 Problem Analysis

In order to analyze the adjacent channel interference problem which has been introduced earlier it is useful to go through the non-overlapping orthogonal channels.

5.5.1 Non-overlapping Orthogonal Channels

The claim of perfect separation between two non-overlapping channels *A* and *B* in IEEE 802.11 implies that none of the following two effects are observed:

1) *Spurious Carrier Sensing*: An interface operating in channel *A* with packets in its transmission queue defers channel access because of activity on channel *B* by another interface.

2) *Increased Interference Noise*: An interface operating in channel *A* fails in successfully decoding the received frames because of excessive interference originating from other transmissions on channel *B*.

In the following subsections we present different states where both effects are clearly visible, thus proving that the separation between “non-overlapping” channels does not hold in general.

5.5.2 The Analysis of Different States

In order to explain the effect of adjacent channel interference in different scenarios, we are going to consider an example with three nodes in three different scenarios. Nodes *A*, *B* and *C* are going to communicate while node *B* consists of two radio interfaces. We are going to consider these three possible scenarios:

1. $A \leftarrow {}_1B_2 \rightarrow C$: Both interfaces of node *B* want to transmit data to node *A* and *C*.
2. $A \rightarrow {}_1B_2 \leftarrow C$: Node *A* wants to transmit data to B_1 interface while node *C* wants to transmit data to B_2 interface.
3. $A \rightarrow {}_1B_2 \rightarrow C$: Node *A* wants to transmit data to B_1 interface while B_2 interface wants to transmit data to node *C*.

Firstly we consider the first case ($A \leftarrow_1 B_2 \rightarrow C$), in this case the two interfaces of node *B* operate on two non-overlapping channels and want to transmit data to node *A* and *C* respectively. Since both flows are generated by the same node (*B*), the interferences between B_1 and B_2 produce one of the two following effects:

- Loss of the MAC layer Acks received from the destination nodes;
- Transmission blocking due to spurious Carrier Sensing (CS).

In the first case, the power emitted by B_1 is not sensed by the CS mechanism at B_2 on the other channel (and vice-versa). So B_2 starts transmission while B_1 is also transmitting. However, the mutual interference causes the collision of data transmitting in one interface with received Ack on the other interface. The weak incoming Ack at the receiver gets corrupted by the strong outgoing signal of the nearby transmitter; hence spurious retransmissions of the same packet occur. In the second case, the adjacent channel interference may trigger the CS on the other interface to report that the medium is busy causing the misleadingly deferral of the transmission. This phenomenon can be considered as a multi-channel version of the Exposed Node Problem, B_1 and B_2 are mutually exposed and inhibit each other's transmission although the external nodes are in interference-free areas.

An analogous phenomenon would occur when the RTS/CTS scheme is enabled. In this case, the interference would cause the loss of the CTS messages. Moreover, due to the spurious frame decoding, a RTS sent by B_1 on one channel can be decoded by B_2 on the other channel. Consequently, B_2 would consider that the channel is reserved to B_1 for the whole NAV duration. We conclude that in this case the negative impact of adjacent channel interference remains in place also with RTS/CTS enabled.

The results suggest that such a "box" with two interfaces has to incorporate a mechanism that solves the Ack and MAC retransmission problems in case of contemporaneous transmissions. Our experiments will be explained in chapter 6. As an example, we let two interfaces within one node transmit a continuous flow of MAC broadcast frames and we measure the actual outbound throughput at each station. The two interfaces operate on two non-overlapping channels. We repeat the experiment by changing the distance between the two antennas. Note that the use of non-acknowledged broadcast transmissions ensures that a drop in the throughput can be directly attributed to the spurious carrier sensing effect. In other words the use of non-acknowledged transmission rules out additional detrimental effects caused by interference noise on data and Ack frames. When the distance between antennas is 1 meter the throughput is reported to be maximum. We have also observed that below 30cm separation between the antenna the throughput starts to decrease quickly and we believe that it may caused by CCA mechanism which starts to defer transmissions and causes degradation in throughput. As a result integrating two IEEE 802.11a transmitters tuned on non- overlapping channels in one single box with few centimeters of antenna separation may lead to poor performance in some cases when CCA mechanism starts to defer transmissions.

Same experiments have been done in [77]; they tuned two interfaces of one node to different non-overlapping channels and let one of them broadcast a continuous stream of frames with DBPSK modulation at 1 Mbps. They observed that the other interface was able to successfully decode frames on the other channel. In other words, the residual power received from a signal transmitted on the other channel was sufficient to successfully decode the frames. In fact, DBPSK modulation at 1 Mbps is also used for the transmission of the PLCP preamble. When using CCA mode 2 the medium is marked busy if the CCA module detects a valid DSSS signal on the air interface, i.e. when a PLCP preamble is detected. This experiment gives a strong indication that the PLCP preamble would be decoded even if the stations are tuned on non-overlapping channels. Based on this, we conjecture that the problem of spurious carrier sensing would remain. These behaviors which are explained are in contrast with the assumption of full decoupling between non-overlapping channels. In the scenarios considered so far we have observed that transmissions in one channel can be detected and even decoded on a different channel, also if nominally "non- overlapping". As expected, such adjacent-channel interference disturbs the frame reception in case of simultaneous transmissions on non-overlapping channels, thus increasing the decoding failure rate and causes more loss of MAC frames. In fact, the out-of-band power leaked from the transmitter on one channel reduces severely the SIR on the other channel at the neighboring receiver, preventing correct frame decoding. This is the well-known "near-far effect". In this case it can not be blamed upon the poor design of the rejection RF filter, but rather on the fact that the spectrum mask defined by the IEEE standard was simply not designed for a scenario where different channels are used by the same node.

As a final factor of this scenario it should also be noted that the maximum number of retransmissions (RetryLimit) and the length of contention window have impacts on the throughput. Increasing the RetryLimit has a general negative impact on the throughput and the length of contention window is related to the number of stations contenting the medium. The more stations contenting to the medium, a larger initial contention window size is needed. Stations double the contention window when collisions occur to reduce the further potentialed collisions. For fixed number of active stations, when the initial window size of all stations is small, the throughput decreases since there are a lot of collisions; as the initial window size increases, the throughput increases until reaching a maximum value; and then as the initial window size further increases, the throughput decreases since it takes longer time to transmit. In other words, to find an optimal initial window size enables obtaining higher throughput for a fixed traffic load is worthy of study.

The second scenario can be the case when the traffic is directed from the external nodes toward the internal node (convergent flows $A \rightarrow_1 B_2 \leftarrow C$). The CS mechanism is never triggered because the transmitters *A* and *C* are now too distant to sense each other on different channels. In this configuration B_1 and B_2 send only Acks, therefore CS is not active there (recall that according to the IEEE 802.11standard [1] the Ack is sent regardless of the state of the medium). On the other hand, the transmissions of the Ack on one radio can still interfere with the reception of the data frames on the other interface, so causes reduction in throughput. The problem lies in the mismatching between the CS range at the sender and the interference range at the receiver. This phenomenon can be considered as a multi-channel version of the Hidden Node Problem, B_2 is hidden to the sender (node *A*) but causes interference at the receiver (B_1). However, differently from the classical Hidden Node Problem, it can not be mitigated by the RTS/CTS scheme which is designed for operation in a single channel since the two links are on distinct channels and therefore the receiver is unable to decode the NAV value from the

RTS/CTS packets. This would make the case for considering improved schemes of the Physical CS mechanism, and specifically of the CCA modes.

Finally we analysis the third scenario with coherent flows ($A{\rightarrow}_1 B_2 \rightarrow C$). In this case A and B_2 are independent sources and send traffic respectively to B_1 and C. In other words, B_1 acts as a receiver while B_2 acts as a transmitter. Clearly, the effect of the adjacent channel interference is now asymmetric, when the interference comes into play, flow $A \rightarrow B_1$ drops and eventually dies out while flow $B_2 \rightarrow C$ remains undisturbed. In fact, the prominent effect is the destruction of the frames received in B_1 (from A) due to the continuous flow transmitted by B_2. Even the MAC retransmissions are not able to recover the flow $A \rightarrow B_1$ because B_2 is a hidden node for A as it operates on a different channel. In this scenario weak incoming signal at the receiver gets corrupted by the strong outgoing signal of the nearby transmitter.

5.6 Modeling of Interference

The main factor that limits capacity in wireless mesh networks is interference; it is a consequence of using a shared communication medium. Hence, an accurate modeling of interference is useful in order to derive theoretical and/or simulation-based results of some practical relevance. In the literature, two main interference models have been proposed [18]; the *protocol* and the *physical* interference models.

In the former model, a communication between nodes u and v is successful if no other node within a certain interference range from v (the receiver) is simultaneously transmitting. Due to its simplicity and the fact that this model can be used to mimic the behavior of CSMA/CA networks such as IEEE 802.11, it has been mostly used in the literature.

In the *physical* interference model, a communication between nodes u and v is successful if the SINR (Signal to Interference and Noise Ratio) at v (the receiver) is above a certain threshold, whose value depends on the desired channel characteristics (e.g. data rate). This model is less restrictive than the *protocol* interference model; it may occur that a message from node u to node v is correctly received even if there is a simultaneous transmitting node w close to v. As a result, higher network capacity can in general be achieved by applying the physical interference model. Note that the *physical* interference model is representative of a scenario that does not use CSMA techniques; instead transmissions should be carefully scheduled so that only sender/receiver pairs that do not conflict with each other transmit simultaneously. In other words, the physical interference model is suited for use with TDMA-like channel access schemes.

Recent research indicates that CSMA/CA is not suitable to meet the high traffic demand of wireless mesh networks. The reason for this is that CSMA/CA is a very conservative mechanism; due to the combination of carrier sensing and collision avoidance techniques, many network nodes are silenced when a certain communication takes place. The ‘silenced area’ grows quadratically (in an idealized setting) with the transmission range, hence CSMA/CA becomes more and more conservative (with a negative impact on capacity) as the nodes’ transmission ranges increase. Since wireless routers typically have relatively long ranges (ranges of several hundreds meters or a few kilometers can be expected [14, 40]), CSMA/CA is deemed not adequate to meet the high traffic demand of wireless mesh networks. This is the reason why existing implementations of IEEE 802.11-based mesh networks disable the collision avoidance mechanism (i.e., the RTS/CTS message exchange) [40], or completely new TDMA-like MAC protocols are proposed for mesh networks [14, 78].

5.7 Research Challenges of Intra-Node Adjacent Channel Interference Problem in Multi-Channel Multi-Radio WMNs

The idea of using multi-channel multi-radio in wireless mesh networks in order to improve the network capacity raises new challenges. The IEEE 802.11 standard allows for the use of multiple channels available at the physical layer, but its MAC protocol is designed only for a single channel. As we mentioned before single channel MAC protocol does not work well in a multi-channel environment. Therefore, an important research challenge is to design algorithms that can decide how a node should make its transmissions to different set of neighbors, with a suitable pattern which ensures the optimal performance in terms of interference and capacity improvements including the effect of adjacent channel interference. To achieve this goal firstly we will do some link budget calculation and with the aid of measurements and simulations we will get more insights for proposing an appropriate solution in order to cope with adjacent channel interference problem.

5.8 Link Budget

In this part we are going to calculate some top level link budget but we should be aware that standard organizations, such as ETSI and FCC, have defined some limits and standards for different factors which are involved in this area. Due to the mentioned reason it will be useful to go briefly through these standards.

5.8.1 IEEE 802.11a OFDM

IEEE 802.11a operates in the 5.0 GHz UNII frequency, with data rates ranging from 6 Mbps to 54 Mbps. It uses Orthogonal Frequency Division Multiplexing (OFDM), which is a multi-carrier system. OFDM allows sub-channels to overlap, providing a high spectral efficiency. The modulation technique allowed in OFDM is more efficient than spread spectrum techniques used with IEEE 802.11b.

5.8.2 IEEE 802.11a Channels

The IEEE 802.11a channel shows the center frequency of the channels. The frequency span of the channel is 10 MHz on either side of the dotted line, as shown in figure 5.1.

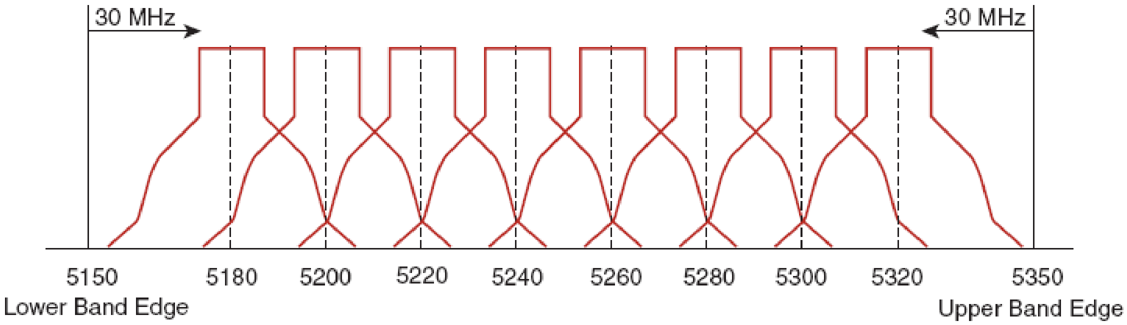


Figure 5.1: Channel Set Example

Valid operating Channel numbers which are defined by the standard organization (ETSI, FCC) in Europe, United State and other countries are illustrated in tables 1, 2 (Appendix B).

According to the standard specifications (ETSI) the 802.11a specification provides for 11 non-overlapping channels, ETSI band (5.5 to 5.7 GHz). Each of these channels is 20 MHz wide. In theory it should be possible to have simultaneous reliable transmission on these channels. In practice though, due to signal leakage from one channel to another, transmissions on these non-overlapping channels may still interfere with one another. The interference level is affected by many factors such as the hardware used, distance between transmitters, antennas used, transmitted power, etc.

5.8.3 Transmit spectrum mask

The coupling (interference) between different channels plays an important role in the interface design. In order to reduce the inter-channel interference the standard specifies a spectral mask and sets limits on the maximum out-of-band power relative to the peak power level, as sketched in figure 5.2.
The transmitted spectrum shall have a 0 dBr (dB relative to the maximum spectral density of the signal) bandwidth not exceeding 18 MHz, –20 dBr at 11 MHz frequency offset,-28 dBr at 20 MHz frequency offset and –40 dBr at 30 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask.

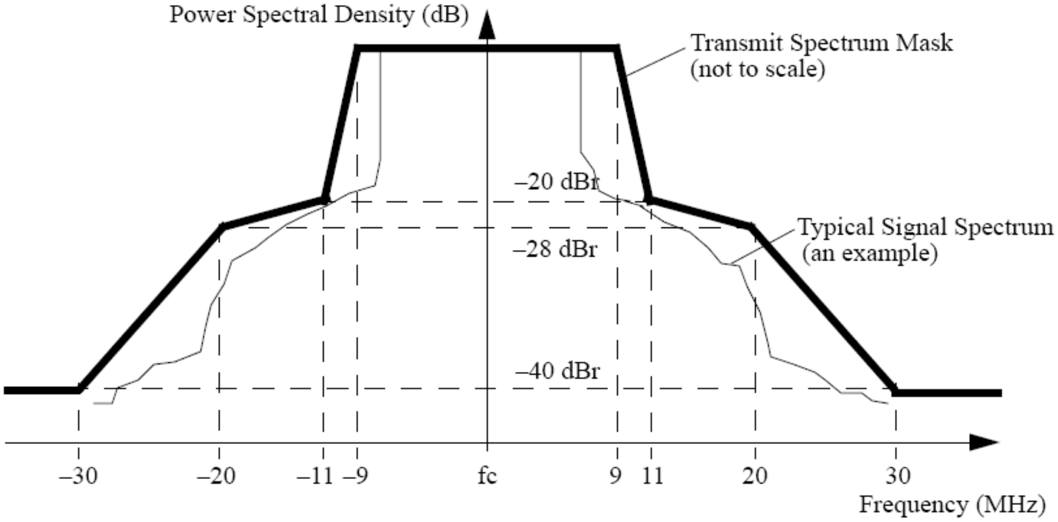


Figure 5.2: IEEE 802.11a Spectral Mask

5.8.4 Channel State

In order to gain access to the channel and transmit the data, an IEEE 802.11 interface senses the channel and performs a Clear Channel Assessment. As we mentioned before in 5.4, in IEEE802.11a channel is considered busy if a preamble can be decoded at -82dBm. If the preamble cannot be correctly decoded or missed altogether, but the power detected is above -62dBm then again the medium is considered busy.

5.8.5 Link Budget Calculations

In this part we are going to calculate the link budget with the typical value of parameters which are listed in tables 5.1 and 5.2 [79]. We believe that a top level link budget analysis is a fairly straightforward exercise. It is a useful step in order to determine the feasibility of a system. A link budget calculation is also a mean to understand the various factors which must be traded off to realize a given cost and level of reliability for a communications link.

Adjacent channel Attenuation	- 50 dB (More than one channel apart)
Equivalent isotropically radiated power *(*EIRP*)* Due to 3 dBm TCP	1000mw (30 dBm) 27 dBm
Antenna gain	3 dBi
Fade Margin	10dB
Frequency	5.5~5.7 GHz

Table 5.1: Typical value of parameters.

Data Rate (Mbps)	Sensitivity (dBm)
6	-94
9	-93
12	-91
18	-90
24	-86
36	-83
48	-77
54	-74

Table 5.2: Receiver Sensitivity.

5.8.5.1 Normal Case

Firstly to gain more insight, we are going to calculate the normal distance between the transmitter and receiver. Due to IEEE 802.11 specification [1] the maximum possible transmit power level in Europe is 30dBm and with 3dBm reduction for TCP (Transmission Control Protocol), the radiated power will be 27dBm.

In order to calculate the normal distance between the transmitter and receiver, we should calculate the pathloss. In the receiver side, for the calculated path loss at 6Mbps data rate due to equation *(1)*, tables 5.1 and 5.2 we have:

Received Power = Radiated power – Path loss - Fade Margin + Antenna gain *(1)*

$-94 = 27 - \text{Path loss} - 10 + 3 \Rightarrow \text{Path loss} = 114$

With calculated path loss and due to Walfisch-Ikegami equation, we can calculate the normal distance between the transmitter and receiver:

Walfisch-Ikegami Path loss Equation:
Path loss = 42.6 + 20log (f (MHz)) + 26log (d (km))
$114=42.6 + 20\log (5\times 10^{3}) + 26 \log d \Rightarrow d = 797$ m

This attained range is the typical node to node transmission distance. When the distance between the sender and receiver increases, the path loss increases and it may happen that nodes can not hear each other.

5.8.5.2 The Isolation of Multi-Radio Nodes

About the multi-radio nodes the distance between the interfaces is just few centimeters and the pathloss do not have any considerable effects. In multi radio nodes the main limiting factor is isolation between two interfaces. As we have observed via our experimental measurements the isolation between 2 radios in Figo nodes, which are explained in earlier chapter, is approximately 50 dB. In order to consider the parallel transmissions case, we are going to calculate the minimal amount of required isolation between radios within one node which is sufficient for having parallel transmissions. It means that the received signal strength which is leaked from one interface should be less than the receiver clear channel assessment threshold (-82 dBm) of the other interface. If the transmit power is 27 dBm, due to 50 db reduction of mask, for the minimal amount of isolation which can solve the problem we have:
$27 - 50 - \text{Isolation} \prec -82 \Rightarrow$ Minimal required isolation between radios $\cong$ 60 dB.
Furthermore, we can calculate the minimal amount of required isolation between radios within one node which is sufficient for having parallel transmission and reception. It means that the received signal strength which is leaked from one interface should be less than the receiver sensitivity (-94 dBm) of other interface. If the transmit power is 27dBm, due to 50 db reduction of mask, for the minimal amount of isolation which can solve the problem we have:
$27- 50 - \text{Isolation} \prec -94 \Rightarrow$ Minimal required isolation between radios $\cong$ 72 dB
As we saw the minimal required isolation between radios for parallel transmissions, transmission and reception is 60 dB and 72 dB respectively. This amount of isolation is not feasible with the available devices (Figo). So the system-as is- will trigger the clear channel assignment of the other radio in parallel transmissions and the received data is corrupted in parallel transmitting and reception case.

5.8.5.3 Antenna Distance

Finally we can calculate the minimal required distance between the antennas within one node. In IEEE 802.11a if the preamble cannot be correctly decoded or missed altogether, but the power detected is above-62 dBm then again the medium is considered busy. So when transmit power is 27dBm and due to 50 dB reduction of mask we have:
$27 – 50 – \text{Required Loss} \leq -62 \Rightarrow \text{Required Loss} \geq 39$
Due to the Walfisch-Ikegami Path loss we can calculate the distance:

Path loss = 42.6 + 20log (f (MHz)) + 26log (d (km))

$39=42.6 + 20\log(5\times10^3) + 26 \log d \Rightarrow d=1.039\text{m}$

One meter separation between the antennas is also suggested by some experimental work in multi-channel multi-radio area. Furthermore in our measurements we have observed the maximum amount of throughput when the distance between antennas is 1 meter. But it should be noted that neither 1 meter separation between the interfaces within one node nor achieving to the calculated amount of isolation is not feasible.

As a result of this part solving the problem of concurrent transmissions, transmission and reception is an important research challenge in multi-channel multi-radio wireless mesh networks and we should take into account these aspects in order to achieve higher throughput.

5.9 Conclusion

During this chapter we have investigated the effect of adjacent channel interference between non overlapping channels in IEEE 802.11. The first lesson to be learned is that the presence of adjacent channel interference can not be neglected in the context of multi-channel multi-radio WMNs due to the near-far effect, since simultaneous transmission and reception take place at relay nodes. In fact, the concept of multiple channels in IEEE 802.11 was introduced to improve the performance in multiple hot-spot scenarios where different channels are used by different access points and clients. This concept was later applied to the multi-hop scenario where a single node can be active on multiple channels at the same time. At this point the notion of “non-overlapping” has been misleading, driving some researchers to erroneous assumption of full decoupling between these channels, thus ignoring the near far effect. The second lesson from the present work is that the inability of the MAC layer to handle adjacent channel interference can have dramatic effects on the throughput. Moreover, based on our experimental works which will be represented in the next chapter, it can be straightforwardly conjectured that ACI would cause a dramatic throughput reduction in multi-channel multi-radio networks. Such findings point to a fundamental problem in using current IEEE 802.11 standard for multi-channel multi-radio mesh networks. As a result, our experiments suggest that current off-the-shelf IEEE 802.11 chipsets without any special mechanism might not be ready to be integrated in a single box with few centimeters of antenna separation.

It should also be noted that the fundamental shortcoming of many previous attempts is the implicit assumption that the multiple radios within one node, operate independently. We believe that appropriate solutions to achieving robust wireless systems with high throughput need the interactions between radios, and innovation in combining these components in a way that uses their strengths constructively.

In next chapter we have done some practical measurements about adjacent channel interference, taking into consideration various factors such as antenna separation, number of channels and radio, transmit-power and packet size. We have compared the interference effects in different channels. This work is motivated by the need to investigate the potential interference in a subset of the nodes currently being deployed in the Figo MeshNet Testbed. Due to the physical proximity, it is critical to investigate the adjacent channel interference of devices that have multiple interfaces that are operating in parallel on different channels.

In order to evaluate the effect of ACI more in detail, we are going to discuss our measurement and simulation results in coming chapters.

CHAPTER 6

MULTI-RADIO MEASURMENTS

In this chapter we are going to measure and analyze the adjacent channel interference issues in multi-channel multi-radio set ups.

6.1 Purpose

Figo nodes are multi-radio nodes which have been introduced in the first chapter and are used during our measurements. The wireless NIC is integrated to their board. They are equipped with IEEE 802.11a network cards. They are running linux kernel 2.4.20-8 and MADWIFI wireless drivers.The goal of this chapter is to analyse the interference issues and evaluate the internal interference between NIC's.
The results of the measurements are divided into two parts. The first part is a motivating part and in second part we are doing more measurements in order to get more insight about the causes of adjacent channel interference. While setting up the throughput experiments on Figo nodes' testbed, we observed that adjacent channel interference strongly affect the achievable throughput.
Many researchers consider the amount of improvement in throughput gain that they can achieve while using multi-radio nodes excluding the effect of adjacent channel interference (ACI). They have achieved a high gain via simulation and theoretical works.
Precise investigation on ACI is needed in order to have an appropriate estimation about the enhancement level in multi-radio throughput. Due to the practical problems and restrictions that exist for measuring parameters in layer-2, we cannot measure parameters in this layer and we should investigate on the amount of RSSI and throughput in the physical interface. Moreover by virtue of uncertainty of effective factors, we decided to do more measurements with changing various parameters such as antenna separation, number of channels and radio, transmit-power and packet size in order to consider the results. Evaluation of attained results shows that some measurements have not been helpful in order to decrease the amount of ACI but due to the little works that have been done by other researchers and the existing probability for finding effective parameters we have done several different measurements.

6.2 Classification

Firstly we are going to analyze the results of prior measurements which are the main motivation for additional measurements. The prior measurements show that the enhancement level of throughput in practical works is different from the theoretical expectation.

6.2.1 The Effect of Transmission Power

In this part the effect of transmission power in internal interference between NIC's is considered. Two Figo nodes were arranged in a topology which is shown in figure 6.1; their antenna connectors connected directly using cables and 50dB attenuation.

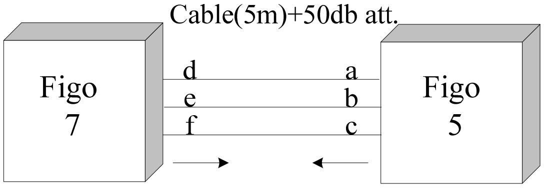


Figure 6.1: Test setup.

	Channel	Channel
d,a	100	100
e,b	120	120
f,c	140	140

Table 6.1: Channel Configuration

Each Figo node is equipped with three interfaces. The possible active links from Figo 5 to Figo 7 are labeled as a, b and c. The possible active links from Figo 7 to Figo 5 are labeled as d, e and f. The channel configuration of links is depicted in table 6.1. As an example link e and b are configured on channel 120.
The amount of throughput is determined by using Iperf [80], an open source bandwidth measurement tool. In this part of our measurements we have two nodes and we want to get more insights by comparing 1, 2 and 3 radios per node, so as a fast and fairly accurate parameter, we use TCP throughput.
Figure 6.2 and 6.3 shows the amount of TCP throughput for transmit power of 0 dBm and 18 dBm respectively. The X-axis in these figures shows the active Iperf streams, as an example when it is labeled dbc it means that link d, b and c are active, so in this case d is transmitting Iperf stream from Figo 7 to Figo 5 and b, c is transmitting Iperf streams from Figo 5 to Figo 7.

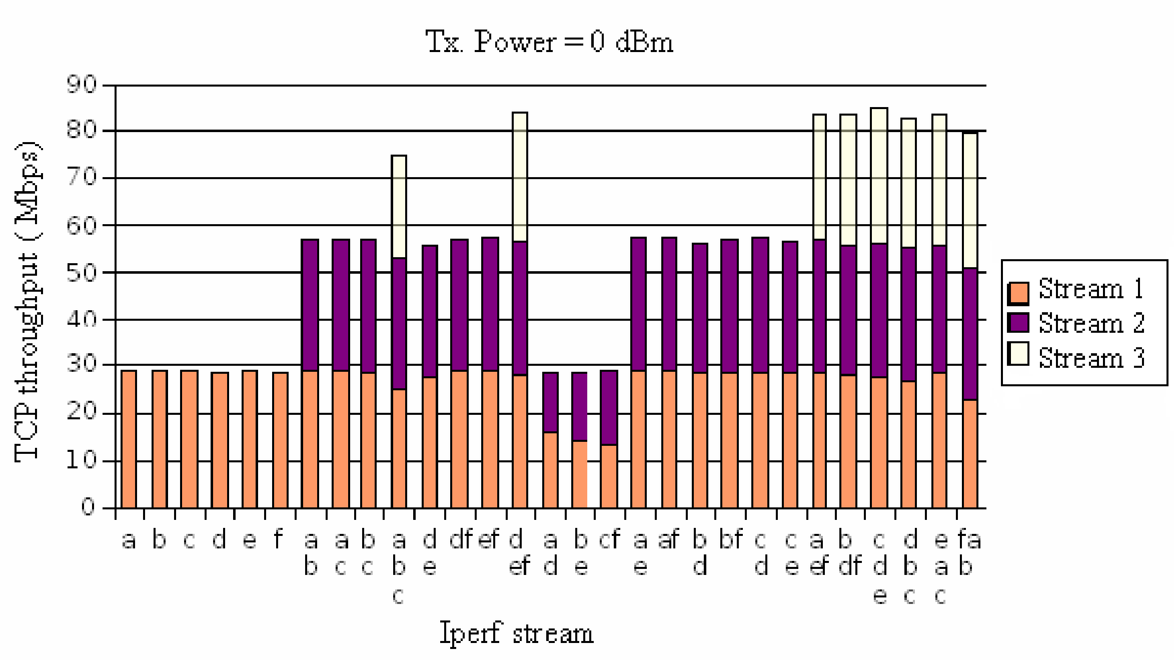


Figure 6.2: TCP throughput with 0 dBm transmission power.

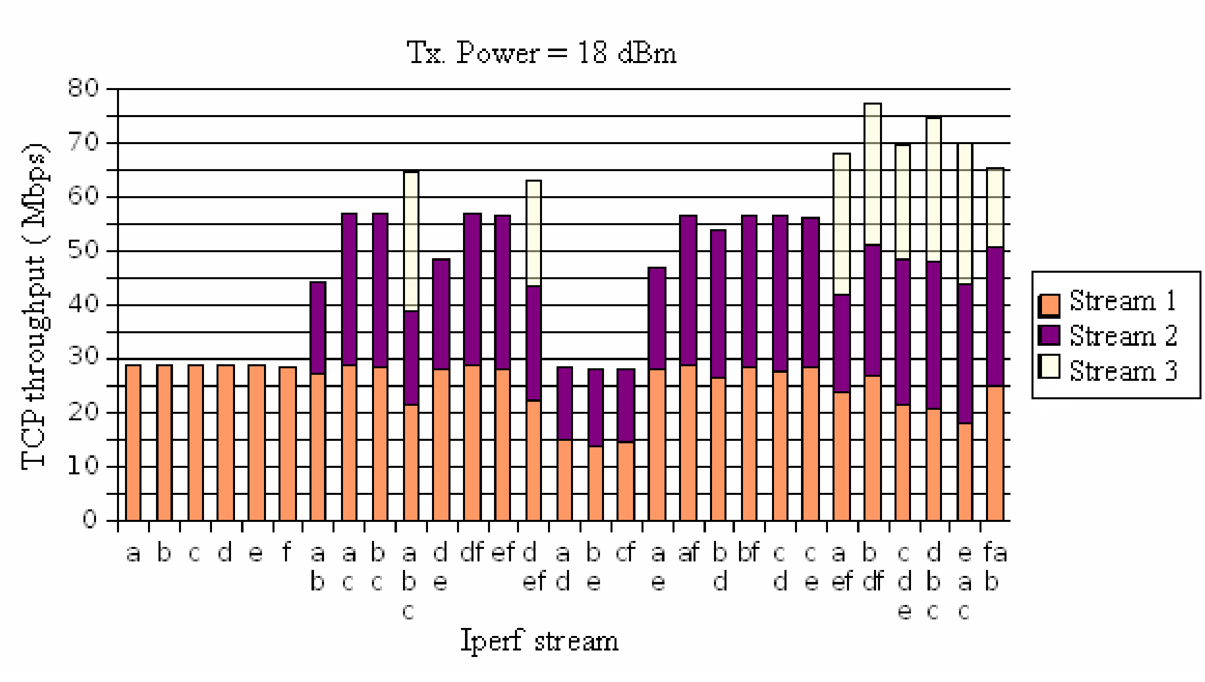


Figure 6.3: TCP throughput with 18 dBm transmission power.

Conclusion

- At low power (0 dBm), no interference for dual radio, minor interference in some cases when all three radios are used in parallel.
- At high power (18 dBm), minor interference for dual radio, a bit more interference for three radios.
- In all cases a clear gain when more radios are used (2 radios > 1 radio and 3 radios > 2 radios).
- So, although some interference is clear, the internal interference between NIC's is not the major cause of multi-radio interference.

6.2.2 The Effect of Antenna Separation

In this part we have the same configuration as figure 6.1, two nodes with three antennas connected to each node. The goal is to evaluate interference between NIC's with different amount of antenna separation. Figure 6.4 depicts the amount of changes in TCP throughput while increasing the antenna separation.

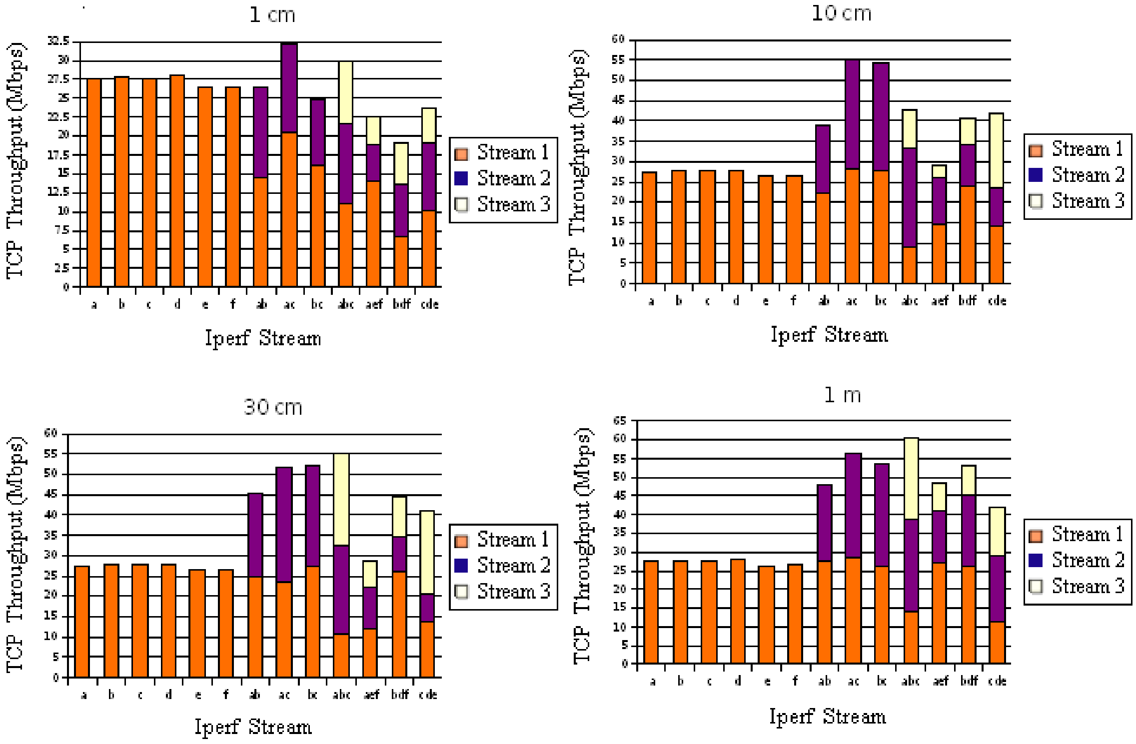


Figure 6.4:Amount of changes in TCP throughput while increasing the antenna separation

Conclusion

- When the distance between the antennas of one node is sufficient (more than 30 cm), there is a clear gain when using 2 radios (the first stream is not influenced, the second varies from 80-100% of maximum throughput).
- Using three radios causes all three streams to drop, cumulative throughput is lower compared to the two-radio case.

6.2.3 "Long Distance" Multi-Radio Test

At short distances multi-radio has clear benefits, although there is clearly some interference. Some tests were performed with two multi-radio Figo nodes further apart to test the influence of interference on "bad" links. Figure 6.5 shows the node placement for this test.

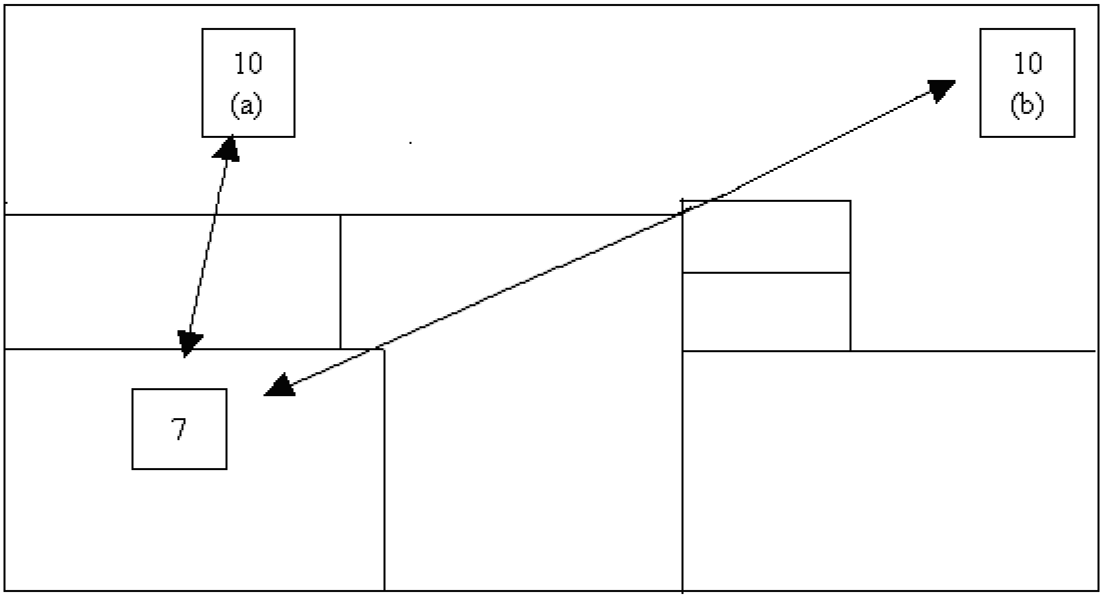


Figure 6.5: Node placement for 'long distance' test

It should be noted that this experiment has done in indoor environment with two Figo nodes, in setup a, the distance between 2 nodes is 10 meter and in setup b, the distance between two Figo nodes is 20 meter.

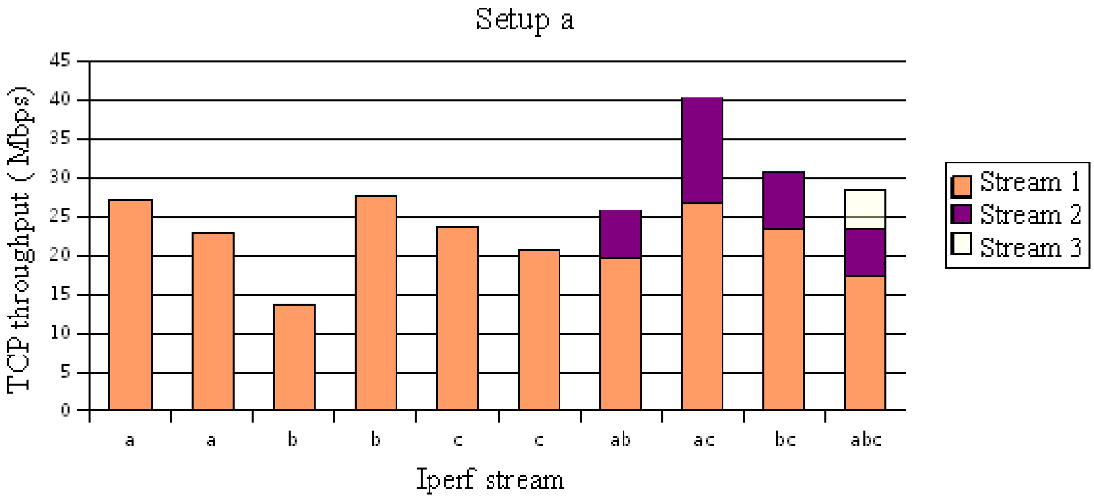


Figure 6.6: Setup a.

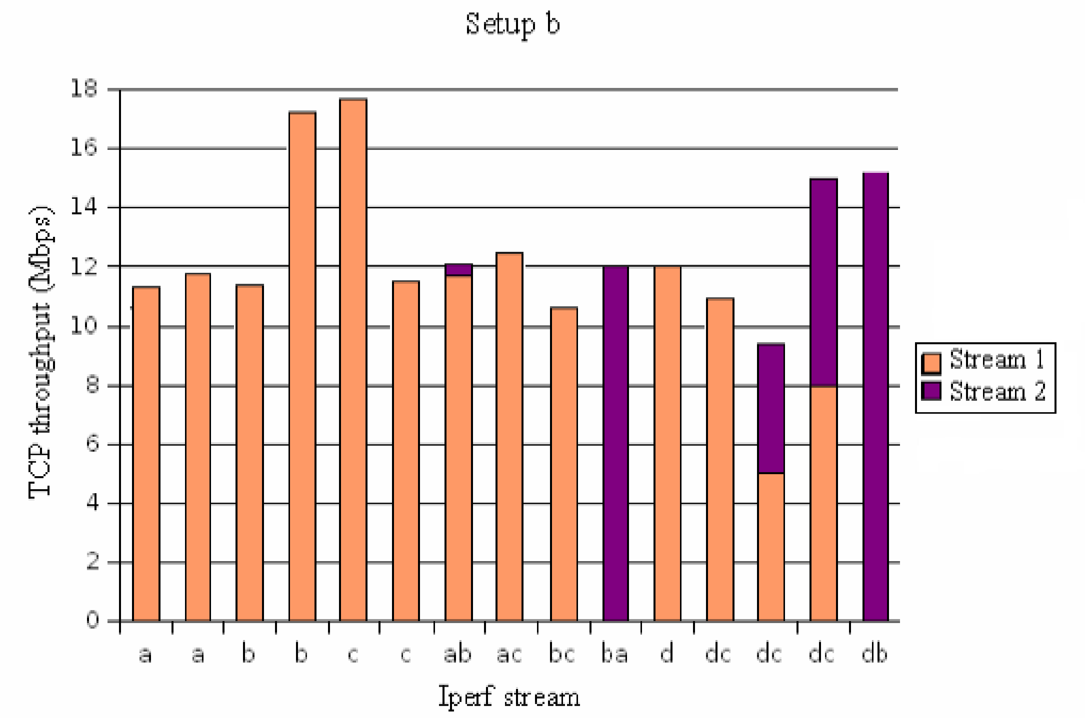


Figure 6.7: Setup b.

Conclusion

- At medium distance (single stream throughput still > 20 Mbps), there is still a benefit when using two radios (first stream does not drop, second stream reaches 20-50% of maximum throughput).
- When using three radios at medium distance, the throughput of all streams drop to a few Mbps. Cumulative throughput is only slightly higher compared to the one radio case and less than the two radio case.
- At long distance, in most cases, the link that was first active causes too much interference for the other link to achieve more than a few kbps of throughput. In some cases, when using two radios, cumulative throughput is lower compared to the single-radio case.

6.2.4 RSSI and PSD Measurements

In this part we analyze the multi-radio interference issue based on RSSI measurements instead of throughput. The PSD of one radio was measured to use as a reference in the analysis, see figure 6.8 for the PSD on the three default Figo channels for different Tx power. Note that the channel power ratio for these three channels is at least -50 dB.

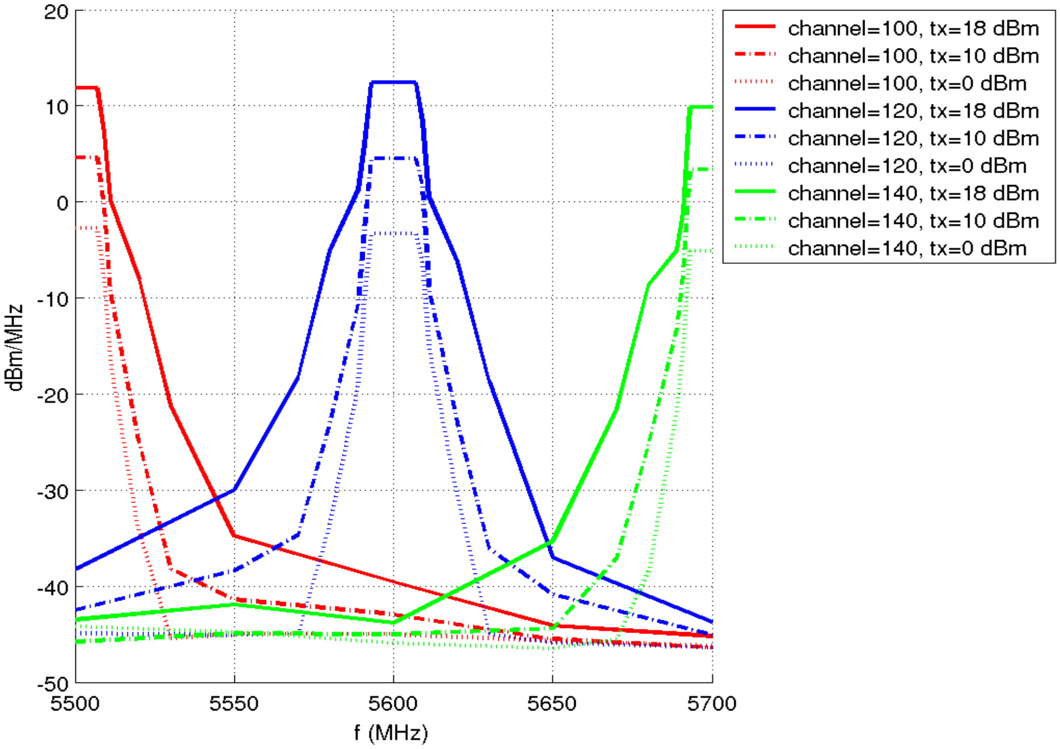


Figure 6.8: PSD of Figo node 10.

6.2.5 Adjacent Channel Interference Analysis

The goal of this part is to analyze the adjacent channel interference caused on parallel links when sending. The following setup is used:

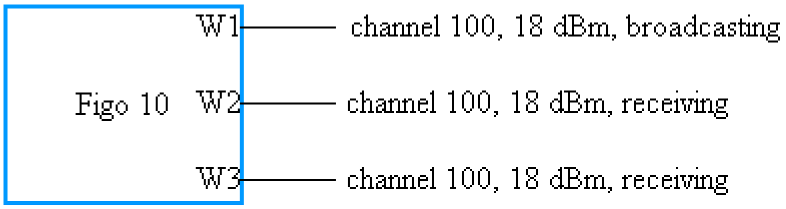


Figure 6.9: Test Setup.

A broadcast ping is sending on interface W1 at maximum power (18 dBm). The other two interfaces (W2, W3) are tuned to the same channel to be able to measure the RSSI of packets from W1. The experiment has been repeated with either W2 or W3 broadcasting, with various antenna separations. The results are shown in the figure 6.10. The colors in figure 6.10 show which interface is broadcasting, as an example W1-W2 means that W1 is broadcasting and RSSI is measured on W2.

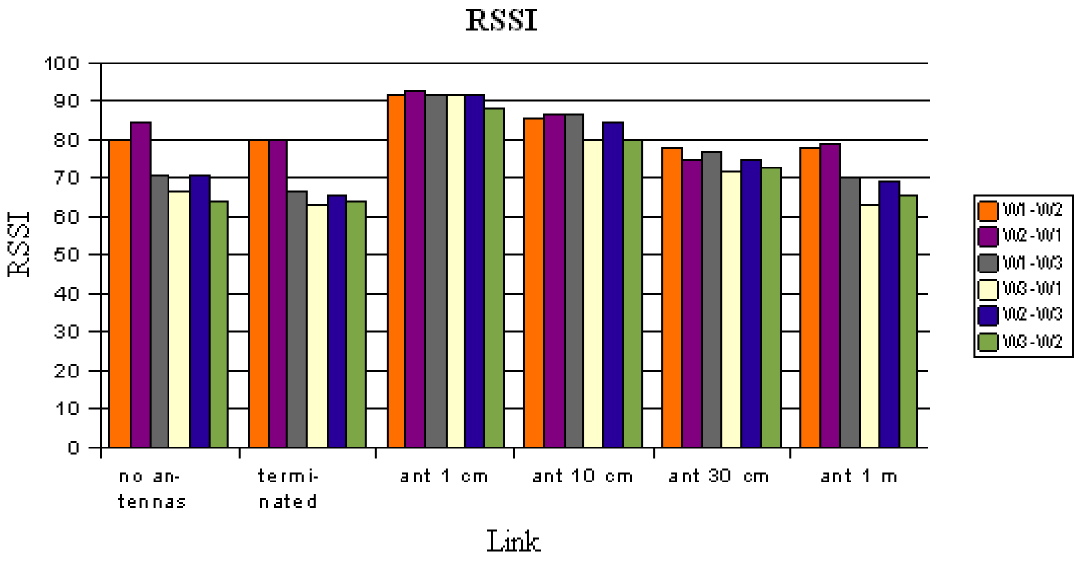


Figure 6.10: RSSI results.

When combining these results with the measured PSD of the radio cards that are used, the RSSI at interfaces due to a transmitting interface on the same node can be estimated:

When either W1 & W3 or W2 & W3 are used:

- Max. RSSI at the same channel with good antenna placement is 70
- Isolation between channels is 50 dB
- Max. RSSI perceived at other interfaces is 70 – 50 = 20 (corresponds to -75 dBm)

AS a result of the primer tests we see the drop in throughput while using simultaneous links. In order to become more precise we are going to do the second part of the measurements in next parts.

6.3 Performance Metrics

In this part of the experiments we characterize the interference observed between non-overlapping channels based on the following three metrics:
Throughput: The amount of data excluding the protocol headers (payload) received successfully at the receiver per second.
Packet loss: The difference between the number of packet sent by the transmitter and the number of packets successfully received at the receiver.
Round Trip Time (RTT): it is a measure of the time it takes for a packet to travel across a network and send back the Ack.
The values of throughput, packet loss and RTT are determined using Iperf. We believe that throughout value calculated by Iperf, can be treated as a fairly accurate measure of the raw wireless link capacity, as in the absence of RTS/ CTS mechanism, the protocol header is a small fraction of the actual traffic.
We measured the effect on the above mentioned metrics by varying the following three factors: antenna separation, transmit power, packet size. Antenna separation between the two transmitting radios and type of the antennas are varied. Packet size of the UDP traffic is varied from very small to very large values of data payload. The experiments are repeated ten times in an indoor area, with approximately similar results.

6.3.1 Experimental Setup

The experiments are conducted with three Figo nodes. The Figo nodes are arranged in a topology which is shown in figure 6.11. Each Figo is positioned 1 meter from each other. They are placed 70 cm above the ground and within line of sight of each other. The experiments are conducted in an indoor area. There are two flows set up. Each flow is monitored using Jperf.
Iperf is used to generate TCP, UDP packets at a desired rate and to measure the throughput, packet loss and Round Trip Time.
The purpose of these measurements is to report the result of varying the TCP window size, UDP bandwidth, round trip time, transmission power and antenna gain on multi-radio throughput and analyze the effect of adjacent channel interference.

6.3.2 The Effect of TCP Widow Size

Firstly we are going to evaluate the effect of changing the TCP window size on throughput. Test set up is shown in figure 6.11 .Tests run with single Iperf sessions.

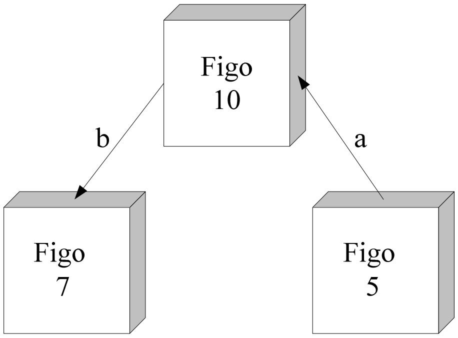


Figure 6.11: Test setup.

	Channel (b)	Channel(a)
I	100	100
II	140	100

Table 6.2: Channel Configuration

In this test, we evaluate the effect of changing the window size in two scenarios (I, II). In scenario I, the middle node (Figo 10) has 2 radios in a common channel (100) and in scenario II, 2 radios work on two separate channels (100-140).
As a result, the throughput can achieve to a higher rate with bigger window size in more cases but it does not show a huge difference when 2 radios are in a same channel. The effect of bigger window size is more effective when the radios work on different channel.

6.3.3 The Effect of UDP Bandwidth

In this experiment the effect of changing the UDP bandwidth on throughput is evaluated. In this test the same set up (figure 6.11) is applied. The experiment has been done for the same two scenarios to evaluate the effect of changing the UDP bandwidth when 2 radios work on same and different channels.
With increasing the UDP bandwidth the throughput can achieve to the higher rate.

As the experiments of changing the TCP window size and UDP bandwidth did not have any added value to our previous experiments, the detailed results and graphs are appended in the Appendix C and are not explained here.

6.3.4 RTT Measurements

The effect of changing channel separation on Round Trip Time (RTT) is discussed in this part. Test set up is shown in figure 6.12.

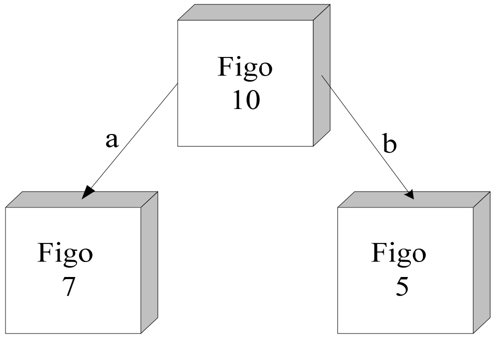


Figure 6.12: Test setup.

	Channel (a)	Channel (b)
I	100	-
II	-	104, 108, 112, 116, 120, 124, 140
III	100	104, 108, 112, 116, 120, 124, 140

Table 6.3: Channel Configuration

The experiments are conducted in an incremental fashion, first taking measurements individually for flow *a* and flow *b (single flow)*, followed by the case when both the flows operate on a common channel *(2 flows on same channel)* and finally when both operate on two non-overlapping channels *(2 flows on different channel)*. This is done to evaluate the advantages of using multiple channels on multiple radios over the use of a single channel, as a function of packet size.

In this experiment, firstly the measurement of RTT is applied when the middle node (Figo 10) pings to Figo7 on channel 100, secondly when the middle node pings to Figo5 in different channels of 100,104,108,112,116,120,124 &140, finally when the middle node pings to Figo5 and 7 simultaneously. (Table 6.3)

Figure 6.13 depicts the effect of channel separation between radios on RTT. It shows the amount of increment in RTT when 2 radios ping simultaneously.

In this experiment the packet size is 1000. Figure 6.14 shows the same scenario when the packet size is increased to 1500.

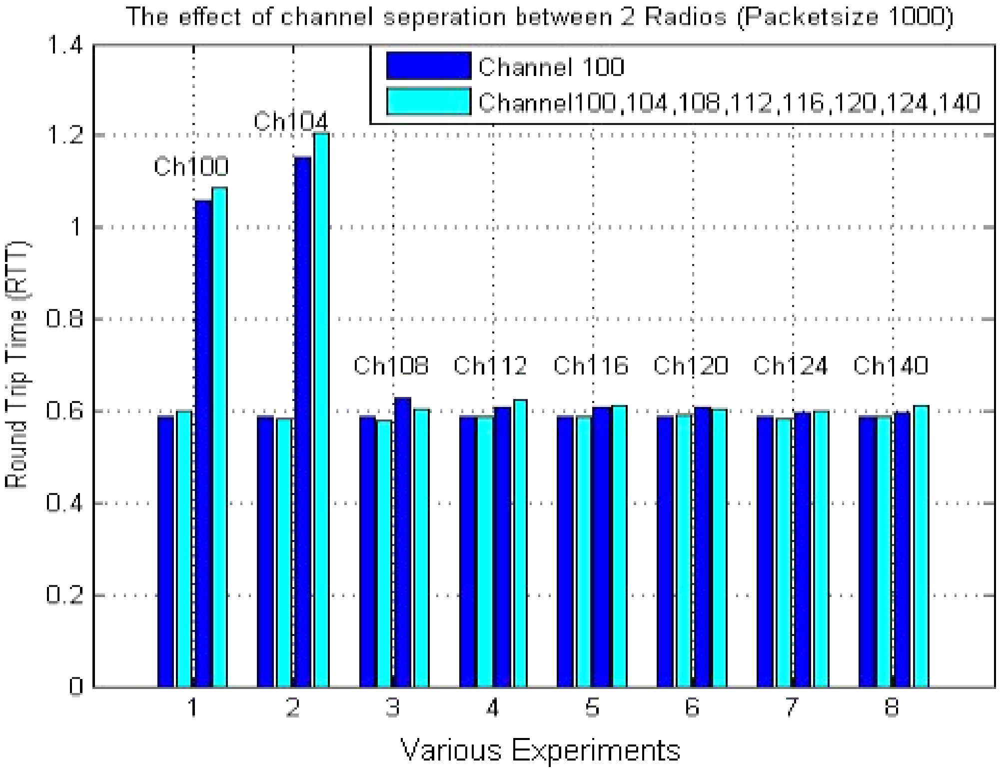


Figure 6.13: The effect of channel separation between radios on RTT.

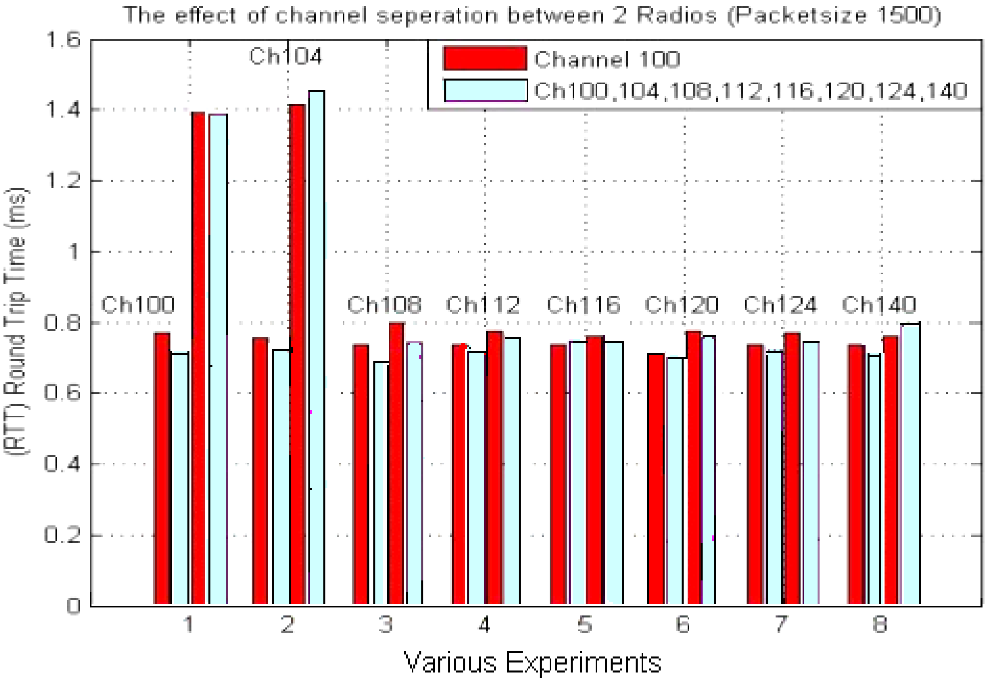


Figure 6.14: The effect of channel separation between radios on RTT.

As we saw in figures 6.13 and 6.14, various experiments have been done and the results are shown in 2 bar graphs. To become more clear and as an example the second set of 4 bars in figure 6.13 will be explained.

. The first bar shows the value of RTT between Figo 7 and 10 when *link a* is active on channel 100.

. The second bar shows the value of RTT between Figo 5 and 10 when *link b* is active on channel 104.

. The third bar shows the value of RTT between Figo 7 and 10 when *link a* is active on channel 100 and simultaneously *link b* is active on channel 104.

. Finally the forth bar shows the value of RTT between Figo 5 and 10 when *link a* is active on channel 100 and simultaneously *link b* is active on channel 104.

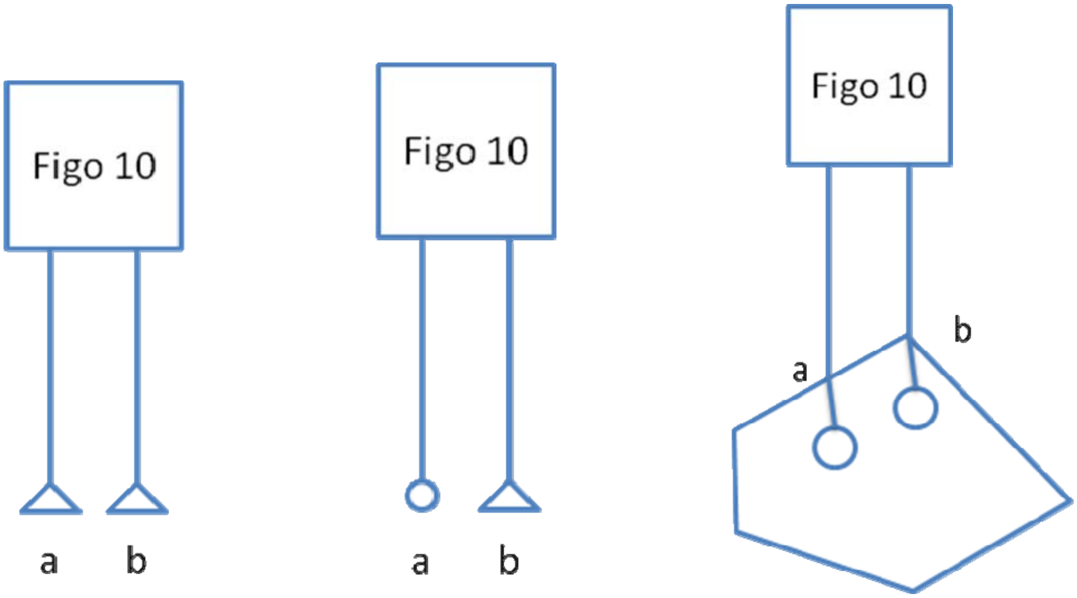
The same procedures are done for different channels.

Conclusion

The results of these experiments are depicted in figures 6.13, 6.14. As it represents, when 2 radios are in a same channel or first adjacent channel, comparing separate and simultaneous ping shows a large difference in RTT, also the effect is more when packet size is bigger. Moreover when the separation between radios increases more, RTT does not affect much.

6.3.5 Transmission Power and Antenna Gain

Via this experiment the effect of changing the transmission power and antenna gain on throughput is evaluated. The maximum allowable output power as measured in accordance with practices specified by the regulatory bodies of ETSI. In Europe, the Equivalent Isotropically Radiated Power (EIRP) should not be more than 1000mW (30dbm). It is more efficient to use less transmission power but on the other hand more ranges can achieve with more transmission power. This experiment represents how Received Signal Strength Indication (RSSI) can changes with changing the amount of antenna gain and transmission power with having the same EIRP.



(a) (b) (c)

Figure 6.15: Using a)2 dipole ant. b)1 dipole ant. & terminates other c)5 GHz ant.

As it is shown in figure 6.15 three scenarios is applied in this experiment. In all three scenarios 'radio b' broadcast the data and 'radio a' is used to measure the RSSI. In first scenario both radios use dipole antenna in second one 1 radio uses dipole antenna and other radio is terminated and finally in third scenario both radios use 5 GHz antenna.

Figure 6.16 represents the Received Signal Strength Indication (RSSI) in these three scenarios.

It should be noted that in this experiment as we increase the transmission power we reduce the amount of antenna gain, in order to have same EIRP in all different parts.

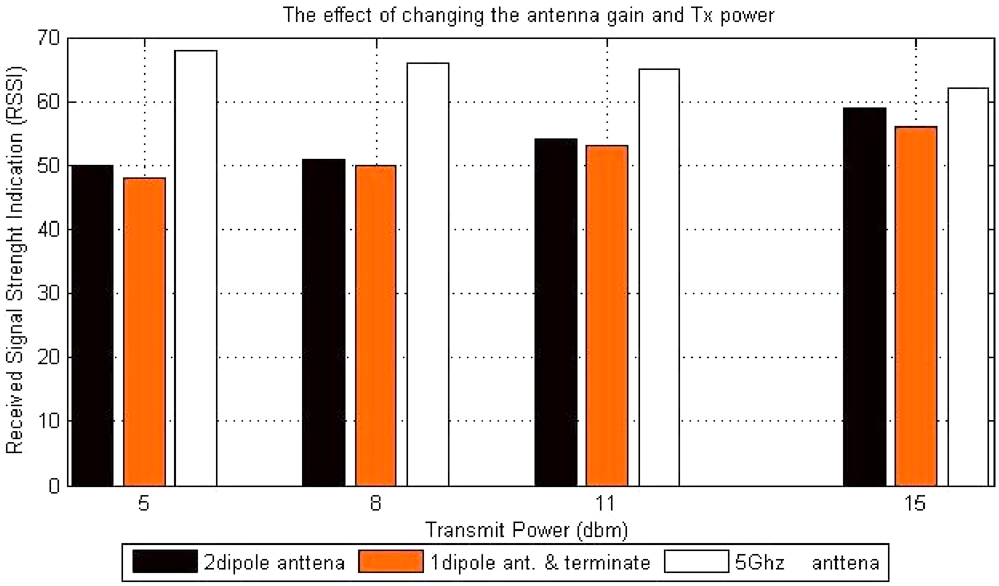


Figure 6.16: The effect of changing the Transmission power and antenna gain.

Conclusion

When 2 dipole antennas are applied, with increasing the transmission power and reducing the antenna gain to achieve the same amount of EIRP, the measured RSSI is increased. In order to analyze and make difference between the direct effect of connectors and effect of antenna (Figure 6.17), one radio is terminated (Figure 6.15 (b)) and same measurement of RSSI are applied. As figure 6.16 shows with increment in transmission power the RSSI increases. So this increment of RSSI is due to the direct effect of the connectors. Finally 5 GHz antenna is applied with same procedure for measuring the RSSI. As figure 6.16 represents in this case with increasing the transmission power, RSSI is decreased. This decrement of RSSI is due to the effect of antennas.

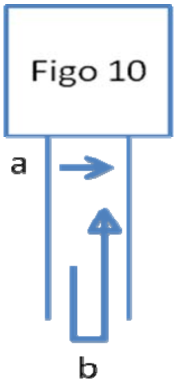


Figure 6.17: Effect of a) Connectors   b) Antennas

As a conclusion in order to reduce the amount of received RSSI, hence reduce the intra-node channel interference and have less effect on adjacent radio within a same node, it is better to use more transmission power and less antenna gain rather than less transmission power and higher antenna gain.

6.4 Conclusion

Multi-radio research for WMNs has primarily focused on theoretical concepts, with very little work done on practical implementation. It is now a common assumption that multiple independent transmissions over these channels can coexist without mutual interference. In this work we demonstrate that this assumption does not hold in general. With extensive set of experiments we illustrate the presence of adjacent channel interference between non-overlapping channels. The Intra-node adjacent channel interference problem, apart from its theoretical significance, is an important practical problem in WMNs.

During this chapter we have measured the amount of RSSI and throughput in physical interfaces, with changing various parameters such as antenna separation, number of channels and radio, transmit-power and packet size in order to consider the results. Evaluation of the results shows that in some cases, the throughput of multi-radio nodes can drop even worse than single-radio case without solving the adjacent channel interference problem.

As a conclusion of all our experiments and measurements, we should mention that due to the attained results, practical experiments validate our theoretical result that current off-the-shelf IEEE 802.11 chipsets without any special mechanism might not be ready to be integrated in a single box with few centimeters of antenna separation.

Finally with the aim of these experiments we get further insight on the problem, we have observed that in order to reduce the amount of received RSSI, hence reduce the intra-node channel interference and have less effect on adjacent radio within a same node, it is better to use more transmission power and less antenna gain rather than less transmission power and higher antenna gain.

CHAPTER 7

MULTI-RADIO SIMULATION RESULTS

7.1 Overview

In traditional wireless mesh networks where all nodes communicate through the same channel the performance can be strongly impaired by mutual interference and contention. It seems that the network performance can be improved by using multiple orthogonal channels and equipping each node with multiple radio devices, e.g. IEEE 802.11 network interface cards. In order to investigate how the main design parameters such as the number of channels and radios affect the capacity, estimate the performance gain that can be achieved under various parameter settings and evaluate the effect of adjacent channel interference, a simulation model was developed and implemented in a Java simulation program in TI-WMC Company. This simulation program is used to gain insight in the behavior of multi-radio multi-channel networks, especially at the lower layers, and to investigate how the potential performance gain of multiple channels depends on different factors such as the number of radios per node and the number of channels used, etc. The key performance measure that is evaluated in the simulator is the average number of simultaneous successful point-to point transmissions in the network. To evaluate this performance measure, the simulation model focuses on the link-layer and physical layer aspects. To keep the simulator not too complex, it abstracts from the details of MAC management; as an example re-transmissions are not included in the simulation model. A simulation is started with a predefined rectangular area. Each node has the same number of radio interfaces with the same transmission power. This simulator takes into account 50 dB isolation between radios within one node.

To each of a node's interfaces a channel will be assigned by some algorithm; this can be done at initialization time, but also during the simulation. Assuming omni directional antennas, the radio path loss between all pairs of nodes is computed according to a simple radio propagation model on the basis of their distances; the received signal power is proportional to $r^{-\gamma}$ when r is the distance between transmitter and receiver (we use γ = 2.5). Based on path loss, the transmission powers, and the channel selection of the nodes, links are identified between the nodes.

One parameter of this simulator is load parameter which can change the amount of injected traffic. If this parameter is equal to 0.5, the probability of having or do not having data to send is equal to 50% in each interface. The average number of successful simultaneous transmissions in the whole network is a good indicator of the network capacity. It is not a realistic capacity figure in terms of absolute values in Mbit/s.

If the transmission is not allowed because of the contention rules, the transmission on this link is marked as *blocked.*

During the simulation the network performance such as the absolute and current (running average of) number of correctly received transmissions, the transmission errors and the blocked (deferred) transmissions as a fraction of all transmission attempts are available.

As we discussed earlier, using different channels enables multiple concurrent error-free transmissions to take place in the same region but it also introduces new challenges like adjacent channel interference and connectivity issue.
It should be noted that although simulation results give more insights about the problem, especially when due to number of node and radio implementation is costly, it is not wise enough to have only simulation-based investigations.

7.2 Purpose

The purpose of these simulations is to report the effect of changing the number of channels on throughput and connectivity ratio, also evaluate the effect of changing the transmission power on throughput and consider the amount of errors at receiver and acknowledgment error. Considering these parameters give more insights about adjacent channel interference.

7.3 20 Nodes Scenario

In this simulation, 20 nodes are applied in size area of 1000×714 meters. As it will be mentioned in following parts the RTS/CTS is on and off.

7.3.1 Multi-Radio

The goal of this part is to evaluate the effect of changing the number of channels on connectivity Ratio. The uses of different channels introduce a connectivity issues. If nodes do not share a common channel, they have no connection.

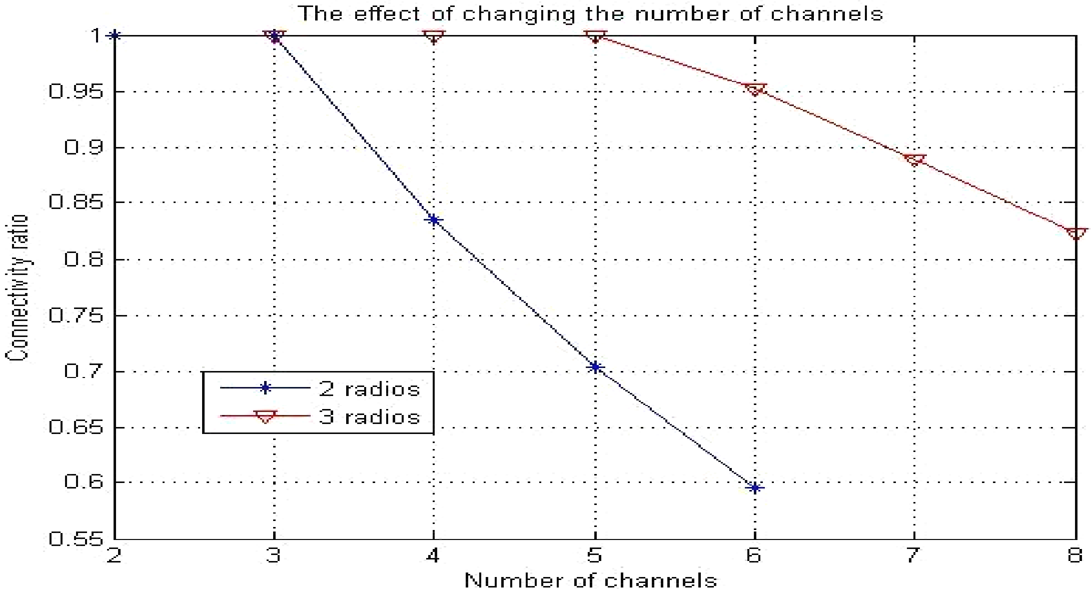


Figure 7.1: The effect of changing the number of channels on connectivity.

The design of a multi-channel wireless mesh network involves taking precautions to avoid loss of connectivity. As it represents in figure 7.1 when the number of channels increases, the connectivity ratio decreases. As a consequence, in order to achieve more throughputs it is better to use more channels but connectivity issues should be taken into account.

7.3.2 The Influence of Number of Channels and Radios

The effect of changing the number of channels on throughput is depicted in this part. As it shows in figure 7.2 the amount of throughput increases when the number of channels increases, it also shows the effect of RTS/CTS.

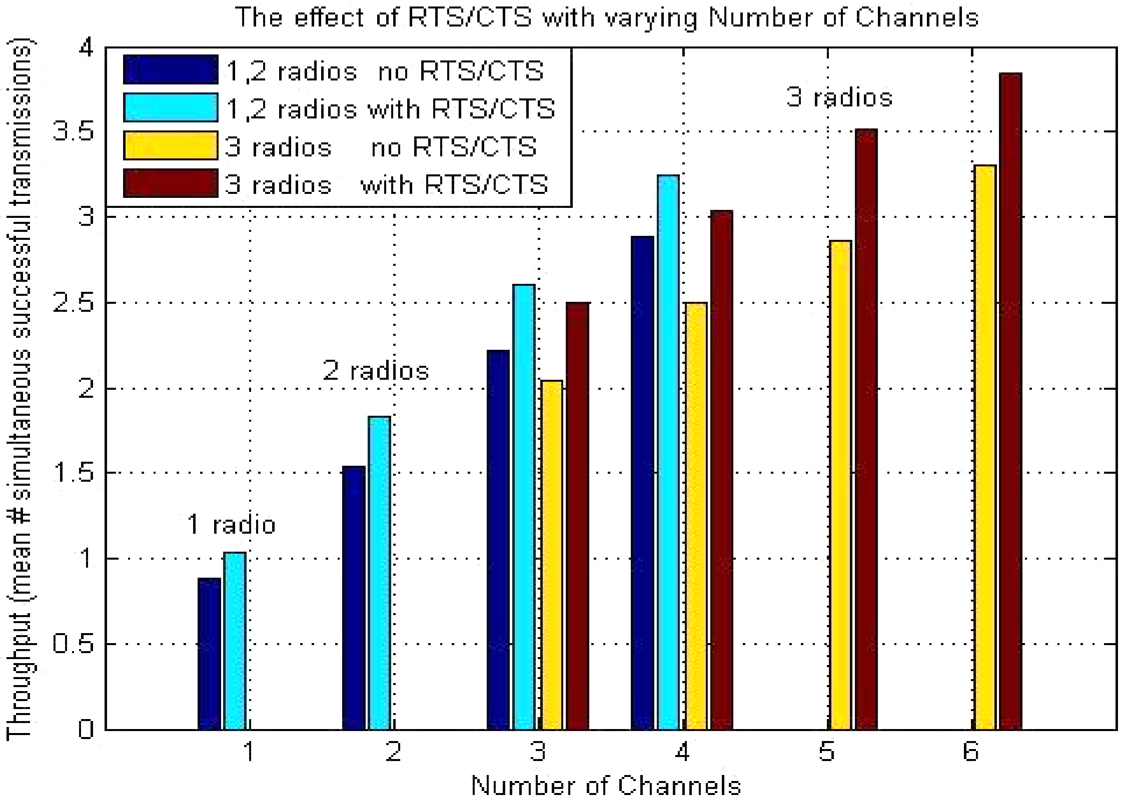


Figure 7.2: The effect of changing the number of channels on throughput.

One can theoritically expected that when the number of channels doubled the throughput should doubled but as it depicts in figure 7.2 it doesnot happen. This results show that interfaces within one node do not work independently. As we consider the amount of collision (error) in the receiver, acknowledgement error and blocked links, we can undrestand that the transmission pattern of one radio has effect on the other radio.

7.3.3 The Influence of Transmission Power

In this part we evaluate the effect of transmission power on throughput. Figure 7.3 shows how the transmission power affects the throughput. When the transmission power is too low, there will be little or no connectivity in the network; because there are no links, there will be no successful transmissions and no throughput. When the transmission power is increased, the number of links will grow as more nodes get within each other's transmission range and the throughput increases as well. When the power is increased further, the throughput declines again, as more and more nodes will get within each other's interference range, and links will increasingly block or interfere with each other's transmissions. Furthermore the effect of adjacent channel interference is more due to more amount of leaked power from one interface to adjacent interface within one node.

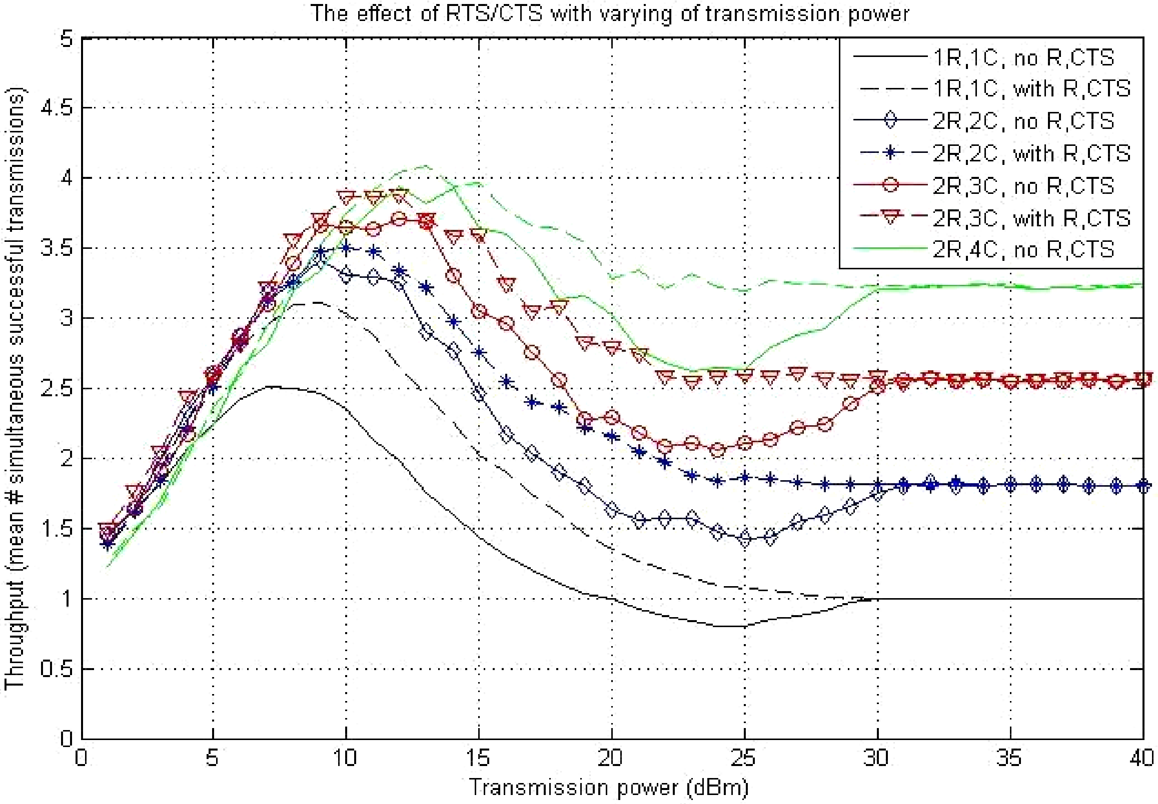


Figure 7.3: The effect of RTS/CTS with varying of Tx power on throughput.

7.3.4 Receiver Error

The effect of varying the transmission power on receiver error (collision) is depicted in this part. When the transmission power is too low, there will be no connectivity. While the transmission power is increased, more nodes get within each other's transmission range and more errors occur. Further increment of transmission power results in more blocked links.

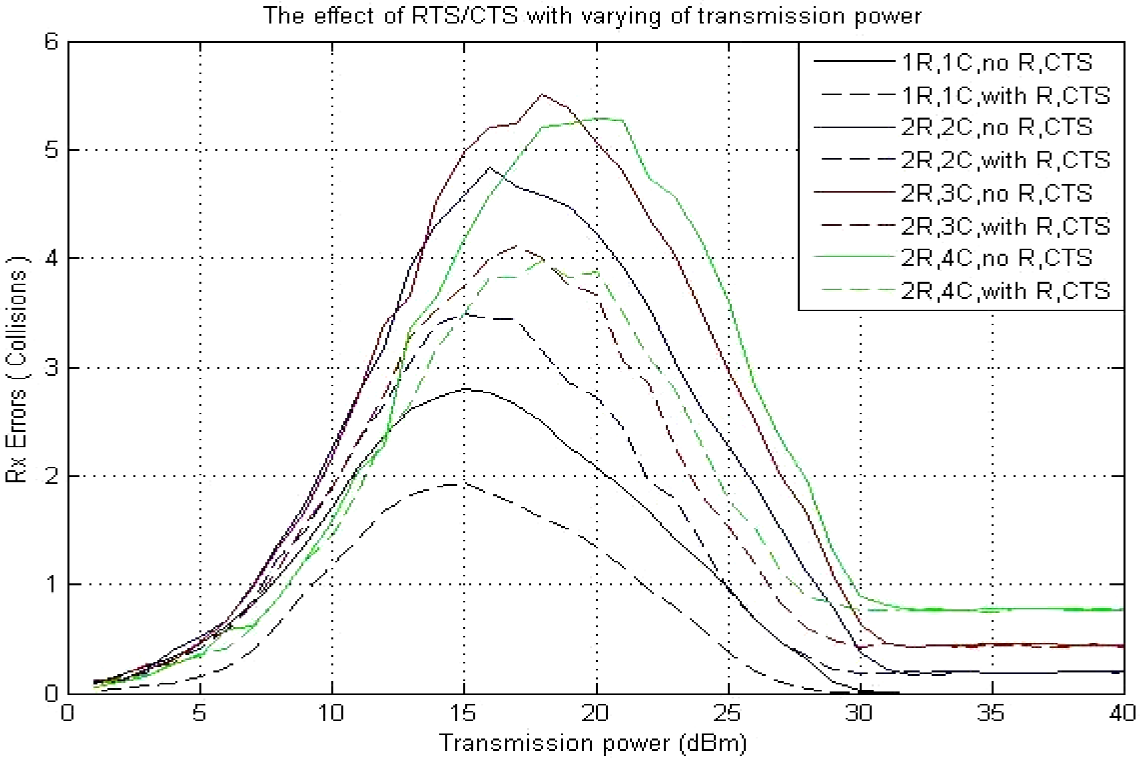


Figure 7.4: The effect of RTS/CTS with varying of Tx power on Receiver errors.

7.4 100 Nodes Scenario

7.4.1 Purpose

The purpose of this part is to represent the effect of changing the number of channels on multi-channel throughput (gain factor). Multi-channel error due to collision at the receivers and acknowledgment error are also reported. Moreover we evaluate the effect of self blocking parameter in two scenarios which 2 radios within same node can or can not send packets simultaneously.

In this simulation, 100 nodes are applied in size area of 1000 × 1430 meters. As it will be mentioned in following parts the RTS/CTS is on and off.

7.4.2 The Effect of Self Blocking Parameter on Throughput

We are going to evaluate the effect of changing the number of channel on gain factor in two scenarios when the self blocking parameter is on and off.

The self blocking is one of the ability of studied simulator which enables nodes to work on two separate scenarios. When the self blocking parameter is on, the radios within one node can not transmit data simultaneously, so if 1 radio is transmitting the other radio is blocked to transmit. On the other hand when the self blocking parameter is off, radios within one node can transmit simultaneously. The effects of changing the number of channels on the multi-channel throughput with on and off self blocking parameter are depicted in figure 7.5, 7.6 respectively.

It should be noted that more amount of throughputs can be achieved with on self blocking parameter.

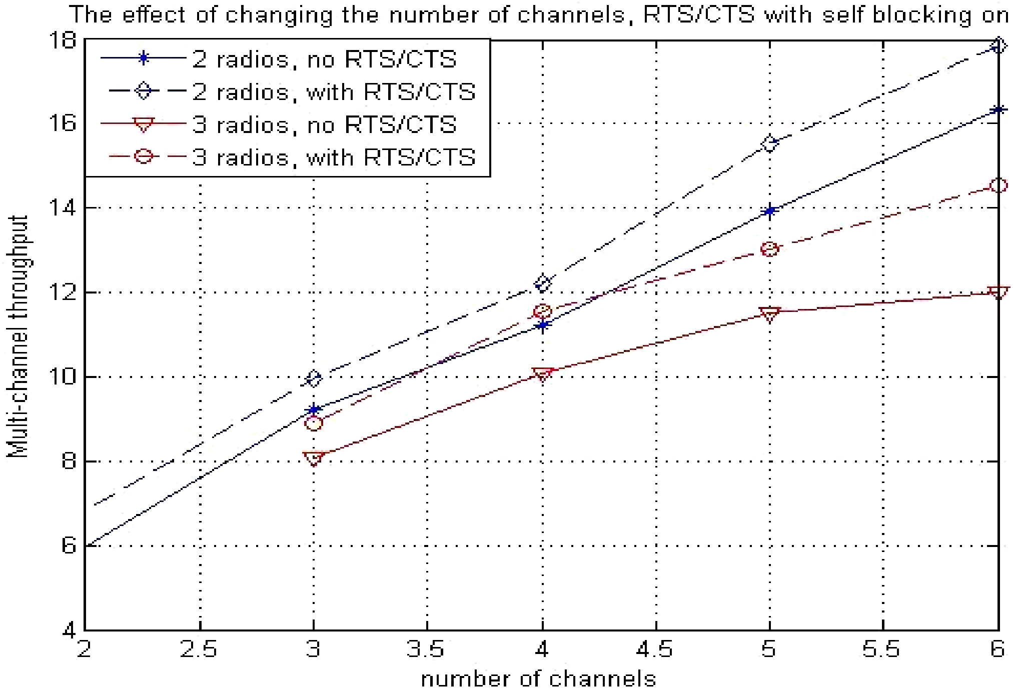


Figure 7.5: The effect of the number of channels on multi-channel throughput.

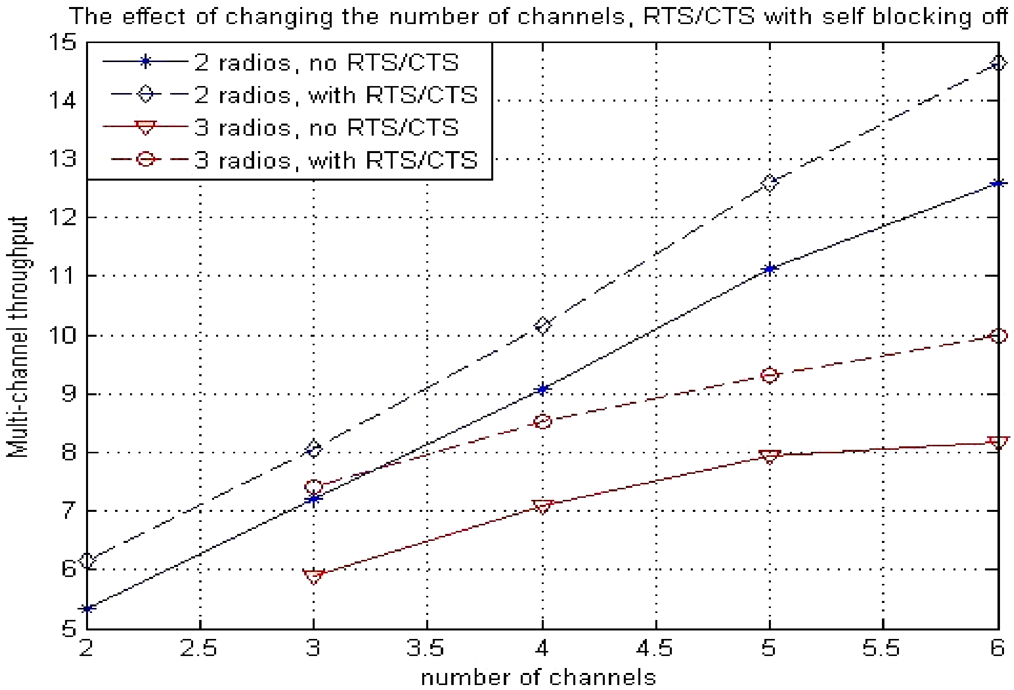


Figure 7.6: The effect of the number of channels on multi-channel throughput.

Figures 7.7, 7.8 show the average effective throughput as a function of the number of channels for 2,3 radios per node, normalized with the throughput of the single-channel equivalent as a refrence. These data can therfore ba considered as multi-channel gain factors.

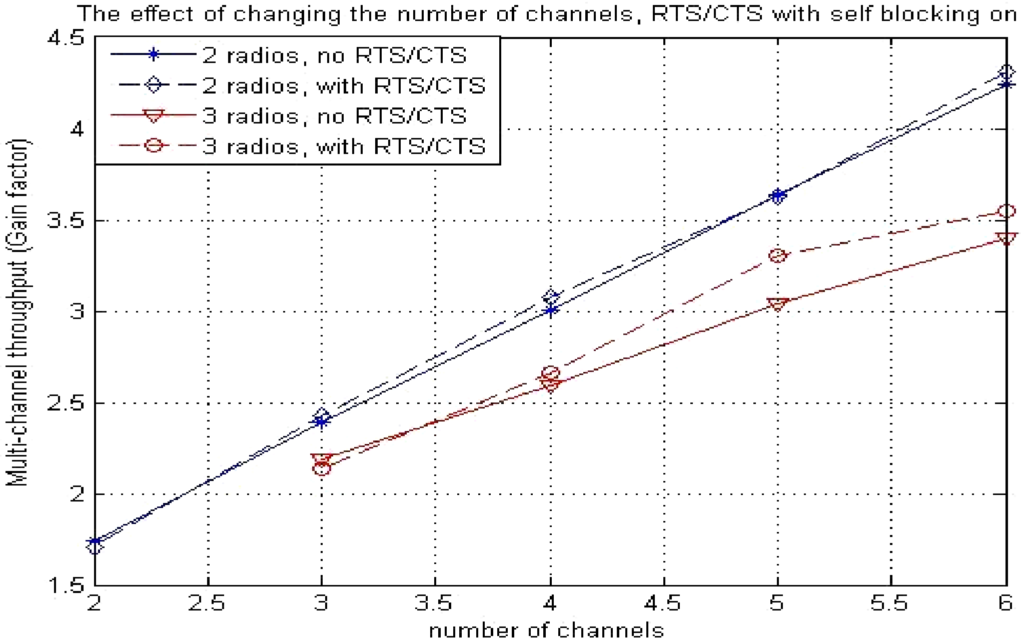


Figure7.7: The effect of changing the number of channels on gain factor.

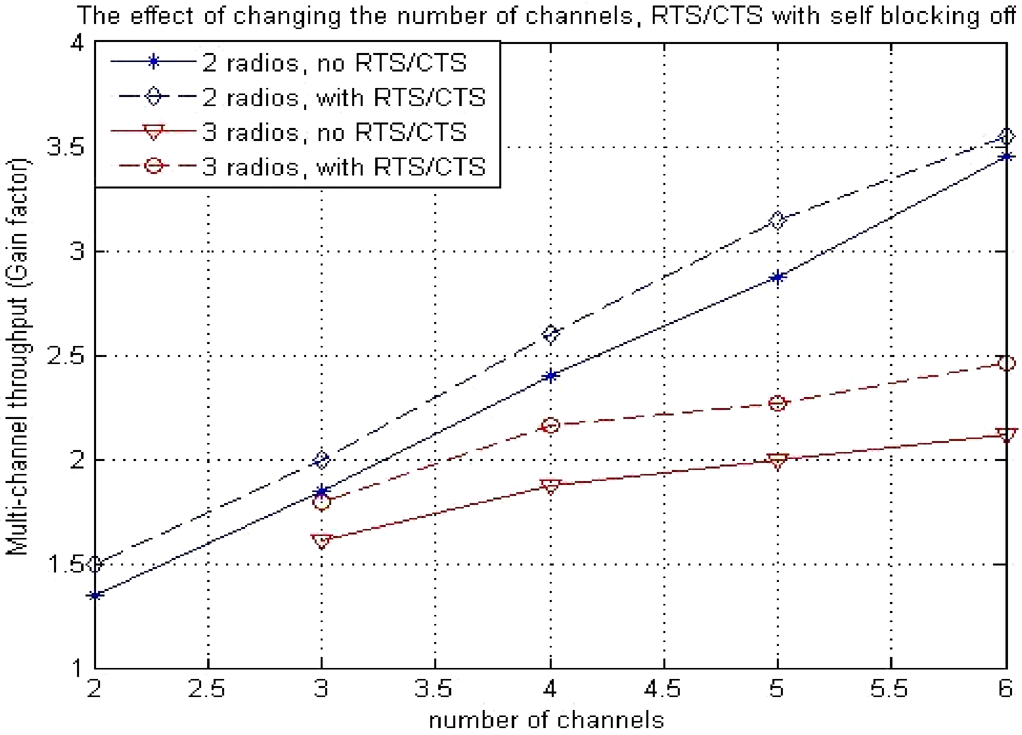


Figure 7.8: The effect of changing the number of channels on gain factor.

7.4.3 The Effect of Simultaneous Transmission on Reciver Error and Ack Error

The self blocking parameter has been introduced in pervious part. To become more accurate we are going to describe the effect of this parameter on receiver and Ack error. If the self blocking parameter is on, the second radio within a node is blocked to transmit while the first radio is transmitting. Now we discuss what happens if the self blocking is off. As we know the IEEE 802.11 is a CSMA protocol which follows the listen-before talk paradigm. It means that a radio is only allowed to transmit if the medium is idle. However due to adjacent channel interference, may carrier sensing mechanism reports the medium is busy for the second radio while the first radio is transmitting. In this case the second radio will misleadingly defer its transmission. On the other hand due to the amount of received interference from the adjacent interface and the threshold of clear channel assessment mechanism, may carrier sensing reports that the channel is idle so the second radio starts transmission while also the first radio is transmitting. In this case transmitting data in one radio may collide with the received Ack of the other radio, so due to the lost Ack the sender starts re-transmission and may same mechanism happens for many times. As a result the throughput decreases from which we expected.

Figures 7.9 and 7.10 depict the receiver error when the self blocking parameter is on and off respectively. Receiver error is due to the collision of packets at the receiver. These two figures show more amount of error when the self blocking parameter is off, as expected.

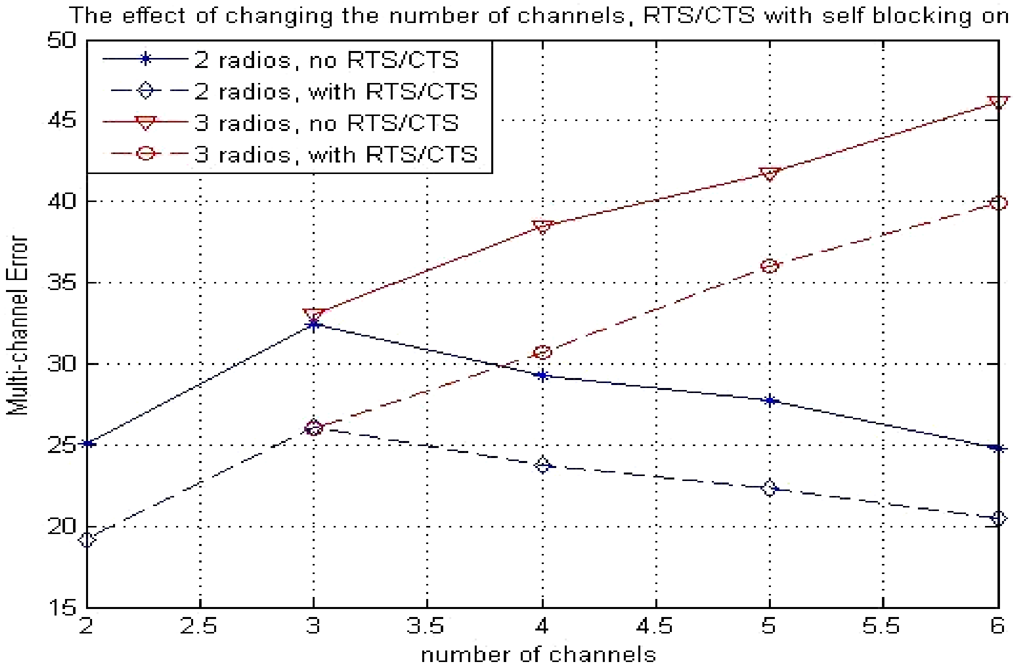


Figure 7.9: The effect of changing the number of channels on multi-channel Rx Error.

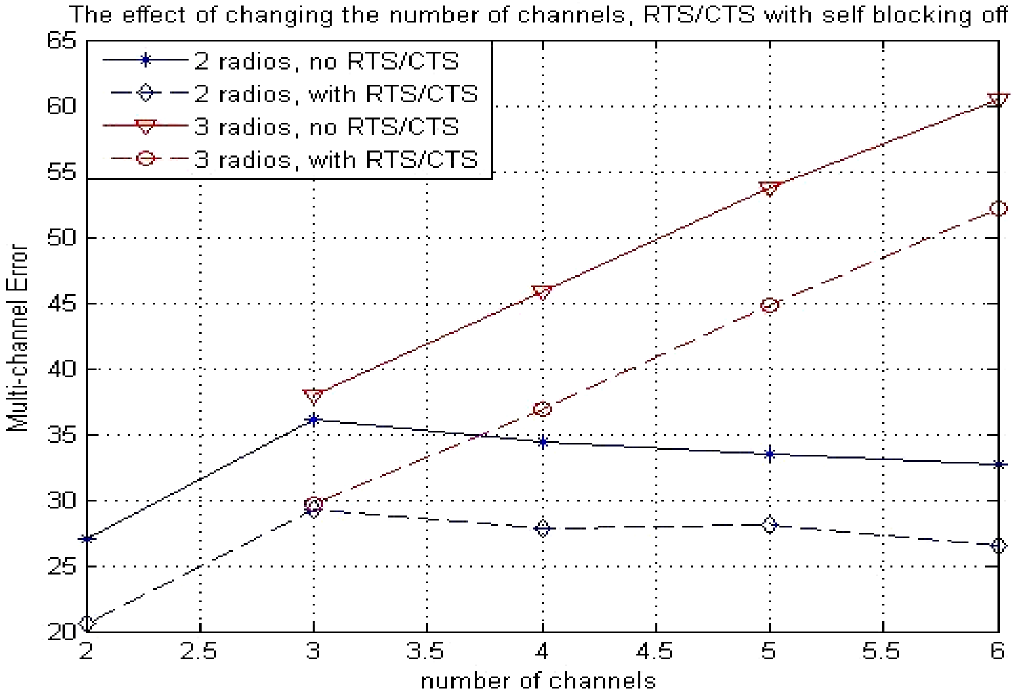


Figure 7.10: The effect of changing the number of channels on multi-channel Rx Error.

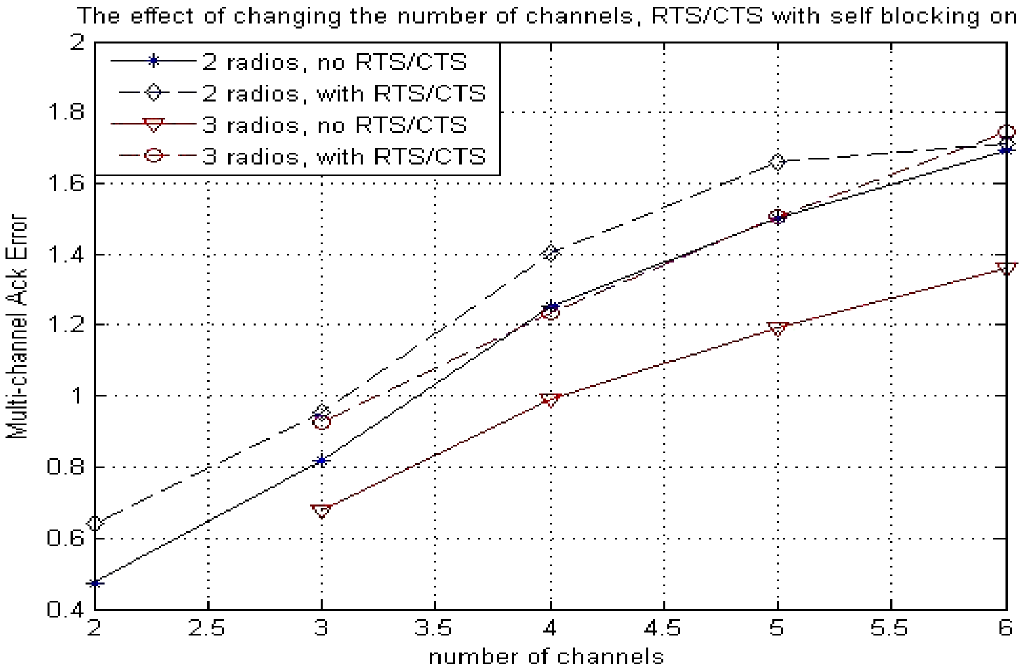


Figure 7.11: The effect of the number of channels on multi-channel Ack Error.

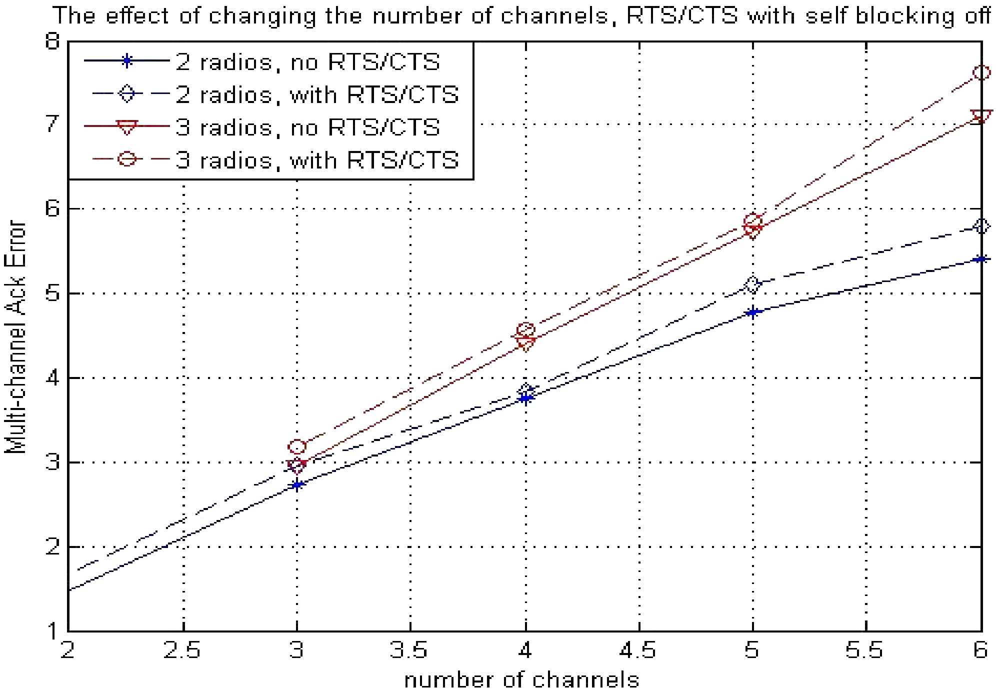


Figure 7.12: The effect of the number of channels on multi-channel Ack Error.

Figures 7.11 and 7.12 represent the mount of Ack error due to lost Ack. Also comparing these two figures with on and off self blocking parameter, it shows that the more amount of Ack error happens when the self blocking is off.

It should also be noted that in order to avoiding too much complexity re-transmissions are not included in the simulation model, so the real amount of error is more than what we have here.

7.5 Conclusion

Many researchers consider the amount of improvement in throughput gain that they can achieve while using multi-radio nodes excluding the effect of adjacent channel interference (ACI). They have achieved a high gain via simulation and theoretical works.

During this chapter a java-based simulator is used to gain more insight in the behavior of multi-radio multi-channel networks. As this simulator takes into account 50 dB isolation between radios within one node, so radios do not work independently and transmission on one radio has effects on the other radio.

Different simulations for various scenarios have been done to report the effects of changing the number of channels, radios and transmission power on throughput. Considering the attained results, the amount of errors at receiver (collision) and acknowledgment error gave us more insights about adjacent channel interference issue.

One of the useful parameter of this simulator in order to model the adjacent channel interference is the self blocking parameter. Considering the effect of this parameter on receiver error (collision) and Ack error which are compatible with our practical measurements, show that the presence of adjacent channel interference can not be neglected in the context of multi-channel multi-radio WMNs.

A radio is allowed to transmit if the medium is idle. As we learned from analysis of ACI, due to adjacent channel interference, may carrier sensing mechanism reports the medium is busy for the second radio while the first radio is transmitting. In this case the second radio will misleadingly defer its transmission. On the other hand due to the amount of received interference from the adjacent interface and the threshold of clear channel assessment mechanism, may carrier sensing reports that the channel is idle so the second radio starts transmission while also the first radio is transmitting. In this case transmitting data in one radio may collide with the received Ack of the other radio, so due to the lost Ack the sender starts retransmission and may same mechanism happens for many times. As a result the throughput decreases from which we expected. Compatible with analysis**,** the attained results of simulation also show more amount of error and Ack error when the self blocking parameter is off, as expected.

CHAPTER 8

CONCLUSIONS OF ANALYSIS PART

As we mentioned before, we have investigated analysis part in chapters 5, 6 and 7. In chapter 5 which is the adjacent channel interference (ACI) chapter, we have analyzed the effect of ACI between non overlapping channels in IEEE 802.11. We have learned that the presence of adjacent channel interference can not be neglected in the context of multi-channel multi-radio WMNs due to the near-far effect, since simultaneous transmission and reception take place at nodes. In fact the notion of “non-overlapping channels” has been misleading, driving some researchers to erroneous assumption of full decoupling between these channels, thus ignoring the ACI effects. Due to the physical proximity, it is critical to investigate the ACI of devices that have multiple interfaces that are operating in parallel on different channels .The inability of the MAC layer to handle adjacent channel interference can have dramatic effects on the throughput. Such findings point to a fundamental problem in using current IEEE 802.11 standard for multi-channel multi-radio mesh networks. We conclude that the implicit assumption that the multiple radios within one node, operate independently is not appropriate.

In order to evaluate the effect of ACI more in detail, we have done some practical measurements and simulations in chapters 6, 7 respectively. In chapter 6 we mentioned that many researchers consider the amount of achievable throughput-gain while using multi-radio nodes excluding the effect of adjacent channel interference. They have achieved to a high gain via simulation and theoretical works. Therefore we have measured the amount of RSSI and throughput in physical interface, with changing various parameters such as antenna separation, number of channels and radio, transmit-power and packet size in order to consider the results. Evaluation of attained results showed that the throughput can drop even worse than single-radio case without solving the adjacent channel interference problem.

In chapter 7 we have done simulations for various scenarios to report the effects of changing the number of channels on throughput also evaluate the effect of changing the transmission power on throughput and consider the amount of errors at receiver and acknowledgment error. Considering these parameters gave us more insights about adjacent channel interference.

As a result, our experiments suggest that current off-the-shelf IEEE 802.11 chipsets without any special mechanism might not be ready to be integrated in a single box with few centimeters of antenna separation and a single channel MAC protocol does not work well in a multi-channel environment because ACI causes a large amount of decrease in throughput. Therefore, an important research challenge is to solve this problem. We believe that appropriate solutions to achieving wireless systems with high throughput need the interactions between radios within one node.

In next chapter we are going to investigate for possible solutions.

PART III SOLUTIONS

CHAPTER 9

PROPOSED SOLUTIONS

9.1 Overview

In general, wireless networks have been designed for single radio networks but as it was shown in the pervious chapters, the network performance will degrade quickly as the number of nodes increases, due to higher contention and collision. As we discussed earlier, one approach to relieving the problem is to utilize multiple radios per node but the idea of using multi-channel multi-radio raises new challenges.

As we know, the IEEE 802.11 standard allows for the use of multiple channels available at the physical layer, but its MAC protocol is designed only for a single channel. A single channel MAC protocol does not work well in a multi-channel environment. As we discussed in earlier chapters, adjacent channel interference cause a large amount of decrease in throughput. Therefore, an important research challenge is to solve this problem.

In this chapter firstly a classification of possible solutions will be discussed, we will continue with the main proposed solution and finally the proposed solution will be evaluated to consider the amount of improvement which we can gain.

9.2 Possible Solutions

In this part, in order to cope with adjacent channel interference problem, different possible solutions are discussed. It will be useful to classify these solutions in 4 separate categories.

. Using commercial of the shelf devices with no fundamental changes in the IEEE 802.11 MAC layer specifications
. Redesigning the IEEE 802.11 MAC layer
. Redesigning the IEEE 802.11 MAC layer, including changes in physical layer
. Architectural solutions

In the first category some kind of solutions are introduced which do not need any fundamental changes in existing IEEE 802.11 MAC layer so they are more efficient from designing and implementation time point of view. As we know changing the fundamental design of the MAC layer is a long term investigation which may need a couple of years for establishing new standards for IEEE 802.11 MAC layer, but for gaining more from multi-channel multi-radio networks such these solutions should also take into account. Some kind of these redesigning of IEEE 802.11 MAC layer solutions also need some modification in the physical layer, which is if not possible, very difficult from practical point of view. The last one is some architectural solutions which can be useful to solve the problem.

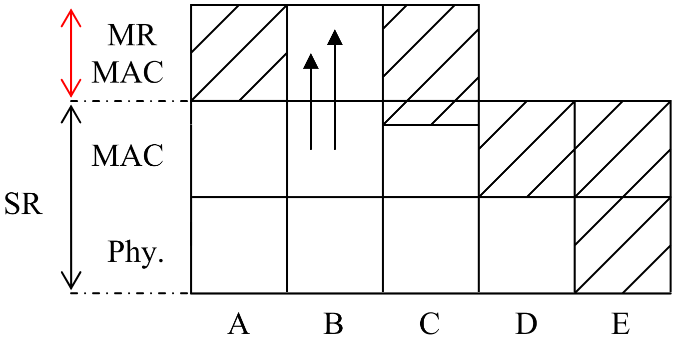


Figure 9.1: Possible MAC Solutions

As it is depicted in figure 9.1, the first category has 3 subclasses A, B and C. In the first category the physical and MAC layer of single-radio do not change fundamentally. On top of the single radio MAC, multi radio MAC is designed. In A multi-radio MAC is worked with out any interaction with single-radio MAC, while in B multi-radio MAC extracts some information from single-radio MAC, and due to these information it works more efficient. In C some small possible changes, mostly in software, happens in single-radio MAC in order to have more efficient designs for multi-radio MAC. A fundamental shortcoming of many previous attempts in multi-radio multi-channel networks is the implicit assumption that the multiple radios within one node, operate independently. We believe that suitable solutions with high throughput need the interactions between radios.
Second category which is shown as D in figure 9.1 is redesigning the IEEE 802.11 MAC layer. It is possible to change the whole MAC layer, although this approach needs a long time investigation and developing new standards but it may reach to much more improvements in performance. As we discussed in previous chapters one of the main results of degradation of throughput in multi-channel multi-radio networks is the collision of Acks with each other or with data which results in many useless retransmissions. So changing the pattern of data and Ack transmissions based on synchronized carrier sensing in both radios can be an example of this approach. The other possible solution of these redesigning is based on the fountain codes coding scheme such as Raptor codes. Such these schemes may need also some changes in the physical layer; it is illustrated as E in figure 9.1. Briefly to become more clear we consider in this part how fountain codes can be useful in order to increase the throughput.
The traditional scheme for transferring data across an erasure channel depends on continuous two-way communication.

- The sender encodes and sends a packet of information.
- The receiver attempts to decode the received packet. If it can be decoded, the receiver sends an acknowledgment back to the transmitter. Otherwise, the receiver asks the transmitter to send the packet again.
- This two-way process continues until all the packets in the message have been transferred successfully.

Many applications, use the ubiquitous transmission control protocol (TCP). A lot of time is spent on waiting for TCP acknowledgements of each packet. The actual throughput of TCP is inversely proportional to the round-trip-time (RTT) between the sender and the receiver. The RTT puts an upper bound on the transmission speed of TCP. Certain networks, such as those used for cellular wireless broadcasting, do not have a feedback channel. Applications on these networks still require reliability. Fountain codes in general get around this problem by adopting an essentially one-way communication protocol.

- The sender encodes and sends packet after packet of information.
- The receiver evaluates each packet as it is received. If there is an error, the erroneous packet is discarded. Otherwise the packet is saved as a piece of the message.
- Eventually the receiver has enough valid packets to reconstruct the entire message. When the entire message has been received successfully the receiver signals that transmission is complete.

Raptor codes in this class produce a potentially infinite stream of symbols such that any subset of symbols of size $k(1 + \xi)$ is sufficient to recover the original k symbols with high probability. ξ is a small number which shows the overhead. This kind of solutions needs not only redesigning the IEEE 802.11MAC layer but also some changes in physical layer. Using these codes changes the pattern of data and Ack transmissions so it can mitigate the negative effects of collision of Acks with data, which results in many useless retransmissions, therefore improves the network capacity.

Finally the last category is architectural solutions. Using multi-technology radios within on node can be a solution to overcome adjacent channel interference problem in multi-radio nodes. As different technologies work in separate frequencies they do not interfere with each other so the network can reach to more throughputs. Using IEEE 802.11a in one radio and IEEE 802.11b or g on the other radio can be an example of such approach.

9.3 Proposal

In this part we use the insights from the analysis and simulation of the previous chapters to drive the design of our multi-radio proposal. We believe that the transmission pattern of nodes should be with an appropriate design which can ensure the best performance in terms of interference and capacity improvements. A suitable solution should try to coordinate the access of the shared channel so that multiple transmitters can transmit more frames with minimal delays. A fundamental shortcoming of many previous attempts in multi-radio multi-channel networks is the implicit assumption that the multiple radios within one node, operate independently. We believe that appropriate solutions to achieving robust wireless systems with high throughput need the interactions between radios, and innovation in combining these components in a way that uses their strengths constructively.

In order to have the coordination among the radios in wireless mesh networks, special mechanisms such as time synchronizations between nodes or control messages are necessary. Global timing synchronization is often difficult, if not impossible, due to clock drifts within each node. The challenge of many researchers is to develop an efficient synchronization mechanism. The control channel used in this proposal enables a node to arrange a rendezvousing data channel with its communicating counterpart. With use of the control channel we are going to have coordination between radios. As a result there exist four different reservation patterns for two data interfaces within one node which are depicted in table 9.1 and figure 9.2. In Tx-Tx mode both interfaces within one node want to transmit data simultaneously, while Rx-Rx means two radios receiving at the same time, finally in Tx-Rx mode one interface receiving while the other is transmitting simultaneously.

As we discussed earlier when two interfaces within one node transmit and receive the data simultaneously a large amount of decrease occur in throughput because the weak incoming signal at the receiver gets corrupted by the strong outgoing signal of the nearby transmitter. In our proposal, due to the mentioned problem, the radios within one node do not have any reservation pattern for transmitting and receiving the data simultaneously.

	TX-TX	RX-RX	TX-RX
1	No	No	No
2	Yes	No	No
3	No	Yes	No
4	Yes	Yes	No

Table 9.1: Possible reservation patterns for 2 radios within one node.

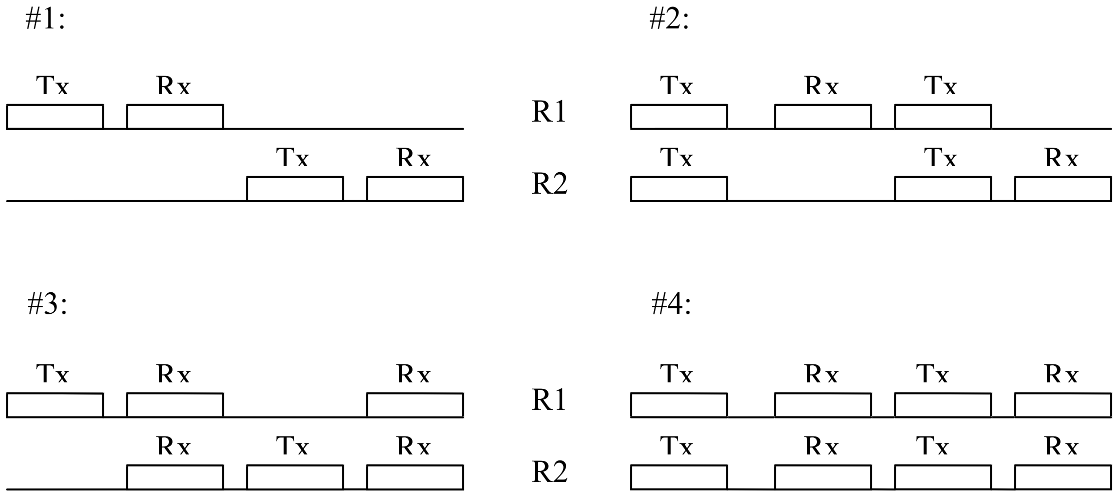


Figure 9.2: Possible reservation patterns for 2 radios within one node.

As we discussed in adjacent channel interference part, if two interfaces within one node want to transmit data at the same time, it may happen that the interference from one radio triggers the carrier sense on the other interface causing the deferral of the transmission. On the other hand, it may happen that the power emitted by one radio is not sensed by the carrier sense mechanism at other radio (due to its threshold), however the mutual interference causes the corruption of the receiving Ack frames, hence spurious retransmissions of the same packet cause reduction in throughput.

So it seems that it is more logical to schedule the radios for not transmitting at the same time, not transmitting and receiving at the same time but for gaining from multi-radio nodes they can receive at the same time. However, when two radios within one node want to receive the data at the same time it may happen that the transmissions of the Ack on one radio interfere with the reception of the data frames on the other radio, so causes reduction in throughput. So we are going to discuss more in detail and consider the probability of this kind of collisions.

Due to aforementioned scenarios we choose the third state of table 1 in our proposed solution and we will show that we can gain more improvement with this choice. So in the proposed solution control channel make coordination between two radios in a manner that they do not transmit, transmit and receive at the same time but they can receive simultaneously.

Before every communication, the nodes must use the control interface to exchange control messages in order to reserve the common data channel for exchanging data. The arrangement made by two communicating counterparts can also be heard by other nodes as the reference for the future data channel arrangement decision; based on the information obtained from common control interface.

When channels are from the same frequency band, due to the physical proximity, the cards interfere with each other even if the channels are non-overlapping. One way to overcome the problem is to assign channels from two different frequency bands to control and data interfaces. As an example, we allocate a channel in IEEE 802.11b frequency band (2.4 GHz band) to control interface and two channels in IEEE 802.11a band (5GHz) to the data channel interfaces.

The operation of reservation based approach follows Control messages-Data-Ack exchange, though Control messages and Data-Ack are operated in different band and can be working in parallel. That is to say, while current data is being transmitted on the data channel, at the same time, the contention resolution of subsequent data transmission can be arranged. Thus, as soon as the current data transmission is completed, the next data transmission can commence immediately.

Each radio has to contend afresh for the channel at every hop. Multiple contention delay would effectively be reduced and the total network throughput may increase as the channel can be reserved in advance.

This solution makes the following assumptions on the WMN architecture that is suitable for applying our scheme:

1. All mesh nodes have two interfaces that work in IEEE 802.11a non overlapping orthogonal channels.
2. Each node has an extra interface for control channel that do not interfere with two other interfaces which work in IEEE 802.11a (e.g. IEEE 802.11b)
3. The channels have been a priori assigned to each interface. The channel assignment is identical for all nodes.

The control channel is used to transmit control messages and data and Ack frames are transmitted on data channel, which is selected during the channel negotiation procedures. Every node is equipped with three transceivers: one control-transceiver and two data-transceivers. The data-transceivers of source and destination nodes have to be on the same data channel before they can exchange data/Ack. Each station which wants to transmit data frames must compete with other stations in control channel. To lower the frame collision probability, each node performs carrier sense before transmitting. If the control channel is sensed as busy, the transmission is deferred until the channel becomes idle again.

To describe the operation of the proposed solution, called MRR (Multi-Radio Reservation), firstly we will introduce the control frames and the channel state table that a node maintains for each interface, followed by an example on how they would be used to reserve the channel in advance.

9.3.1 Control Frames

The control frames in MRR serve similar functions as those in IEEE 802.11 DCF (RTS/CTS), to acquire the channel for the collision free transmission of the data frames, and to inform neighboring nodes of this acquisition. The main difference is the ability to make advance reservation of the wireless medium.

. *Request To Reserve (RQTR)*: this act like the RTS in IEEE 802.11 DCF. The RQTR includes the channel id (*idr*), the reservation time (*tr*) and the reservation duration (*dr*). It is worth noting here that *tr* is the *offset* time after the RQTR is received at the receiver. This way of representing the time of an action is similar to the *duration* field in RTS/CTS frame that is used to calculate the Network Allocation Vector (NAV). The rest of the fields will be explained in the example below.

. *Reply To Reserve (RPTR):* this act like the CTS in IEEE 802.11 DCF. Similar to RQTR, it contains *idr*, *tr* and *dr*. Note that the reservation time and duration represented by *tr* and/or *dr* in the PRTR may be different from that requested by the RQTR. This happens when the receiver proposes another reservation time and/or duration.

. *Confirm To Reserve (CFTR):* When the replied reservation time and/or duration is different, the requesting node must confirm with a CFTR to agree or cancel the reservation. This contains the updated *tr*, *dr* and a *reservation cancel* flag set if the reservation is to be cancelled.

Similar to the RTS/CTS operation in IEEE 802.11 DCF, the RQTR/RPTR/[CFTR] operation in MRR is a contiguous series of frames with a short interframe space (SIFS) separating them.

It should also be noted that the CFTR frame is optional since it is only required if the reservation request had been changed by the receiver.

9.3.2 Radio State Schedule (RSS)

Each node maintains a radio state schedule (RSS) for each of its interfaces. The RSS contains the reservation information of the channel the interface is on. From the received control frames, a node will update the RSS with the time and duration the channel will be busy because of a successful reservation, either by itself, or by a neighboring node using the same channel. Table 9.2 shows an example of a RSS.

Channel A		Channel B	
Start Time	Duration	Start Time	Duration
τ_{r1}	t_{data1}	τ_{r2}	t_{data2}
.	.	.	.
.	.	.	.
.	.	.	.

Table 9.2: Example of Radio State Schedule (RSS)

9.3.3 Example

In this section, we provide an example of how advance reservation can be done in MRR. Figure 9.3 shows 4 nodes with two IEEE 802.11a interfaces and one control interface. As we mentioned earlier, the control channel does not interfere with the two other interfaces but two IEEE 802.11a interfaces suffer from adjacent channel interference, and we want to reduce this negative effect as much as possible in order to achieve more throughput in the network.

In this example, node *A* wants to send data to node *B*. Node *A* sends a RQTR to node *B* requesting for channel time t_{r1} after the RQTR frame, for a duration of t_{data1}. Node *B*, on receiving the RQTR, computes the actual reservation time requested by adding the offset t_{r1} to its actual clock time and checks its RSS to ensure that channel1 is not occupied at that time. It updates the RSS with this reservation accordingly and sends back to *A* a RPTR with the channel time of t'_{r1} after the RPTR frame.

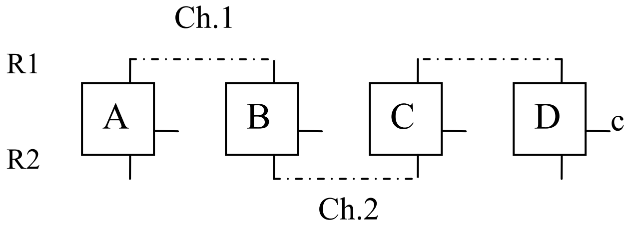


Figure 9.3: Topology of the example. Each node has one control interface c, and two data interfaces.

Now node *B* wants to send to node *C* on channel 2 using the other interface. Even while the transmission of the data on channel1 is going on, node *B* can begin to reserve the channel 2 by sending a RQTR to node *C*. Figure 9.4 shows the timing diagram for the reservation of channel between node *A* and node *B* and *C*.

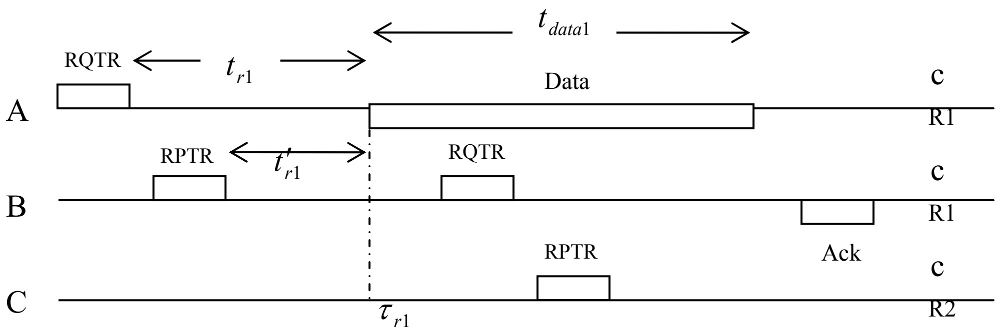


Figure 9.4: Timing diagram of the interaction between the interfaces of node *A*, *B* and *C*. Each side of the horizontal line represents a data and control interface.

There might be situations when the channel requested has been reserved for another transmission. For example, when the RQTR from node *C* reaches node *D*, the RSS of *D*'s indicate that a prior reservation overlaps with the requested time. The new request would not be accepted as it would disrupt the existing reservation. Hence, node *D* will reply with RPTR containing a proposed new reservation time of t'_{r3}. If this new reservation time is acceptable to node *C*, it will send a CFTR with the new adjuster time. Otherwise, it will send a CFTR with *reservation cancel* flag set. Figure 9.5 shows the timing diagram of such an interaction.

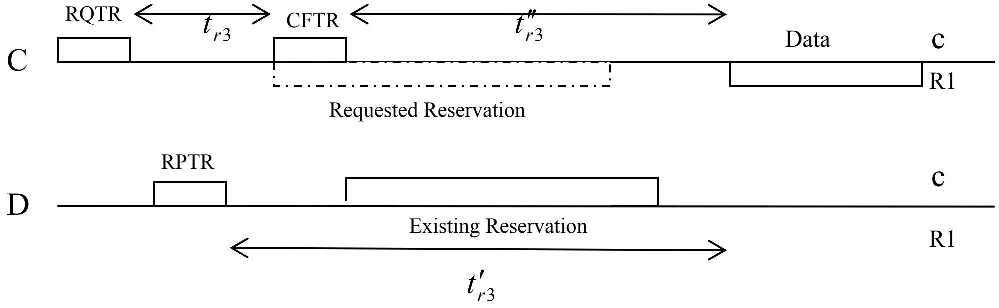


Figure 9.5: Timing diagram of the interaction between node *C* and *D*. Node *D* proposes a new reservation time since part of the requested time has been reserved earlier.

9.4 Key Features

In this part, we will highlight some key features of the proposed solution:

1. Set aside a separate, orthogonal common control channel for reservation purpose which is a way to limit the effects of multi- radio version of hidden and exposed terminal problems because reservation frames sent over this channel could be

heard by all the nodes within the range.

2. MRR makes use of IEEE 802.11 PHY as its physical layer. Modification is performed on the upper part of the MAC layer in terms of the operation and control frame formats.
3. Common control channel allows neighboring nodes be aware of the reservation. This is also the reason why a CFTR frame has to be sent if there are any changes to the original reservation request. Similar to the RTS/CTS mechanism in IEEE 802.11a DCF, this reduces the effects of the multi channel hidden-node problem version which is discussed earlier. Reservation frames sent over control channel could be heard by all the nodes within the interference range.
4. The reservation scheme in MRR uses offset timing derived from the instance when the frame is received at the receiver. This removes the necessity of global clock synchronization, a challenging issue in reservation protocols. However, some timing allowances have to be factored into the offset to account for the propagation delay of the frames to nodes at different distances from the transmitted.

9.5 Evaluation of Proposal

In this part we are going to evaluate the proposed solution. The main goal of this part is to compare the capacity of the proposed solution to the single-radio scenario. As we discussed earlier a collision may happen when two interfaces within one node have the same reservation time for receiving the data. We analyze this state and as an example we compute the success probability for receiving the correct data in both interfaces.

In IEEE 802.11 a packet is encapsulated in a MSDU (MAC Service Data Unit), which is the basic data unit transmitted over the air. So, the time to transmit a frame is equal to time to transmit a MSDU. Figure 9.6 shows the transmission scheme of a single MSDU.

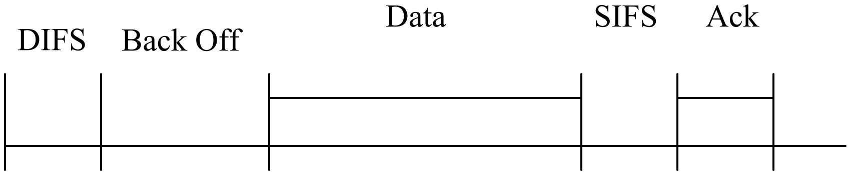


Figure 9.6: Data Frame Transmission Scheme in IEEE 802.11.

The DIFS (Distributed Inter Frame Space) and SIFS (Short Inter Frame Space) are fixed waiting times. The Back Off is a random waiting time to solve competition, and the Ack and data can be computed. The data transmission includes also some special fields like a preamble. Table 9.3 depicts the involved timing parameters.

Parameter	Typical Value
DIFS	34 μs
SIFS	16 μs
Back Off(average)	67.5 μs
Preamble	16 μs
Signal	4 μs
Symbol Interval	4 μs
Service field	16 bits
Tail field	6 bits

Table 9.3: Typical Parameters for MSDU.

The total transmission time of a single MSDU is the time to transmit the data T_{Data}, plus the time to transmit the acknowledgement T_{Ack}, plus the time for DIFS, Back Off and SIFS. The transmission time of the data and Ack depend on the selected rate. The length of these transmissions is the sum of the data or Ack and the various overheads. The data transmission includes also some special fields like service and tail field. According to the IEEE 802.11 specification [1] T_{Data} equals:

$$T_{Data} = T_{\Pr eamble} + T_{Signal} + \frac{16 + L + 6}{C} + \frac{T_{Sym}}{2} \quad (1)$$

Where L is the length of the frame in bits and C is the physical channel rate in bps. An additional time of half an OFDM symbol should be added to compensate for rounding of to the next complete OFDM symbol ($\frac{T_{Sym}}{2}$). Working out the same formula for the Ack, and filling in the parameters the transmission times in μs become:

$$T_{Data} = 24\mu s + \frac{L + 22}{C} \quad (2)$$

$$T_{Ack} = 24\mu s + \frac{134}{C} \quad (3)$$

Where L is the length of the frame in bits and C is the physical channel rate in bps. The average duration of the transmission of one frame is now:

$$T_{Frame} = T_{DIFS} + T_{Backoff} + T_{Data} + T_{SIFS} + T_{Ack} \quad (4)$$

$$T_{Frame} = 34\mu s + 67.5\mu s + (24\mu s + \frac{L + 22}{C}) + 16\mu s + (24\mu s + \frac{134}{C})$$

$$T_{Frame} = 165.5\mu s + \frac{L + 156}{C} \quad (5)$$

Now if the transmitted bits L divided by this duration, the throughput of such a burst is:

$$R = \frac{L}{165.5\mu s + \frac{L+156}{C}} \text{ Mbps} \quad (6)$$

As R is the maximum throughput, the time between two successive frames is zero and network is loaded with 100% load, but this amount of load causes a large amount of collision therefore in reality most of the time the network is loaded with less than the maximum load, as a result the time interval between frames is not zero. The average time between two frames is defined as $T_{ave.}$. This is illustrated in figure 9.7.

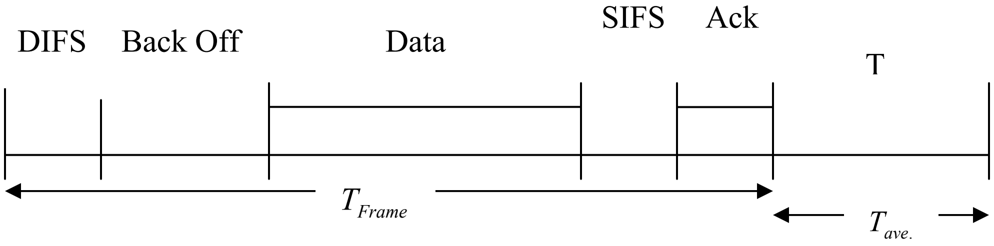


Figure 9.7: Data Frame Transmission including $T_{ave.}$

Assume that two interfaces within one node are both in the receiving time interval. One interface should not transmit the Ack during the data reception of other interface in order to have a successful reception, it means that if during the data reception time of one interface the other interface transmits the Ack, it will cause a collision therefore the vulnerable time for having the data and Ack collision is $T_{Data} + T_{Ack}$.

As shown in figure 9.8, there is a successful reception if the Ack of the other interface does not collide with the data of this interface.

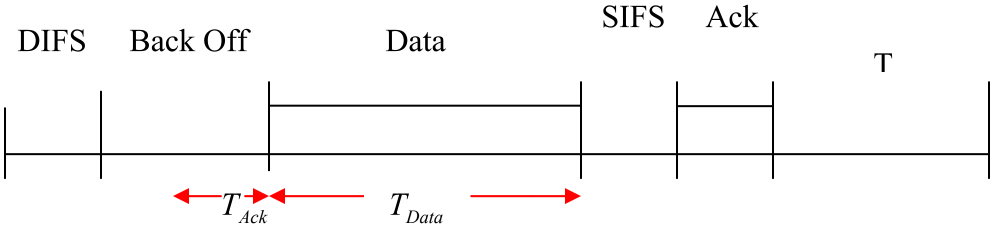


Figure 9.8: Vulnerable Time

Now in order to evaluate the solution it is useful to have an example with realistic values: If we assume that the size of the frame is 1500 bytes, and the physical channel rate is 6 bps, we can calculate T_{Data} and T_{Ack} via equation *2* and *3*.

$$T_{Data} = 24\mu s + \frac{L+22}{C} = 24\mu s + \frac{1500 \times 8 + 22}{6} = 2027.66\mu s$$

$$T_{Ack} = 24\mu s + \frac{134}{C} = 24\mu s + \frac{134}{6} = 46.33\mu s$$

As we explained earlier the vulnerable time for having the data and Ack collision is $T_{Data} + T_{Ack}$ therefore the probability that one interface transmits Ack during the data reception of other interface is:

$$\Pr(Collision) = \frac{T_{Data} + T_{Ack}}{DIFS + Backoff + T_{Data} + SIFS + T_{Ack} + T} \quad (7)$$

Substituting the calculated T_{Data} and T_{Ack} in equation *7* gives:

$$\Pr(Collision) = \frac{2027.66 + 46.33}{34 + 67.5 + 2027.66 + 16 + 46.33 + T}$$

$$\Pr(Collision) = \frac{2073.99}{2191.49 + T} \quad (8)$$

Equation *9* shows the relation between the frame rate and $T_{ave.}$. In this equation r_f is the frame rate. We need to calculate the $T_{ave.}$.

$$T_{Frame} + T_{ave.} = \frac{1}{r_f} \quad (9)$$

Calculating the R in equation *6*, the maximum frame rate is:

$$R = \frac{L}{165.5\mu S + \frac{L+156}{C}} = \frac{1500 \times 8}{165.5 + \frac{1500 \times 8 + 156}{6}} = 5.47 \text{ Mbps} = 455 \frac{frame}{\text{sec}}$$

As we discussed earlier due to large amount of collision is not wise to load the network with maximum frame rate. A realistic percentage for a typical traffic patterns is approximately 50~60% [81], therefore in order to get more insight about realistic values we calculate the $T_{ave.}$ for different percentage of frame rate. The results are listed in table 9.4.

Percentage of Frame rate	r_f	$T_{ave.}$ (sec.)
90	409.5	0.00034
80	364	0.00064
70	318.5	0.00103
60	273	0.00156
50	227.5	0.00229

Table 9.4: Frame rate and $T_{ave.}$

Now we should substitute the $T_{ave.}$ in equation *8* in order to calculate the probability of collision and to be able to compare the capacity of proposed solution with single-radio scenario we should calculate the success probability which is:
Pr(Success) = 1 – Pr(Collision).
As we mentioned before when both interfaces of a node are in the receiving time interval there is a successful reception if the Ack of the other interface does not collide with the data of this interface. The results of collision and success probabilities are shown in table 9.5.

Percentage of Frame rate	Pr(Collision)	Pr(Success)
90	81%	19%
80	72%	28%
70	63%	37%
60	54%	46%
50	45%	55%

Table 9.5: Probability of collision and success

Now with these results we can further evaluate MRR. Due to the reservation pattern of MRR we can have parallel reception. In traffic patterns of typical real networks the percentage of frame rate is approximately 50~60%, and due to attained results, we can have roughly 50% successful transmissions for parallel receiving.
It should also be noted that with reservation pattern of MRR, interfaces within one node can not transmit and receive simultaneously. Furthermore they can not transmit simultaneously so this reservation pattern is alleviated a large amount of collision and re-transmission which is discussed in adjacent channel interference chapter. Furthermore due to attained results, we can mention that from the node perspective, two parallel receptions with success rate of 50% are equal to one successful reception in a single interface. From performance point of view these two schemes are equal, but if two interfaces reserve the time for parallel reception, it results in more transmission and interference in the whole network.
In order to compare MRR with single radio single channel case we use a simple example which is extended to more number of nodes and channels. This analysis is network level effects of reservation scheme. Firstly we consider the scenarios which are depicted in figure 9.10. In *a* and *c* nodes are equipped with two data interfaces while in *b* and *d* nodes are single radio single channel.
In this example nodes are in the interference range of each other so in each time slot just one successful transmission can take place in each channel. There are 3 nodes in scenario *a* and *b*; in each time slot just one successful transmission can happen in scenario *b* while due to the possible parallel receptions two successful transmission can happen in scenario *a* in channel 1 and 2, it should be noted that the probability of success for two links are not 100%. If we assume the percentage of frame rate is approximately 50~60% then we can achieve considerable gain in throughput using MRR in a whole network. In scenario *c* and *d* if we consider the same situation as mentioned, the throughput of MRR will be two times more than single-radio case.

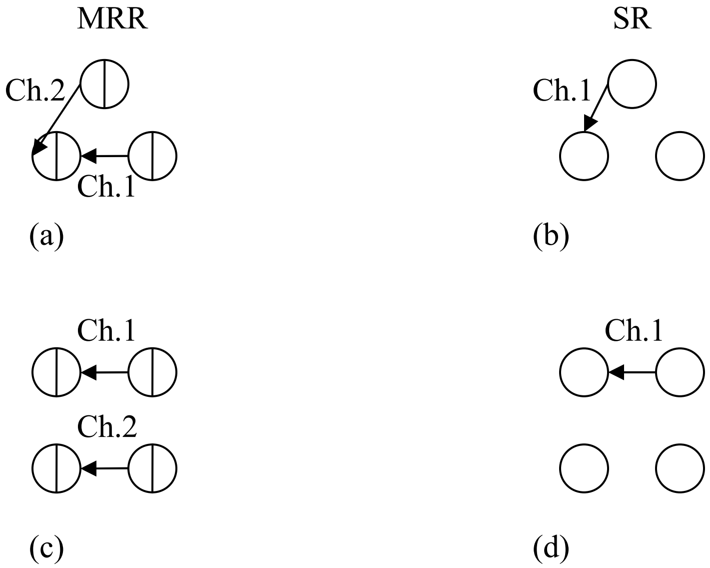


Figure 9.10: Scenarios with single-radio single channel in *b* and *d*, multi-radio multi-channel in *a* and *c*.

By continuing this pattern up to 20 node and considering scenarios with two radio per node and increasing the number of available channel from two to ten, we can compare the maximum amount of successful concurrent transmission in MRR with single radio case. Figure 9.11 illustrates the upper bound which can be achieved by using MRR.

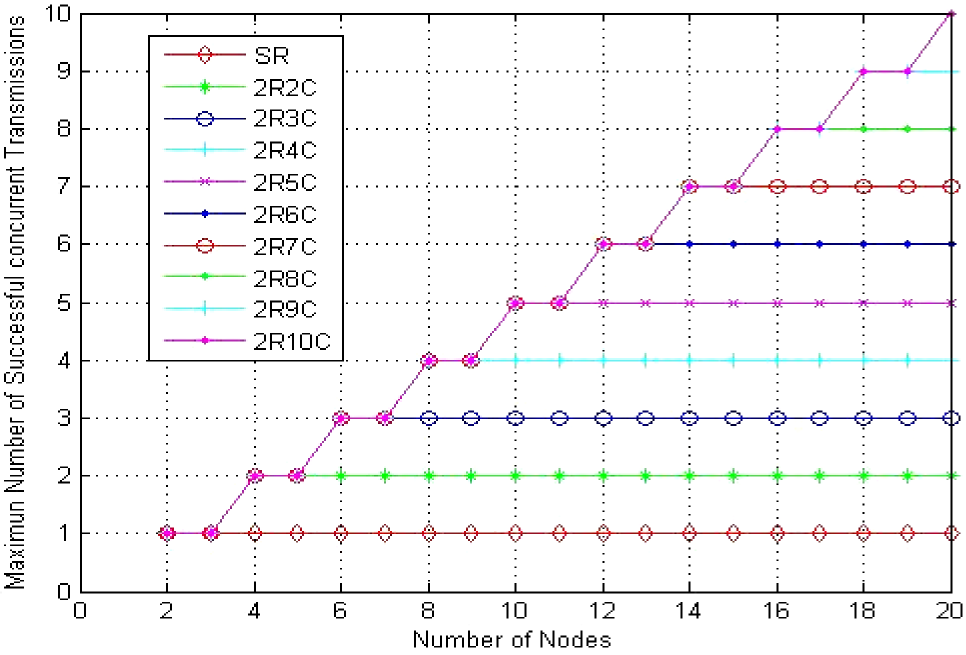


Figure 9.11: The amount of achievable upper bound capacity of MRR normalized with Single-radio single channel case.

The amount of achievable upper bound capacity of MRR is normalized with single-radio single-channel case in figure 9.11. As an example it shows that in a network with six nodes the amount of achievable capacity with 2radio, 2channel MRR is two times more than single-radio single channel case and for MRR with 2radio, 3 channel the achievable capacity is 3 times more than single radio-single channel case.

It should be mentioned that with applying more channels we can reach to more amount of capacity.

It should be noted that these bounds can be viewed as the best case bounds on network capacity because we assume that there is a good channel assignment scheme in the network which enables the nodes to communicate with others.

Channel assignment schedule specifies at what time a node would be listening on what channel. A good channel assignment is important for better performance of the system and it increases the possibility of having more concurrent transmissions in the network.

Nodes can transmit data and communicate to each other if they are in the same channel therefore the design of a multi-channel wireless mesh network involves taking precautions to avoid loss of connectivity. As a consequence, in order to achieve more throughputs it is better to use more channels but connectivity issues should be taken into account.

In order to evaluate the exact amount of improvement by applying MRR and consider the reservation pattern, much more analysis with precise simulator which can take into account the different real traffic patterns are needed.

CHAPTER 10

CONCLUSION AND FUTURE WORK

10.1 Conclusion

As we mentioned in earlier chapters the assumption of perfect independence between non-overlapping operating channels does not always hold in general. If two transceivers are in close proximity to each other, as it is the default setup for multi-radio systems, then the assumption that multiple independent transmissions over non-overlapping channels can coexist without mutual interference does not work anymore. Although in theory non overlapping channels can work simultaneously but in practice, due to signal leakage from one channel to another, transmissions on these non overlapping channels interfere with one another. The interference level is affected by many factors such as the hardware used, distance between transmitters, antennas pattern, transmit power, etc.

During this work, we have investigated the analysis of adjacent channel interference issue. In order to evaluate the effect of ACI more in detail, we have done some practical measurements with changing various parameters such as antenna separation, number of channels and radio, transmit-power and packet size. Moreover, in order to get more insights about adjacent channel interference, we have done simulation for various scenarios to report the effects of changing the number of channels, radio, transmission power on throughput and we have considered the amount of errors at receiver (collision) and acknowledgment error. With evaluation of attained results, we have learned that the presence of adjacent channel interference can not be neglected in the context of multi-channel multi-radio WMNs.

The attained results of analysis part show that using multi-channel multi-radio networks without taking into account the adjacent channel interference issue, causes some amount of reduction in throughput, as our measurements have shown in some cases multi-channel multi-radio behaves worse than single radio networks. So our main goal was to evaluate different situations and with an appropriate solution not only remove the worse than single radio case but also be as much as possible near to multi-radio theoretical region. Figure 10.1 shows this explanation.

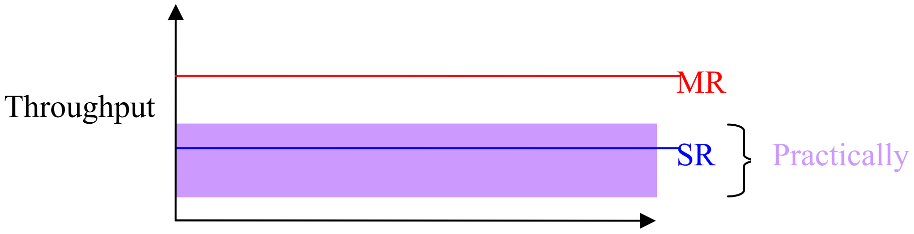


Figure 10.1: Single-radio, Multi-radio expected throughput lines. The shaded region shows what happen practically with out taking the ACI into account.

As a result, our experiments suggest that current off-the-shelf IEEE 802.11 chipsets without any special mechanism might not be ready to be integrated in a single box with few centimeters of antenna separation and a single channel MAC protocol does not work well in a multi-channel environment because ACI causes a large amount of decrease in throughput. Therefore, an important research challenge is to solve this problem. We believe that appropriate solutions to achieving wireless systems with high throughput need the interactions between radios within one node.

Our proposed solution has been explained in chapter 9 called MRR (Multi-Radio Reservation). With special reservation pattern of MRR, interfaces within one node can not transmit and receive simultaneously so the total throughput rids of the collisions which happen when weak receiving signals get corrupted with outgoing strong signals. Furthermore interfaces can not transmit simultaneously so the total throughput also rids of the collisions which happen when Ack received from the destination node in one interface get corrupted with transmitting data on the other interface and this may result a large amount of reduction in re-transmissions. It should be noted that reservation pattern of MRR remove the aforementioned negative effects which cause multi-channel multi-radio nodes behave worse than single radio nodes in some cases (figure 10.1). Moreover with applying MRR we can have parallel receiving, but as it mentioned before, from node perspective, two parallel receiving with success rate of 50% are equal to one successful receiving in a single interface. From the performance point of view these two schemes are equal, but if two interfaces reserve the time for parallel reception, it results in more transmissions and interference in the whole network. As a consequence if no parallel actions happen per node still with using reservation we can minimize the negative effect of interference. As we evaluated in chapter 9, applying multi-channel schemes result in considerable benefits in the network.

Although it seems that MRR can be suitable from ‘throughput gain’ point of view but it is a bit costly solution as it requires two data interfaces and one control interface per node. As an extension to this solution and in order to gain more from MRR, we can extend the usability of the control channel also for power saving mechanisms. Also it may be possible to use the control channel for data transfer, for example broadcast frames can be transmitted in common control channel.

Although in traffic pattern of typical real network the percentage of frame rate is approximately 50~60% and we can have roughly 50% successful transmissions for parallel receiving and more higher probability for less amount of frame rate. But in order to reduce the cost of the proposed solution and still gain from multi-channel multi-radio concept it is possible to equip each node with one data and one control interface. Control radio may use for reservation and power saving schemes.

It should be noted that if the number of channels is more than the number of interfaces per node, interfaces should switch on different channels. Although using one data interface is less costly to implement but in this case, network suffers much more delay comparing to have two data interfaces per node.

As we mentioned in MRR the control channel does not interfere with the two other interfaces as they work in different frequency band. As an example we suggested IEEE 802.11a and b which are situated in different frequency bands. But assigning an appropriate portion of frequency spectrum for control channel if we cannot use IEEE 802.11b is still a challenge.

10.2 Future Works and Recommendation

While this solution has the potential to improve the performance in multi-channel multi-radio WMNs, challenges are still present, especially when extending it to WMNs utilizing multi-channel multi-radio without having identical pre-assigned channels to interfaces. In this section, we highlight some of the key challenges as a future work.

1. Our proposition can be improved by adding the possibility of reserving more than one frame by only one RQTR/RPTR exchange. Within reservation duration, the transmitter could potentially send out more than one data frame. Issues like fairness and acknowledgement granularity would have to be investigated. Fairness is a key challenge when we allow more than one frame reservation. In this work, we assume each reservation contains one data frame.
2. As we explained in the simulation chapter, in order to investigate how the main design parameters such as the number of channels and radios affect the capacity, estimate the performance gain that can be achieved under various parameter settings and evaluate the effect of adjacent channel interference, a simulation model was developed and implemented in a Java simulation program in TI-WMC Company. This simulation program is used to gain insight in the behavior of multi-radio multi-channel networks, especially at the lower layers. To evaluate the performance, the simulation model focuses on the link-layer and physical layer aspects. To keep the simulator not too complex, it abstracts from the details of MAC management; as an example re-transmissions are not included in the simulation model. Furthermore the mechanism of reservation is not mentioned in this simulator. As a consequence, in order to be able to precisely evaluate the amount of gain which can achieve by this proposal, further developments in the simulator are needed. It should be noted that with applying realistic traffic patterns and investigate more analysis and simulation we can gain more insights for further precise evaluation of MRR.
3. As an extension to this solution, we can use dynamic channel assignment instead pre-assigned channels. It may possible that each node manages two lists of busy and idle channels. The main idea is that for every communication, a sender must initiate an RTS like control message which piggybacks its busy channels to the receiver. The receiver compares its free channels with the busy channels from sender to select a data channel for the subsequent communication and reply a CTS like control message with additional channel selection information. Upon receiving CTS from receiver, the sender will send a reservation packet to inform nearby nodes about reservation of the selected channel. Then both sender and receiver will switch their data interface to the selected channel, and commence data transmission. It can be more efficient to give preference to the channel that was used for the last successful transmission (in the mose recent past).

It should be noted that in order to gain more from MRR, we can extend the usability of the control channel also for power saving mechanisms. Also it may be possible to use the control channel for data transfer, for example broadcast frames can be transmitted in common control channel.

As a final recommendation, one data interface can work in IEEE 802.11a and the other interface, by exploiting the concept of cognitive radio, can scan the environment in order to find the best channel with the least possible interference.

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APPENDIX

PART A Capacity

***Lemma 2**:* Suppose m and c are positive integers. Then, a (m, c)-network can support at least 1/2 the capacity supported by a $(1, \left\lfloor \frac{c}{m} \right\rfloor)$-network.

***Lemma 3**:* The maximum number of flows for which a node in the network is a destination, *D(n)*, is $\Theta(\frac{\log n}{\log\log n})$, with high probability.

***Theorem 1**:* The upper bound on the capacity of a (m, c)-arbitrary network is as follows:

1) When $\frac{c}{m}$ is *O(n)*, network capacity is $O(W\sqrt{\frac{nm}{c}})$ bit-meters/sec under channel model 1 and $O(W(\sqrt{nmc})$ bit-meters/sec under channel model 2.

2) When $\frac{c}{m}$ is Ω(n), network capacity is $O(W\frac{nm}{c})$ bit-meters/sec under channel model 1 and $O(Wnm)$ bit-meters/sec under channel model 2.

***Theorem 2**:* The achievable network capacity of a (m, c)-arbitrary network is as follows:

1) When $\frac{c}{m}$ is *O(n)*, network capacity is $\Omega(W\sqrt{\frac{nm}{c}})$ bit-meters/sec under channel model 1 and $\Omega(W\sqrt{nmc})$ bit-meters/sec under channel model 2.

2) When $\frac{c}{m}$ is Ω *(n)*, network capacity is $\Omega(W\frac{nm}{c})$ bit-meters/sec under channel model 1 and $\Omega(Wnm)$ bit-meters/sec under channel model 2.

***Theorem 3**:* The upper bound on the capacity of a (m; c)-random network is as follows:

1) When $\frac{c}{m}$ is *O(log n)*, network capacity is $O(W\sqrt{\frac{n}{\log n}})$ bits/sec under channel model 1 and $O(Wc\sqrt{\frac{n}{\log n}})$ bits/sec under channel model 2.

2) When $\frac{c}{m}$ is Ω *(log n)* and also $O(n(\frac{\log\log n}{\log n})^2)$, network capacity is $O(W\sqrt{\frac{nm}{c}})$ bits/sec under channel model 1 and $O(W\sqrt{nmc})$ bits/sec under channel model 2.

3) When $\frac{c}{m}$ is $\Omega(n(\frac{\log\log n}{\log n})^2)$, network capacity is $O(\frac{Wmn\log\log n}{c\log n})$ bits/sec under channel model 1 and $O(\frac{Wmn\log\log n}{\log n})$ bits/sec under channel model 2.

Theorem 4*:* The achievable capacity of a (*m, c*)- random network is as follows:

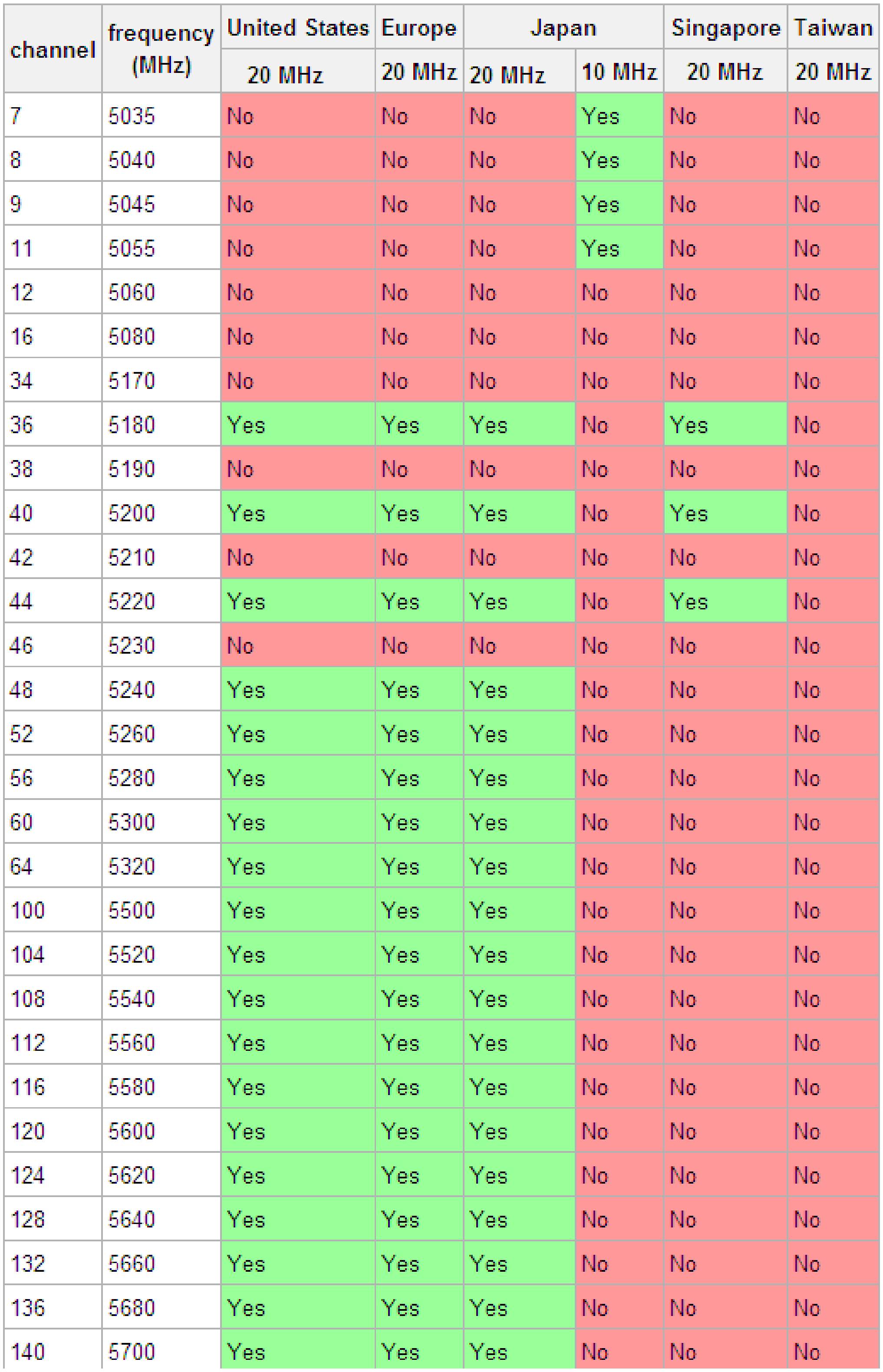
1) When $\frac{c}{m}$ is *O(log n)*, $a(n) = \Theta(\frac{\log n}{n})$, and the network capacity is $\Omega(W\sqrt{\frac{n}{\log n}})$ bits/sec under channel model 1 and $\Omega(Wc\sqrt{\frac{n}{\log n}})$ bits/sec under channel model 2.

2) When $\frac{c}{m}$ is $\Omega(\log n)$ and also $O(n(\frac{\log\log n}{\log n})^2)$, $a(n) = \Theta(\frac{c}{mn})$, and the network capacity is $\Omega(W\sqrt{\frac{nm}{c}})$ bits/sec under channel model 1 and $\Omega(W\sqrt{nmc})$ bits/sec under channel model 2.

3) When $\frac{c}{m}$ is $\Omega(n(\frac{\log\log n}{\log n})^2)$, $a(n) = \Theta((\frac{\log\log n}{\log n})^2)$, and the network capacity is $\Omega(\frac{Wmn\log\log n}{c\log n})$ bits/sec under channel model 1 and $\Omega(\frac{Wmn\log\log n}{\log n})$ bits/sec under channel model 2.

Theorem 5*:* The capacity of a (*m, c*)-network is $O(W\sqrt{\frac{nm}{c}})$ bit-meters/sec under channel model 1, and $O(W\sqrt{nmc})$ bit-meters/sec under channel model 2.

PART B Operating Channel numbers by different standard organizations



channel	frequency (MHz)	United States	Europe	Japan		Singapore	Taiwan
		20 MHz	20 MHz	20 MHz	10 MHz	20 MHz	20 MHz
7	5035	No	No	No	Yes	No	No
8	5040	No	No	No	Yes	No	No
9	5045	No	No	No	Yes	No	No
11	5055	No	No	No	Yes	No	No
12	5060	No	No	No	No	No	No
16	5080	No	No	No	No	No	No
34	5170	No	No	No	No	No	No
36	5180	Yes	Yes	Yes	No	Yes	No
38	5190	No	No	No	No	No	No
40	5200	Yes	Yes	Yes	No	Yes	No
42	5210	No	No	No	No	No	No
44	5220	Yes	Yes	Yes	No	Yes	No
46	5230	No	No	No	No	No	No
48	5240	Yes	Yes	Yes	No	No	No
52	5260	Yes	Yes	Yes	No	No	No
56	5280	Yes	Yes	Yes	No	No	No
60	5300	Yes	Yes	Yes	No	No	No
64	5320	Yes	Yes	Yes	No	No	No
100	5500	Yes	Yes	Yes	No	No	No
104	5520	Yes	Yes	Yes	No	No	No
108	5540	Yes	Yes	Yes	No	No	No
112	5560	Yes	Yes	Yes	No	No	No
116	5580	Yes	Yes	Yes	No	No	No
120	5600	Yes	Yes	Yes	No	No	No
124	5620	Yes	Yes	Yes	No	No	No
128	5640	Yes	Yes	Yes	No	No	No
132	5660	Yes	Yes	Yes	No	No	No
136	5680	Yes	Yes	Yes	No	No	No
140	5700	Yes	Yes	Yes	No	No	No

Table1: Valid operating Channel numbers by different standard organizations

Regulatory Domain	Band(GHz)	Operating Channel Number	Channel Center Freq. (MHz)
ETSI	U-NII Band 5.15~525	36 40 44 48	5180 5200 5220 5240
ETSI	U-NII II Band 5.25~5.35	52 56 60 64	5260 5280 5300 5320
ETSI	ETSI 5.5~5.7	100 104 108 112 116 120 124 128 132 136 140	5500 5520 5540 5560 5580 5600 5620 5640 5660 5680 5700

Table 2: Valid operating Channel numbers by ETSI.

PART C The Effect of varying TCP window size and UDP bandwidth

Experimental Setup

The experiments are conducted with three Figo nodes. The Figo nodes are arranged in a topology which is shown in figure 1. Each Figo is positioned 1 meter from each other. They are placed 70 cm above the ground and within line of sight of each other. The experiments are conducted in an indoor area. There are two flows set up. Each flow is monitored using Jperf.
Iperf is used to generate TCP, UDP packets at a desired rate and to measure the throughput, packet loss and Round Trip Time.
The purpose of these measurements is to report the result of varying the TCP window size, UDP bandwidth, round trip time, transmission power and antenna gain on multi-radio throughput and analyze the effect of adjacent channel interference.

The Effect of TCP Widow Size

Firstly we are going to evaluate the effect of changing the TCP window size on throughput. Test set up is shown in figure 1 .Tests run with single Iperf sessions.

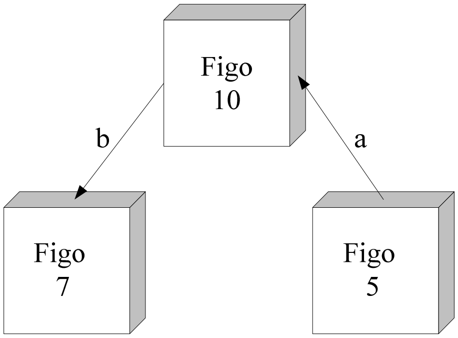


Figure 1: Test set up.

	Channel (b)	Channel(a)
I	100	100
II	140	100

Table 1: Channel Configuration

The TCP window size is the amount of data that can be buffered during a connection without a validation from the receiver. It can be between 2 and 65,535 bytes. A small window size will give poor performance. In IEEE802.11a all data transmissions are acknowledged by the receiving radio and the transmitter makes a number of retransmission attempts if such an Ack is not received. If the TCP window size is set too small, the number of Ack is more, also more retransmission may happen due to the lost of these Acks so there is more interference in whole network. The end result is that actual throughput is very low and the number of retransmissions is excessively high. If conversely, the TCP window size is set too big, the transmitter waits unnecessarily long before retransmitting in sparse network or may cause a large amount of retransmission in case of collisions. These represents lost time and more retransmission thus reduces the throughput.

In this test, we evaluate the effect of changing the window size in two scenarios (I, II). In scenario I, the middle node (Figo 10) has 2 radios in a common channel (100) and in scenario II, 2 radios work on two separate channels (100-140). Figure 2 represents the results.

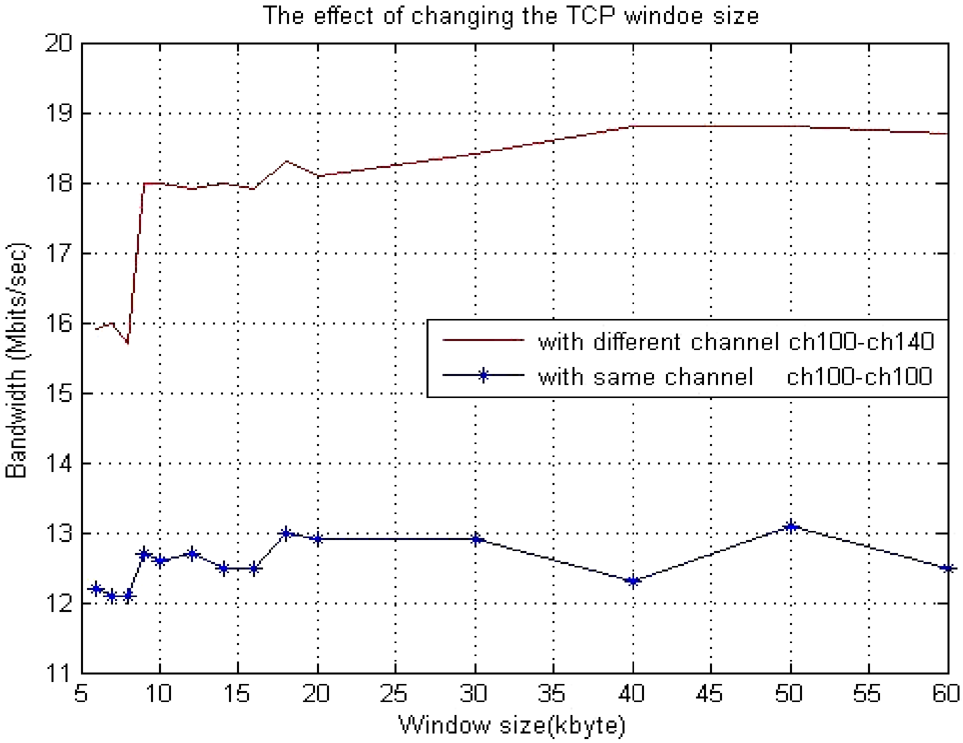


Figure 2: The effect of changing the TCP window size in two scenarios.

Conclusion

Generally the throughput can achieve to a higher rate with bigger window size in more cases but it does not show a huge difference when 2 radios are in a same channel. The effect of bigger window size is more effective when the radios work on different channel.

The Effect of UDP Bandwidth

In this experiment the effect of changing the UDP bandwidth on throughput is evaluated.

In this test the same set up (Figure 1) is applied. The experiment has been done for the same two scenarios to evaluate the effect of changing the UDP bandwidth when 2 radios work on same and different channels. Figure 3 represents the results.

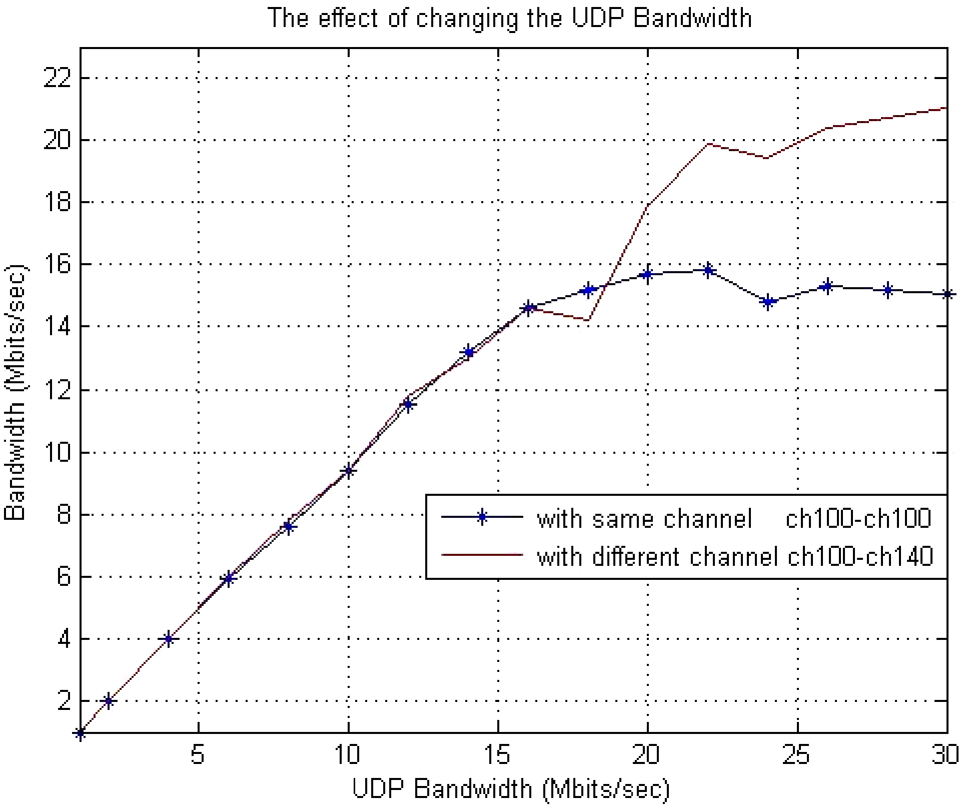


Figure 3: The effect of changing the UDP Bandwidth in two scenarios.

Conclusion

With increasing the UDP bandwidth the throughput can achieve to the higher rate. With increasing the UDP bandwidth up to 16Mbits/sec, the result is approximately same for two scenarios but with more increment, more throughput can achieve when 2 radios are in different channels. As mentioned before, in this experiment Iperf is used to generate UDP packets and to measure the throughput. Moreover it is also possible to measure the packet loss. Figure 4 shows the percentage of packet loss/total datagram, with varying the UDP bandwidth. It should be noted that as it is expected due to higher amount of adjacent channel interference, more lost of datagram happens when 2 radios work on a same channel.

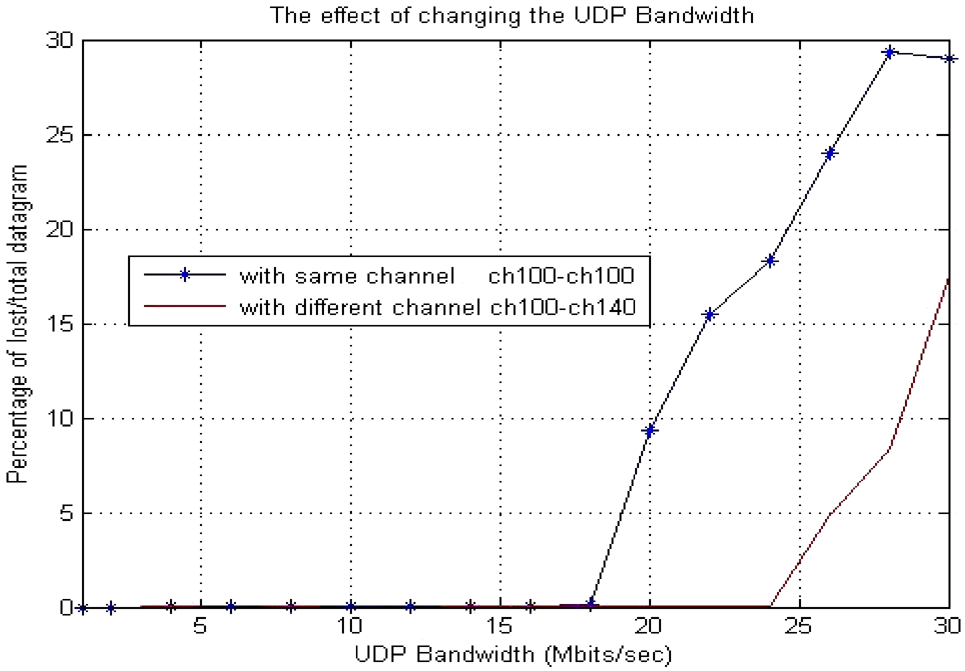


Figure 4: Percentage of lost/total datagram with varying the UDP Bandwidth.