ASSIGNING AND SCHEDULING PARTIALLY OVERLAPPING CHANNELS IN WIRELESS MESH NETWORKS

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Abstract

The design and the management of Wireless Mesh Networks (WMNs) are currently associated with the most active research area within the current wireless networking paradigms. WMNs inherit features from existing wireless networking technologies such as WLANs, mobile ad hoc networks. Because WMNs are easy to deploy and with low power consumption, there is a phenomenal growing interest in seeing WMNs as the next wireless backhaul networks, and an alternative to the existing wired infrastructure.

The earliest development of WMNs had begun with single-channel single-radio mesh networks. This technology then evolved towards multi-channel single-radio mesh networks, and then to multi-channel multi-radio mesh networks. WMNs operate in North America on IEEE 802.11 2.4 GHz spectrum, which provides up to 11 channels. Despite the availability of 11 channels, only 3 (1, 6, 11) orthogonal channels can be used concurrently. The efficiency of multi-channel multi-radio wireless mesh networks can be improved with the increase of the number of channels used concurrently and of multiple radios. In this study, we investigate how to design a scalable channel assignment and a scheduling algorithm, which both exploit partially overlapping channels in order to increase the throughput in comparison with the one that can be obtained only using three orthogonal channels. In order to accurately take into account the radio interferences, we use the physical interference model to estimate the interferences among wireless links. We then introduce the definition of transmission configurations, which are sets of links, which can transmit concurrently. These links can be assigned with channels of overlapping or orthogonal in nature. We then design a TDMA based scheduling allowing a transmission configuration to transmit concurrently in a time slot.

Finally, we evaluate all our algorithms through extensive simulations. Our numerical experiments show that we can gain up to 25% for the throughput by appropriately managing all the available channels.

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I dedicate this thesis to my parents, who always pray and offer continous moral support by wishing me well in my career.

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Chapter 1

Introduction

In this chapter, we give a brief introduction to Wireless Mesh Networks (WMNs) in Section 1.1, then we give a few insights of the motivation behind the work in this thesis in Section 1.2, the problem statement in Section 1.3 and our contributions in Section 1.4.

1.1 Introduction to Wireless Mesh Networks

Wireless Mesh Networks (WMNs) in wireless networking are currently among the most active research areas due to the numerous opportunities they provide for *last few miles* access and exciting challenges they offer to the community at the same time. Compared to traditional WLANs, they are empowered to offer many desirable features, such as large coverage, high network capacity, cost effectiveness, scalability and resiliency [1]. WMNs consists of mesh routers (MRs) and mesh gateways. MRs communicate in a multi-hop fashion forming a relatively stable network and every MR relays data of neighboring MRs. Due to the inter-communication among MRs, if an MR fails the rest of the nodes can still communicate with each other, directly or through one or more intermediate nodes. Some MRs have the additional capacity of being Internet gateways, which always have a wired link that carries the traffic between the MRs and the Internet [1] [22].

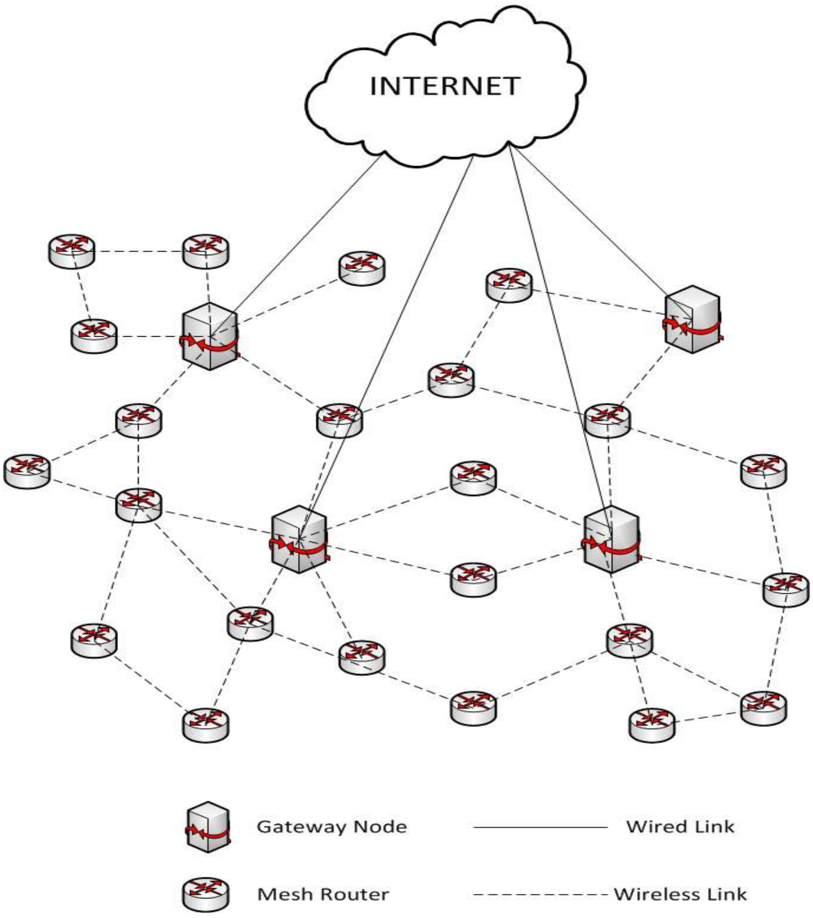


Figure 1: Wireless Mesh Network

WMNs do not form a self-contained unique technology, but are made up from integrating various existing wireless networking technologies and protocols. Typically, WMNs inherit almost all characteristics of the more general ad-hoc network paradigm [22], but unlike in ad-hoc networks, there is no limitation on energy consumption by MRs. Some fundamental benefits of WMNs are their ease of deployment and affordable cost. Figure 1 represents a typical WMN, it consists of a group of MRs connected to one or more gateway(s) by wireless connections shown as dotted lines. These gateways in turn connect to the Internet by a wired connection represented by a solid line. Figure 1 shows that most of the MRs are connected to more than one MR allowing a MR to be able to send and receive through any other neighboring link in case of a link failure.

1.2 Motivation

Most of the WMN devices are built upon IEEE 802.11b/g and the traffic patterns in the WMN is assumed to be fairly stable over a long duration of time [22]. Because backhaul networks deal with very large traffic demands, hence adopting a random access scheme (CSMA) at MAC layer may result in less throughput because of more collisions and overlapping interference among the channels of the spectrum. To reduce collisions and to increase the throughput of WMNs by efficiently managing the overlapping channels, it motivated us to adopt a tightly synchronized communication scheme such as TDMA (time-division multiple-access) [17]. In TDMA, several transmission links can be scheduled concurrently if mutual radio interferences do not prevent the signal to be decoded with an acceptable BER (bit error rate) at each receiver. Besides, the multi-hop nature of WMNs requires an efficient routing protocol. In contrast to *ad-hoc* networks, WMNs need less mobility and face less energy consumption issues. Moreover, the traffic pattern between the nodes is relatively stable over a certain period of time. In addition, to reduce the computation burden of the MRs, we assume a centralized framework of WMNs, where all decisions are computed in a central server. A WMN when operated upon a distributed CSMA/CA at MAC layer, allows a MR to be equipped with automated route discovery. A WMN is dynamically self-organized and self-configured, with the nodes in the network automatically establishing an ad-hoc network and maintaining the mesh connectivity. On the other hand, this is not allowed when operated upon a centralized TDMA framework.

Although many studies have already done a lot of research work, many challenges still exist in WMNs and these challenges can be further explored to propose more efficient and scalable solutions than the existing ones. The design and the management of WMNs need a proper handling of several difficult combinatorial problems. Among those, channel assignment (CA) involves binding each radio to a channel in a way that efficient utilization of available channels can be achieved while meeting traffic and connectivity requirements. Traditional CA strategies assume inherently that available channels for operation are non-overlapping channels (NOC). But the number of such channels is usually very limited, e.g, IEEE 802.11b 2.4 GHz band provides only 3 NOCs (1, 6, 11) out of total 11 channels. CA problem is very well solved with only using orthogonal channels. Some recent studies have shown that exploiting partially overlapping channels (POC) improves spatial channel reuse and can lead to a significant increase in network throughput by allowing more simultaneous transmissions [6] [7]. But it remains unclear what is the best way of assigning channels when assuming the overlapping channels.

Another problem in WMNs is scheduling, which allows the wireless transmission links for data transmission. These links carry downlink and uplink traffic between the MRs and the gateways by improving throughput, fairness and by decreasing end-to-end delays. It is even more difficult to study and propose new algorithms when CA and scheduling problems are combined. Most of the existing work on scheduling assumes only a relaxed approach by only considering one way traffic, which is not a realistic assumption for commercial networks. Without proper scheduling strategy of WMNs, the customers may not be served properly, causing many problems. Above mentioned combinatorial problems are even harder to tackle if a physical interference model is assumed [10]. All these factors lead us to investigate channel assignment and scheduling further assuming the physical interference model with increased interest.

1.3 Problem Statement

Every MR is equipped with one or more radio and each radio is assigned a channel of overlapping or orthogonal in nature. The problem we considered in this thesis is to maximize the throughput of a WMN using all 11 channels of the 2.4 GHz spectrum. Given a set of MRs, #radios/MR, power of a MR to transmit and the traffic demands of MRs, maximize the throughput of WMN. We decomposed this problem into following several stages.

- Determine the neighbours of every MR and gateway.
- Find the uplink routes for all MRs to gateways and downlink routes towards every MR from each gateway.
- Distribute the traffic evenly on the links by minimizing the maximum amount of traffic on any link (edge) on the path.
- Assign the channels on these links.
- Define transmission configurations, which are a set of links that can simultaneously transmit.
- Assign data rate on the link, the maximum throughput of the link in one time slot.
- Order and schedule the configurations in time slots (mapping the configurations to time slots).

1.4 Contributions

We introduce a comprehensive step-by-step layered approach to manage in an efficient manner the traffic, and the available channels in multi-radio multi-channel

TDMA based WMNs. We propose a set of scalable algorithms, which handle successively efficient routing, end-to-end traffic estimation, channel assignment, transmission configurations and scheduling. A transmission configuration that is defined throughout this paper is a set of links able to transmit inside the same TDMA slot. Different from existing work, we operate on several physical layer leverages, such as partially overlapping channels and multiple data rates, while relying on an accurate SINR-based interference model. Moreover, transmission configurations are designed to both, achieve the highest possible network throughput as well as to give more transmission opportunities to critical links adjacent to the gateways. Also, configuration scheduling is done with the aim to increase throughput and fairness among the links.

1.5 Organization of Thesis

The thesis is divided into six chapters. In Chapter 1, we give an introduction to WMNs and its challenges, the problem statement and contributions. The WMNs standards are explained in Chapter 2. It also contains a description of the classification of wireless networks, channels of 802.11 2.4 GHz spectrum and a detailed study about some of the issues of layers in TCP/IP Internet protocol stack of WMNs. The introduction for the channel assignment problem and the scheduling problem is also explained by giving insights of the interference models and their limitations. Chapter 3 provides a survey of some of the most recent existing work done, on the channel assignment and scheduling problems. Chapter 4 describes the basic formulation of physical interference model, and the newly proposed channel assignment and scheduling algorithms. In Chapter 5, we discuss the implementation of the algorithms and their validation. Therein, we also discussed the results of the experiments. Finally, Chapter 6 concludes and discusses avenues for future work.

Chapter 2

Background

In this chapter, we give details of the IEEE 802.11 2.4 GHz spectrum in Section 2.2 and classification of the WMNs in Section 2.3. We then explain the WMN architecture, as well as the challenges of WMNs in Section 2.4, also by explaining the problems that arise at some layers of the TCP/IP Internet protocol stack model when developing a WMN. A brief introduction is also given for the POCs in Section 2.5 and Interference models in Section 2.6. Finally, this chapter is concluded with a more detailed description about channel assignment, routing and scheduling in Sections 2.7, 2.8 and 2.9, respectively.

2.1 Definitions

We define few terms that we use further to give more understanding of the WMNs.

Infrastructure networks consist of the networked devices, such as a set of wireless access points or wireless routers. Each device must connect to an access point before having access to other computers on the network. For example, in cell phone communications, the calling user when dials the number it connects to its nearest access point or cell tower, it then resolves the address of the called user and connects to it.

Therein, begins the communication between calling and called users.

Ad hoc networks allow each device's network adapter to communicate directly with other devices unlike in *infrastructure networks.* This provides an inexpensive and quicker way to connect than using infrastructure mode. While both ad hoc and infrastructure networks can provide a secure connection, infrastructure mode supports various encryption methods while ad hoc mode offers a large range of connection speeds and can be significantly faster compared to infrastructure mode.

Interference Range is the distance within which two transmissions interfere with each other.

Point-to-Point (PTP) communications are between any two points, generally between two mobile users.

Point-to-Multi Point (PTM) is for broadcast and multicast, where the data flows between the broadcasting station to a set of receivers.

Multi Point-to-Multi Point (MTM) allows any node to be active in communication with many other nodes.

Radio is a frequency which a node uses for communication to transmit or to receive.

2.2 IEEE Standards

IEEE 802.11 is a physical layer standard for wireless networks. Over the years, this standard has evolved into many other sub-standards and the most popular versions of this standard are 802.11a, 802.11b and 802.11g [23] [17], which are amendments of the basic 802.11 standard. While the 802.11a standard operates on the 5 GHz band, both '*b*', '*g*' standards operate on 2.4 GHz. Each of the standards define specifications about the number of channels it can support, the channel bandwidth, transmission power and the coverage distance, etc. The 5 GHz band offers up to 23 NOCs and 2.4

GHz band offers up to 3 NOCs [23].

802.11a

This was the first amendment on the basic 802.11 standard. It operates in the 5 GHz band with a maximum raw data rate of 54 Mbps. Because of the high frequency, the channels in this band cannot travel longer distances as they are absorbed by walls and other solid objects. The significant advantage of this standard is the maximum speed that it offers. The devices operating in this band do not interfere much while the disadvantage is with its high cost.

802.11b

It was developed at the same time as 802.11a. 802.11b is more widely accepted for WLANs when compared to its earlier standard, because of the frequency band it supports (2.4 GHz). With smaller frequency, the channels can travel longer and good for crowded networks. It supports a maximum data rate of up to 11 Mbps. The substantial increase in throughput and with lower cost of the hardware, led to the acceptance of 802.11b as a common WLAN standard. However, the devices operating in 802.11b suffer interference from other products operating in the 2.4 GHz band, which is a drawback.

802.11g

This standard came into existence in early 2000's and is a mix of good features from both of its predecessors. It supports a data rate of up to 54 Mbps like 802.11a and operates in 2.4 Ghz band like 802.11b. 802.11g hardware is fully backward compatible with 802.11b hardware. Like 802.11b, 802.11g devices suffer interference from other products operating in the 2.4 GHz band. Some of the other devices that operate in

2.4 GHz range are microwave ovens, bluetooth devices, baby monitors and cordless phones.

In this work, we assume MRs are equipped with radios which support 802.11b/g standard. However, all our proposed algorithms can still work with other standards with minor modifications.

2.3 Classification of Wireless Networks

The classification of wireless networks is presented in Figure 2. Wireless networks are being classified into Point-to-Point (PTP), Point-to-Multi Point (PTM) and Multi Point-to-Multi Point (MTM) [25]. The major difference between any two different types of wireless networks lies in the mode of connectivity, like *Infrastructure* or *Ad hoc*.

PTP networks allows two devices connect together like in mobile phone communication for voice. PTP networks are reliable, but are not scalable for backbone networks, since backhaul networks support a large number of users. PTM networks are for broadcasting stations. Because of the broadcast nature, PTM networks are moderately scalable for backbone networks and still face issues with reliability and adaptability. For an efficient and effective way of communication, users do not need to experience longer delays but smaller costs, MTM networks offer features that provide high reliability, adaptability and scalability to accommodate a large number of users. Since MTM networks contain many hops to cover a large number of users, the transmission can be done without much transmission power, which is another major advantage of MTM networks.

The work of this thesis focuses on Wireless Mesh Networks (WMNs) which belongs to the class of MTM networks.

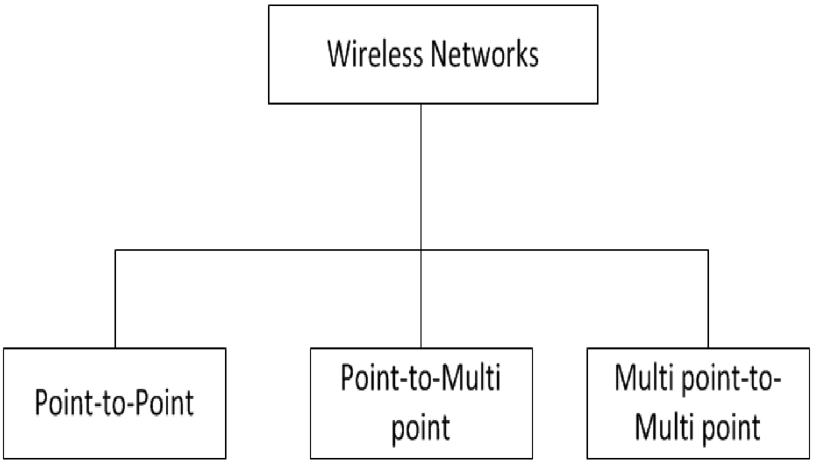


Figure 2: Taxonomy of Classification of Wireless Networks

2.4 Overview of Wireless Mesh Networks

2.4.1 Wireless Mesh Network Components

Three types of devices exist in a WMN [23]: WMN clients (MC), WMN routers (MR) and WMN gateway.

WMN Clients (MCs) are the end-user devices such as laptops, PDAs, etc, which may or may not be mobile and require very less power as their coverage is for very short distances. These MCs may have the routing capability and may or may not be always connected to the network.

WMN Routers (MRs) are in the WMN to route the aggregated traffic. They cannot terminate nor originate the traffic. MRs unlike in mobile ad hoc networks are less mobile and have reliable characteristics like low power consumption because of the multiple hops. Importantly, the medium access control (MAC) protocol in a MR supports multiple-channels and multiple interfaces to enable scalability in a multi-hop environment.

WMN Gateways are MRs with additional functionality and have direct access to the wired infrastructure to Internet. Since the gateways in WMNs have multiple interfaces to connect to both wired and wireless networks, they are expensive. Therefore, only a few WMN gateways exist in a WMN. Moreover, their placement has a significant impact on the performance of the network.

2.4.2 Wireless Mesh Network Architecture

Since WMNs need to support a large number of users and to provide a wide coverage, the network is divided into multiple shorter hops interconnected with MRs forming a mesh. Every MR in the WMN has some knowledge of the network or at least about the neighboring MRs connected directly or indirectly. A MR always pushes or receives packets from its immediate neighbour. Additionally, a MR also relays packets of its neighboring MRs along its path with its own packets resulting in savings on the power consumption of neighboring MRs by avoiding typical long and direct communications to the gateway. A MR is usually equipped with multiple wireless interfaces built on the same or different wireless access technologies, which help in connecting with other MRs. If any link outage occur, a WMN remains scalable because a MR forwards packets in an alternate path since a MR is at least connected to more than one neighboring MR, which is allowed in a mesh network. Some of the MRs are equipped with additional functionality which acts as a bridge between the WMN and the Internet by wired network connection. So MRs in backbone networks are responsible in carrying the traffic from the clients in a hop-by-hop fashion and connects to Internet through the gateways and vice-verse for the traffic coming from the Internet. Because of this, back-haul WMNs can also be called as infrastructure WMNs.

Some of the MCs are cellular base stations, cell phones, laptops, PDAs etc. As shown in Figure 3, client networks can be cellular networks, Wi-Fi networks, etc. MCs form a small *client* WMNs and may connect to one or more MRs of the backbone

WMN. Depending upon the destination of traffic generated, client networks can be of two types:

Client WMNs: In client WMNs, if a node's destination of traffic lies in the same client network, then the traffic can be reached to the destination by hop-by-hop fashion through neighboring peers if connected in an *ad hoc* fashion or through an access point if connected in *infrastructure* fashion. If it is an *ad hoc* mode within client networks, then the traffic has no need to travel through the back-haul MRs of the WMN.

Hybrid WMNs: If the *client WMNs* adopt *ad hoc* mode, then the complete network can be called a hybrid WMN because the backbone WMN is *infrastructure* mode. So the combination of both ad hoc and infrastructure modes makes it is a hybrid WMN.

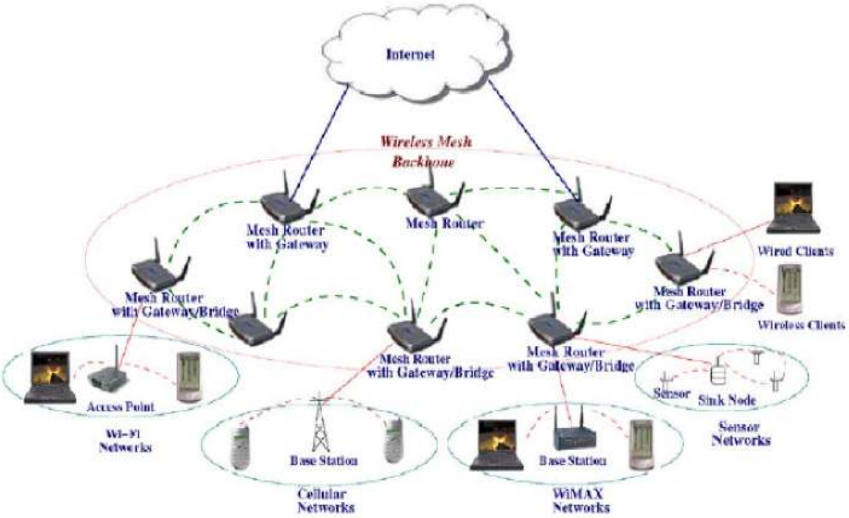


Figure 3: Detailed WMN Architecture [17]

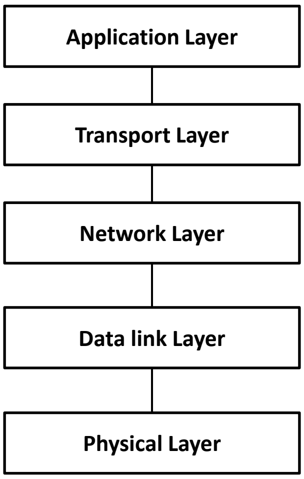


Figure 4: Layers of TCP/IP Internet Protocol model

2.4.3 Problems and Challenges in WMNs

WMNs offer many sophisticated services to the end users. To provide such sophisticated access to the networks, there exist many complicated issues that lie on setting up and maintaining a WMN [25]. Because WMNs are not a completely new technology, but instead evolved from many existing wireless technologies, it is obvious that it can still face many issues of the standards it inherits. Every network standard suite is a mix of several layers where each layer performs its own functions. Figure 4 represents the layers of the TCP/IP Internet protocol stack model. Some of the issues of each of these layers are well explained in [25].

We next discuss some of the issues of the layers of Figure 4 that plays a major role in impacting the performance of a WMN.

Physical Layer Issues (Layer 1)

There are two major issues in the physical layer or layer 1 of the TCP/IP Internet protocol model: *Radio Assignment* and *Interference.*

Radio Assignment: In traditional WMNs, a node is equipped with only one radio allowing it to transmit or to receive at any point of time which is not quite efficient and not scalable if the demand for traffic increases. Those are the traditional single radio-single channel networks allowing a node tuned to only one dedicated channel making it half-duplex. In the next upgrade, a radio was able to tune to more than one non-overlapping channel making them single radio-multi channel networks. Since the evolution of mobile data networks, the necessity for the data transfer has been increasing enormously. Because of the dropping in hardware prices over the years, it is affordable for a node to support more than one radio. As a result, a node is now able to send and receive at the same time on multiple radios allowing a duplex mechanism. In less crowded networks or less busy networks, some of the unused radios can be in idle state by not consuming much power. There has also been some studies on investigating the maximum number of radios a node can support. A radio can be of two types:

Directional Antennas transmit the signal only in a limited direction which allows the signal to be more intensive and can travel for longer distances. The directional antennas are mostly used in microwave networks.

Omni-directional Antennas which spread the signal in all directions in space and the coverage distance of the signal cannot be as long as with directional antennas.

Interference: In wireless networks, there may be some overlapping power levels with neighboring communications because of the directional or omni-directional antennas. This interfering of power levels results in corruption of the data. Interference is a very vast topic and a more detailed study about it is explained in Section 4.2.

Medium Access Control Layer Issues (Layer 2)

Medium access layer is a part of the data link layer or layer 2 of the TCP/IP Internet model and is responsible for the *channel access mechanism*. Traditional MAC protocols differ slightly from wired networks to wireless networks. Like in wired networks, MAC protocols of wireless networks are also classified into contention based, time based and reservation based protocols. Some of the most commonly used wireless MAC protocols are illustrated below.

Carrier sensing multiple access with collision avoidance CSMA/CA is a contention based protocol. With this scheme, a node's successful transmission depends on some probabilistic value. This protocol is most commonly used for IEEE 802.11 or Wi-Fi networks. In CSMA/CA, a node can transmit in a shared medium if it understands the medium is not being used by any other node. When any other node tries to transmit and if it observes that the medium is busy, then it waits for a random back-off time to avoid collision and then attempts to re-transmit after waiting for the back-off time.

TDMA is called time division multiple access. Every link of the network is being assigned a channel and not all the links can be active simultaneously because of the channel overlapping property. Two links are non-conflicting only if they are assigned with non-overlapping channels or the links are sufficiently distant apart to avoid the interference if assigned with the same or overlapping channels. In case of TDMA, few links can simultaneously transmit at the same time. A large time frame is divided into many time slots and each time slot is associated with a set of links.

In our work, we assume the medium access control technique to be TDMA. In addition, the links are classified into groups called transmission configurations and all the links of a transmission configuration can transmit concurrently in one time slot. A link can be part of more than one configuration. More details about how transmisson configurations are defined and conditions are explained in Section 4.4.1.

Network Layer Issues (Layer 3)

Network layer is the layer 3 of the TCP/IP Internet model. This layer is also called IP (Internet Protocol) layer and is responsible for traffic flow characteristics, i.e., *routing*. Routing information expresses the shortest path or route between any two nodes. The nature of the information available to the nodes on the routes between source and destination depends upon the type of framework of WMNs. In case of centralized framework of WMNs, the central server may contain all the route informations and every node has access to the server. In case of distributed framework, the information about the routes of each individual node is contained within its node. Since practical WMNs are dynamic in nature because of the addition or removal of nodes, the routing information has to be updated periodically to have the latest possible routes.

There exist several algorithms to solve the shortest path problem and the most commonly used algorithms are: Dijkstra's algorithm, Bellman-Ford algorithm, Floyd-Warshall algorithm and Johnson's algorithm [5] [24]. In the context of this thesis, we considered a static WMN which does not change for a specific duration of time and we used Dijkstra's algorithm in computing the shortest paths. Since our work belongs to planning of a WMN, we consider WMN to be static. Another reason for considering WMN as static is, the nodes in backhaul WMN are stable for relatively longer duration i.e., there are not frequent changes in the structure of the network.

Transport Layer Issues (Layer 4)

Transport layer is the layer 4 of the TCP/IP Internet model. This layer is responsible for the end-to-end proper transmission of data over the network. The transport protocols should efficiently utilize available network resources and allocate them fairly.

Both fairness and delay are two major important issues in WMNs for packet transmission. There has been a lot of work done on these issues. *Fairness* is the property of a network to give a proper amount of share for every node in the packet transmission to avoid holding the maximum data at any point of time. For example, a node with larger amounts of data has to be given transmission opportunities more often to let its packets push forward. *Delay* is another important factor of the network to not make any node to wait longer. For example, if the nodes near a gateway are given more priority, then the nodes far from the gateways wait for a long time to get the share for the bandwidth for the transmission. Every node has to be given a proper share so as not to make a node delay for long. Another important issue is the end-to-end delivery of packets. Only with a proper strategy, all these issues can be handled carefully. The polynomial algorithms we have developed in this work for scheduling considers the fairness and delay by properly ensuring the end-to-end delivery of packets.

Topological Issues

Since the purpose of a WMN is to offer a high speed Internet access to end users, it is always a complicated issue to deal with the deployment of nodes which affects the capacity of WMNs. Providing QoS to the users depends upon the number of MRs being deployed in that area. Another sub-issue deals with the placement of gateways. The gateways have to be placed so that all MRs can connect to Internet and serve efficiently.

Our work considers allowance of multiple gateways and the decision on placement of gateways is up to the service provider's demand, i.e., it is very flexible and the provider can place a gateway anywhere in the network without much complication. More about our assumptions for placement of gateways is illustrated in Chapter 5. A gateway offers many services to MRs and not necessarily every gateway offers same services as all other gateways. We assume that every MR must receive all services that all the gateways offer. So every gateway is connected to all MRs of the network as a downlink route to provide the service. For the uplink routes, a MR can connect to more than one gateway depending upon the MR location. Our algorithm lets the MR connect to closest gateway(s) possible and to multiple gateways if it is placed at a equal distant. The advantage here is the reliability when connected to a closest MR, and for those MRs at rather equal distance, use the least congested path.

2.5 Partially Overlapping Channels

WMNs are based on existing IEEE 802.11 standards for radio and MAC layers. The popular variants are 802.11b and 802.11g which operate in the ISM 2.4 GHz band and have 14 available channels. Among 14 channels, channel 14 is only allowed in Japan, channels 12 & 13 are allowed in most parts of the world and only channels 1 to 11 are legal to use in North America. These channels are spaced 5 MHz apart, beginning with channel 1 centered on 2.412 GHz as shown in Figure 5. 802.11 also specifies a spectral mask defining the permitted power distribution across each channel resulting in a channel width of 22 MHz for 802.11b and 20 MHz for 802.11g [4]. In both cases, the maximum number of orthogonal channels (OCs) or non-overlapping channels (NOCs) is 3, and are numbered 1, 6, 11.

2.6 Interference

A lot of work has been done on proper handling of the interference problem to attain the maximum efficiency of WMNs. Most of the MRs in WMNs are equipped with omni-directional antennas. Because every MR behaves the same and spreads the

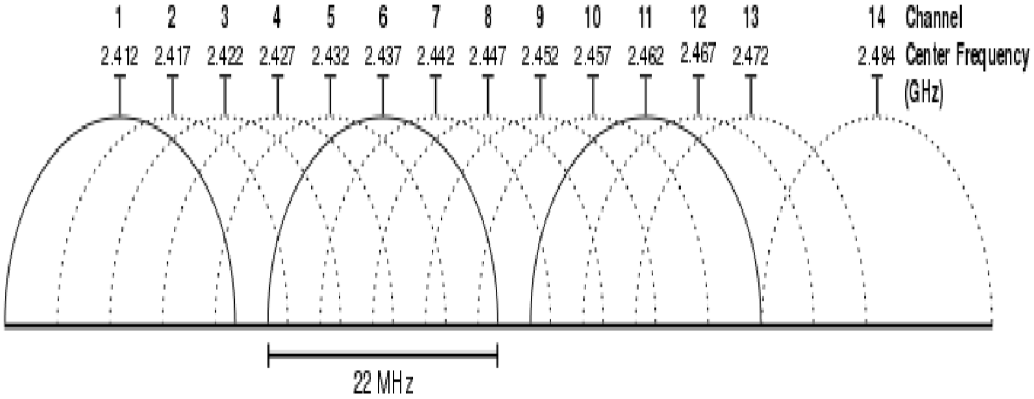


Figure 5: Frequency Spectrum of 2.4GHz Band

signal accordingly, there may be a high possibility that signal of one MR can interfere with signals of neighboring MR resulting in the corruption of data which is called Interference. Interference in wireless networks is a major issue to be handled carefully. Every node transmits with some power which defines the coverage distance of the node's signal or the transmission range of the node. The higher the power being used, the more the transmission range of the node. If a node operates on higher power levels, then possibility of the node's signal interfering with any other signal increases due to increase in its coverage. However, the inherent advantage with the architecture of WMNs is to have many intermediate hops in order to avoid using the higher power for a node for transmission. Because of the existence of many intermediate hops, many links need to be active at the same time. With the fact that NOCs are very limited, it is very difficult to let many links active at the same time because of the co-channel interference and self-interference which we will explain in the following sections. As a result, for many links to be simultaneously active or for more spatial re-use, it may be necessary to exploit all the available channels of the spectrum but still face issues with adjacent channel interference.

Due to the limited number of NOCs in 802.11 b/g, recent studies [8] [9] indicate that utilizing partially overlapping channels (POCs) can increase network throughput dramatically. Indeed, POCs do not cause significant interference for concurrent transmission links if sufficient physical distances separate each transmitter from the receivers on other adjacent channels. Clearly, this minimum physical distance depends also on channel separation. The fundamental problem in wireless networks is to estimate their throughput capacity. The throughput of a wireless network varies upon what type of interference model is assumed and how it is handled. The links can be assigned only orthogonal channels and transmit at the highest possible data rate, but it allows only small number of links to be active. On the other hand, POCs can be assigned on the links, but needs to deal with interference. But allowing the interference can be compensated by the additional transmissions, even if they need to transmit at a smaller data rate. Our work in this thesis is to investigate the trade-off between allowing more interference, without loosing too much in the data rate.

We now explain some of the intereference types based on which the interference models are developed.

2.6.1 Co-channel Interference

There are several ways for the co-channel intereference to occur, some of the most important reasons are:

1. Two neighboring nodes are transmitting using the same channel and are in the interference range of each other.
2. Concurrent transmissions on the same channel if assigned on more than one radio of the same node.

For example in cellular networks, the area is divided into blocks called cells (Cell 1, Cell 2,....., Cell n). So the frequency spectrum used in one Cell 1 can be re-used in another geographical Cell n only if this cell is out of interference range of Cell 1. Thus for a receiver in Cell 1 besides the intended signal from within the cell, signals at the same frequency arrive at the receiver from a transmitter located far away in some other Cell n which leads to detoriation in receiver's received signal. This corruption occurs because the receiver gets confused as both received signals are of same frequency, and does not know which one to accept.

2.6.2 Adjacent Channel Interference

It results if two neighboring nodes are assigned channels that are partially overlapping to each other. From the previous works [21], it is found that POCs do not have the same degree of interference as co-channel interference but less. The effect of interference from adjacent channels is reduced as the channel separation or geographical distance is increased.

2.6.3 Self-Interference

A mesh node can consists of multiple radios. Self interference occurs when the radios of a node are assigned with partially overlapping channels. As mentioned in [14], some of the facts to overcome the problem of self-interference are:

1. The maximum number of parallel transmissions from a single node must be restricted to the number of maximum orthogonal channels available, which is 3 in case of 802.11b or 802.11g.
2. Ensuring that within a single node the channels assigned to the incident links are mutually orthogonal.

2.6.4 Interference Models

An interference model defines which links can be active simultaneously without interfering to any other link. Some of the interference models that have been used in the literature are discussed below.

K-hop Interference Model

With this model, no two links within K hop distance from each other can successfully transmit at the same time [26]. When $K = 1$, this condition restricts a node to either transmit or receive but not both at the same time.

Protocol Interference Model

This model is also called the binary interference model. Under the protocol model, a successful transmission occurs when the intended receiving node falls inside the transmission range of other non-intended transmitters. If two links $\ell = (u, v)$ & $\ell' = (u', v')$ are active in communication, the data reception at node v is collision free only when no other node is simultaneously transmitting within the interference range of node v. According to [11], this interference model is mathematically quoted as,

$$|u' - v| \geq (1 + \delta)|u - v| \text{ and } |u - v| \leq R_C$$

where R_C denotes the communication range of node u and δ is a positive parameter. When this condition is satisfied, then the data received at node v is collision free.

Interference Range Model

Interference range model is explained in [15] as a simplified model of the protocol interference model mentioned in [11]. Again, assuming two links $\ell = (u, v)$ and $\ell' = (u', v')$, this interference model is expressed as,

$$|u' - v| \geq R_I \text{ and } |u - v| \leq R_C$$

Here, R_I stands for the interference range and R_C stands for the communication range and both are related as $R_I = R_C(1 + \delta)$ to compare protocol and interference range models. In protocol model, just the distance between the transmitter and receiver is considered. On the other hand, the interference range model requires the separation between the intended receiver and non-intended transmitter to be greater than a fixed quantity, the interference range. Similarly, when this condition is satisfied, then data at node v is collision free.

Physical Interference Model

Physical interference model is the most commonly used model to calculate the interference because of the realistic constraints it considers [10] [31]. The communication on a link ℓ is successful only if the power received at the receiver is more than a threshold. More generally, it is represented as:

$$\textsc{sinr} = \frac{P_\ell}{N + \sum_{\ell' \neq \ell} P_{\ell'}} \geq \beta \tag{1}$$

where P represents the transmission power on the link ℓ, N represents the thermal noise on the frequency band of operation. This model also takes into account the noise from the other transmissions that occur simultaneously along with this link. β is a threshold value which is a physical layer dependent constant. The transmission is successful only if the SINR value at the receiver is above β. In this thesis, we used the physical interference model to calculate the interference among wireless links.

2.7 Channel Assignment

An important issue in a WMN is its *capacity* [3]. A WMN when operated with a variable number of channels results in variable capacities and interference plays the pivotal factor which decides the measure of the capacity. The interference that exists in wireless medium severely degrades the WMN capacity. The only alternative as a first step towards increasing the capacity of a WMN is to carefully use the multiple channels available in the spectrum. Channel Assignment (CA) is the process of assigning channels onto the radios of a node. In a WMN environment, CA can lead to channel utilization and a proper CA strategy can reduce the consequences of interference. The traditional WMNs only consists of one radio interface per node and so only one channel is assigned on all radios. The standard physical interference model calculates the interference among links assuming that all links are assigned the same channel.

With single channel WMN, the capacity of a WMN is very limited to only one link being active of a MR at any point of time. Since IEEE 802.11 spectrum consists of more than one non-overlapping channel, it is worth for an engineering effort in trying to assign different non-overlapping channels to the interfering links to increase the overall spatial reuse. There have been numerous approaches in exploiting the capacity of a WMN [23] such as channel switching and directional antennas. Unlike omni-directional antennas where the signal is spread out in all the space, MRs when equipped with directional antenna spread power only in limited direction making it to travel even farther because of the higher power levels. The critical issue with the directional antennas is with the practical deployment in large scale networks. With channel switching technique in WMN, a radio interface of any MR can switch between channels over the time. However, it can even lead to poor performance of the WMN if no proper tight synchronization of time is maintained, which is an additional overhead to deal with.

Due to the decrease in prices of the commodity hardware in recent years, it has become economical in equipping a node with more than one radio interface. So it is possible for a MR can be assigned as many number of radios as channels. However, the maximum throughput gets saturated after a fixed number of radios and then the change in the throughput is negligible with the additional radios. One of our objective in this work is also to find the maximum number of radios that leads to the maximum throughput.

With the existence of multiple channels in 2.4 GHz wireless spectrum, the problem is to address the issue of assigning which channels to what transmissions. However, the objective is assigning channels to the radios to mitigate interference and increase the overall spatial reuse. Some of the most commonly used channel assignment techniques used in literature as mentioned in [29] are described next.

Static Channel Assignment

In the context of *static channel assignment*, a channel when assigned for a radio will exist for longer durations of time. This is also called fixed channel assignment. With static assignment mechanism, a WMN do not behave differently for changing wireless conditions. This mechanism is well suited to back-haul networks. Tt is known that in back-haul networks, the traffic is assumed to be constant for particular amount of time needing the behavior of MRs to be preserved for that amount duration. These channels assigned on radios can be updated periodically to meet the latest traffic demands. However channel switching is infrequent in back-haul networks as it leads to small overhead.

Dynamic Channel Assignment

This is a good approach for the dynamically varying conditions of the wireless medium. In this type of mechanism, channel assigned on a radio needs to be switched to another channel frequently. However, if the channel switching is done more often, it results in additional overhead which requires a more challenging design. If a new channel is assigned on any MR, then accordingly the channels needs to be updated on other nodes, without which, the capacity of a WMN can change drastically. To avoid these kinds of issues, it is necessary to maintain a tight synchronization of time and coordination among nodes. Since the number of orthogonal channels are few in number, it is not always possible to dedicate channels onto the radio interfaces. So it is necessary to update channels on a frequent basis [22].

Hybrid Channel Assignment

In hybrid channel assignment, the radios of a node are classified into fixed and flexible [18]. The fixed radios are assigned with channels like in static channel assignment and the flexible radios are able to switch the channels assigned on them. When two nodes are communicating, the receiving node switches its channel on the flexible radio to the channel assigned on the fixed radio of the transmitting node allowing the MRs to listen to a common channel. This design scheme inherits the characteristics from both static and dynamic assignment.

2.8 Routing

Routing is the networking technique for determining routes for the MRs to send or receive the traffic. The traffic can be voice or data (emails, pictures, videos) and the routing of these types of traffic can be done for telephone networks, electronic data networks (Internet) and the transportation networks (back-haul networks). The routing can either be pre-determined before transmission begins or computed on the fly. Two basic transmission technologies that are used for the data transmission are described next.

Circuit Switching

In case of circuit switching technology, a dedicated point-to-point connection is established between sender and receiver. Circuit switching needs constant bandwidth available for the communication request until it terminates. This kind of technique is commonly used for voice communications in telephone networks. It includes both public switched telephone networks (PSTN) and cellular mobile communications. A dedicated path once set up cannot be re-used for another request until the scheduled connection terminates. For example, when a user dials a number for a voice connection, the nearest base station receives the request and it communicates with its neighboring base station if the destined user is in its coverage. If the user is found, then it establishes a point-to-point connection. When it is established, then for no other connection request can this path be re-assigned unless the initial connection terminates. If only one path is dedicated, then it is called as *single path routing*. It is also possible to assign more than one dedicated path for the connection request if necessary to provide the back up in case of any failure. This technology is also very commonly used in backhaul optical networks.

Packet Switching

Unlike in circuit switching, this technique allows no path to be dedicated for any communication and instead a path can be shared by more than one connection. This kind of technique is most commonly used for data networks, i.e., for emails, text messages, pictures and videos. The data to be sent is divided into chunks called packets and each packet contains a header which stores the final destination and the immediate neighbor (updates everytime). These packets are forwarded from one router to another intermediate router until it reaches destination. During transmission, different packets may take different routes and all the packets have to be re-assembled at the final destination and only then the data is re-organized in the order it was sent and gives back to the receiver. These intermediate nodes can be routers or bridges which have routing tables defined in their internal memory. The routing tables contain information about the address of the other nodes and how can they be reached. Every router fills the information of its routing table by using some standard protocols, e.g., *Routing Information Protocol* (RIP) or *Open Shortest Path First* (OSPF). These routing tables are updated periodically or when a change occurs in the network then the change will be broadcast-ed to all other routers in the network. When a router receives a packet, it opens up the header of the packet, looks for the final destination and finds from its routing table the next intermediate node to be reached on the path to reach the final destination. It is possible that a router contains more than one path for the packet to reach the immediate neighbor or the ultimate destination. Depending upon the networking constraints, router chooses the best hop and sends the packet to the next hop. Because a router can have more than one path to reach the destination, the route information can be single or multiple.

Single Path Routing: if a MR contains only one path to reach another node in its routing table. In this case, if any failure occurs then the connection either has to be re-set or the MR has to wait until a new path is determined. This is most commonly used in traditional networks. Unlike circuit switched networks, a single path here can be shared by more than one connection. By *single path routing*, it does not mean that the route is of minimum cost, i.e., in practice, every route is associated with some cost and if the route with the minimum cost is chosen then it is called as *single shortest path* between sender and receiver. To determine the route with the least possible weight, few algorithms that are most commonly used in literature and in practice are mentioned in Section 2.4.3

Multi-path Routing: if a MR contains more than one path to reach the immediate hop or the final destination. In this case, if any route fails then the router can switch to another route for transmission of packets. Another advantage with multiple paths is, if a router has many packets to transmit then it can distribute packets proportionally on more than one path to avoid congestion or to reduce the delay in the network. In case of *multi-path*, it means that more than one route with the same minimum cost is chosen as another route or the routes are ordered in increasing order of costs. Networks today are sophisticated and very intelligent and are capable to determine and store more than one path to reach the destination, so that a MR can switch between the routes if it needs to. Most of the algorithms mentioned earlier can be used to compute the multiple shortest paths other than *Dijkstra's* algorithm, because it is only used to compute the single source shortest paths.

After the routes are determined, a MR should be able to send the data to its immediate hop or MR. But, there are several constraints which restrict how data is transmitted from one MR to another such as which packets to deal with or which link to choose. These constraints are taken care by the scheduling techniques which are mentioned in Section 2.9.

2.9 Scheduling

Scheduling is the technique which lets the transmission of data from one MR to another. In a network, every MR either wants to send data or to receive data and only with a proper scheduling decision, packets can be received or sent properly. Lack of a proper decision results in the corruption of data due to interference or delay because of congestion. The scheduling algorithm is incorporated into *media access control* layer of the *data link layer* (layer2) of the TCP/IP Internet model. Some classes of the MAC protocols according to [16] are channel partitioning, random access and taking turns. A short description of each of these techniques are explained below.

Taking Turns

The concept of taking turns is most commonly used in *token ring* networks where a MR can transmit only if it holds the token and then passes to other node. The decision about which node can be given chance to hold the token is determined by analyzing several factors such as delay and priority of nodes.

Another variant of taking turns is *polling*. All nodes are connected to a server, and it is server's responsibility to choose (*poll*) a node either to transmit or receive. If a node is chosen, then it can either send data to server or can send to any other node. Again, the decision of whom to choose depends upon several factors like above such as delay and priority.

Random Access Protocols

Random access protocols of the MAC layer allows all the nodes to start transmitting if they have packets to send. The earliest version of the random access protocol is ALOHA, where every node starts transmitting as soon as they have some data. This may result in collision if more than one node transmits towards a base station. A refinement of ALOHA is carrier sensing multiple access CSMA. In the previous section, we have explained about CSMA/CA in data link layer issues, and here we give the difference between ALOHA, CSMA and CSMA/CA. With CSMA, a node first listens to the medium. If it observes that the medium is idle, i.e., no other node is using the medium then the node can start transmit. Though this works better than ALOHA, it still fails when two nodes start sending at the same time. CSMA in short can be called as listen before talking. So if two nodes start talking to each other at the same time then the message cannot be clearly received. The major disadvantage of CSMA lies in the fact that even after the collision of data the corrupted message is still transmitted over the channel which results in wastage of channel bandwidth. With a further development in the generic version of CSMA is the CSMA with collision detection CSMA/CD. Unlike in CSMA with CSMA/CD when there is a collision on the medium instead of wasting the whole bandwidth it ceases the transmission by randomly backing off for some time. So the node can again try to transmit after the *back-off* time period finishes. The simplest observation with CSMA is, if the propogation delay increases, then the probability is higher for a collision to occur. With CSMA/CA, it avoids the collision which can occur from hidden node problem, i.e., a collision at the receiver can occur when the receiver is part of the coverage areas of two senders. CSMA/CD is mostly used for wired networks but not for the wireless networks. It is because of change in power sensitivity of MRs is different in both types. Even though CSMA/CD can detect collisions, it is CSMA/CA that is used in the MAC protocol for 802.11 in practical wireless networks.

Channel Partitioning

This is another MAC technique that can be used for scheduling, which is further classified into TDMA, FDMA and CDMA. The most commonly used of these are TDMA and FDMA. FDMA is called the frequency division multiplexing access where every user or a node is assigned one or more frequencies for the transmission. It allows multiple users to simultaneously transmit at the same time but with different frequencies. Figure 6 represents a FDMA where the frequency is shared between multiple users for a duration of time.

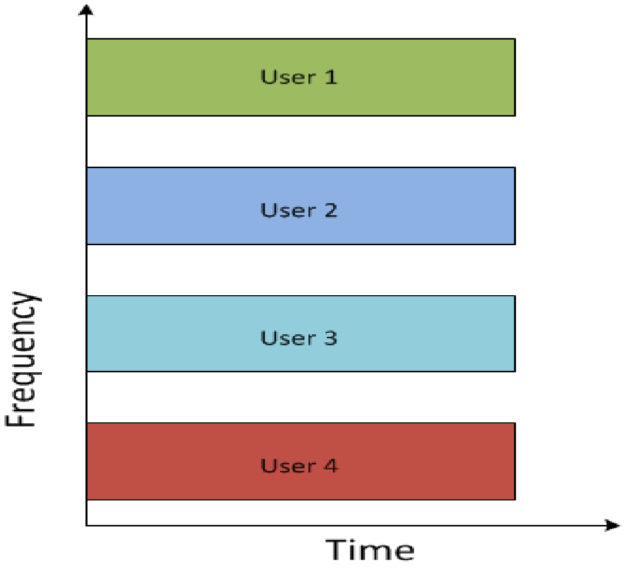


Figure 6: Frequency Divison Multiplexing

On the other hand, TDMA is called time division multiplexing access, where the time frame is divided into multiple time slots and each time slot allows multiple users to simultaneously transmit as shown in Figure 7.

Since a WMN is a multi-hop network which is composed of many links operating at different frequencies of 2.4 GHz spectrum, we try to gain the advantage from the spatial re-use of the links of network. Spatial re-use is one of our major objective when developing our algorithms, to maximize the number of active links at any point of time by considering the factors such as link load and the links adjacent to gateways. We use TDMA as the channel partitioning technique in our work.

Each access scheme has its own pros and cons. CSMA is fully distributed contention-based well suited to environments with no central entity and characterized with bursty and unpredictable traffic. In case of high traffic conditions, many collisions could occur which results in less throughput as many nodes contend for the medium at the same time.

In contrast, TDMA is a synchronized access scheme, typically managed by a central

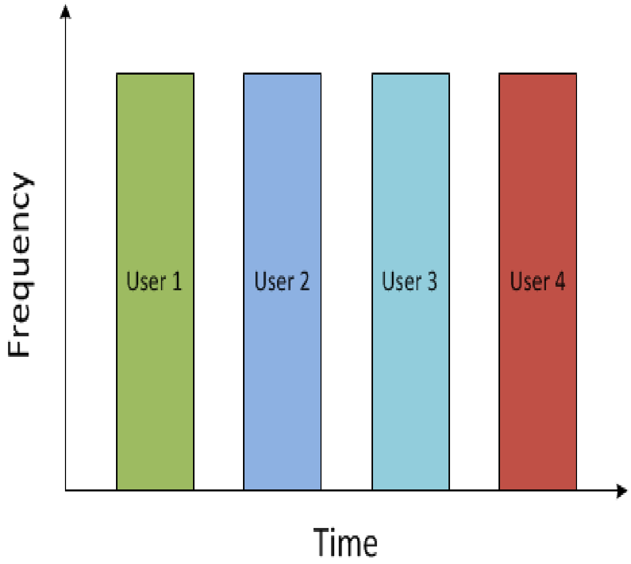


Figure 7: Time Divison Multiplexing

entity responsible of defining a frame schedule. No collision occurs in TDMA (at least theoretically) as only compatible transmissions are allowed in each slot. The result is high network utilization and throughput. The drawback is, TDMA is efficient only in conditions with stable and known traffic demands, and when there is no router mobility [22]. Otherwise, TDMA is less efficient that CSMA as some slots are empty while other ones are crowded.

Since our work assumes a stable traffic, we consider TDMA as our MAC based access scheme.

Chapter 3

Literature Review

In this chapter, we present and compare some of the previous work on WMNs and their advantages and disadvantages. Section 3.1 gives a detailed introduction about WMNs in the context of the channel assignment and scheduling problems. In Section 3.2, we present some of the existing work done on the WMNs.

3.1 Introduction

Most of the introduction to WMNs has been given in the earlier chapters. Here, we further extend our introduction in the context of the work done to exploit the advantages of the WMNs. A WMN as explained in [28] is a *converged network*. It means, a WMN by itself is not a very own unique standard but inherits features from existing wireless technologies such as WLANs, mobile ad hoc networks, etc. Over the years, much effort has been done from both academic and industry researchers to design and manage WMNs. All their efforts put together makes the WMN technology to be highly efficient in realistic networks when compared to many other existing wireless standards.

Today, the standard becomes very reliable but still many issues are still open and have to be resolved. Since WMN is a *converged network* from other standards, it also brings some of the advantages and dis-advantages from those existing standards. In this section, we present some of the previous work done on the WMNs for the *channel assignment* and the *scheduling*, the type of parameters they assumed. As explained in earlier chapters, *channel assignment* is the process of mapping the available channels onto the radio interfaces of a node and *scheduling* is the process of transmitting the data from one node to another node, one time slot at a time, until it reaches the destination. Most of the algorithms proposed in the literature can be classified into two types of approaches: heuristics and exact methods. Heuristics are the algorithms which may not give the best possible answer but are scalable and can run in polynomial time. On the other hand, optimization problems can be assured to give the best possible solution, but may need very large amounts of time to compute the solution. Both problems are known to be NP-hard. Some of the work done on these approaches are presented in the following sections.

3.2 Partially Overlapping Channels are Better

There has been lots of work done which claims POCs perform better than OCs in improving the aggregated network capacity with exploitation of all available channels. We classify the existing work by their radio assignments, interference models that used for calculating the interference, channel assignment techniques they use for assigning the channels and then scheduling techniques for transmission of data. We also give a brief summary of the works done using exact methods.

3.2.1 Radio Assignments

In [17], Liu *et al.* prove that POCs has the potential of increasing throughput capacity in WMNs by allowing more links to transmit simultaneously using only one non-switched radio per node. Their simulation results shows that POCs can gain up to 30% over OCs. Authors in [17] use only one gateway and maximum of two hops in their simulations, from which the improvement is not obvious. Like in [17], authors of [31] also claim that POCs perform better than OCs, but use half-duplex radios on every node which makes a node to transmit on one radio and receive on another radio. Simulation results of this work shows that POCs perform better than OCs by 43% by considering one gateway, but without true scheduling of end-to-end delivery of packets. The channels are assigned on the nodes by giving priority on the increased distance from gateway. Hoque *et al.* [14] considered multiple radios per node but with full-duplex functionality radios. They show that, even in such a case, POCs lead to better performance when compared to OCs. Their results indicate that a capacity gain of more than 15% on average and up to 30% by using POCs over OCs. In measuring the performance, they use the percentage of assigned links for a given link load. Another major drawback of this work is they ordered nodes upon the node degree allowing a node with many incident links to be given highest priority. Another interesting work which argues POCs are better than OCs is by Skalli *et al.* [28], which considered 3 radios per node. Among the three radios, one radio is a default radio which is used for the network management. Recently, Duarte *et al.* [6] have also proposed a channel assignment with multiple radios and showed that the POCs does better than OCs. All of these works with different claims in their algorithms and settings of the simulations, also yield different amounts of increase in throughput with POCs. Most of these channel assignments are static assignments, i.e., channels are mapped to radios for longer intervals of time. Liu *et al.* [18] has proposed a hybrid channel assignment technique by employing multiple radios and prove that POCs yield better network capacity improvements, though this type of channel assignment mechanism is not suitable for realistic networks. In this hybrid assignment, the radios are being classified into fixed and flexible interfaces. On a fixed interface, a channel is assigned for a longer duration of time like in previous static assignments. Where as the flexible interface is dynamic in nature of a receiver node and always gets tuned to the channel on the sender's fixed interface. Their work also tells that if a node is idle, then the flexible interface is assigned with a default channel like in [28] which is used for network management.

3.2.2 Interference Models

As mentioned in the earlier chapters, there are many types of interference models that exist in literature and different works use different interference models depending on the nature and complexity of the problem they consider. Research work done in [17], [31] use the physical interference model, which is the most realistic model for capturing the interference. Unlike in these works, [14] developed its own interference model for their channel assignment based on some testbed values from [8]. They used interference matrix (I-matrix) as a parameter to check the least interfering channel and if it can be assigned. The I-matrix values they used are not actually valid in all circumstances and especially with variable power levels. On similar lines, [6] has also proposed new channel assignment schemes developing the work of [14]. Unlike in these works, [28] have assumed the protocol interference model or binary model which is not a very good model in capturing the interference, as it only measures the interference between any two links at any point of time. In [18], authors have developed a new interference model which calculates the interference of a node only from its neighbors. Their distributed framework of channel assignment mechanism considers the channel overlap and the amount of activeness of the neighbour.

3.2.3 Channel Assignment Techniques

Channel assignment algorithms proposed in [6], which is an update of [14] and [28], ordered the links in decreasing order of traffic. Both [14] and [6] use the same I-matrix to determine the least interfering channel although the former's algorithm may result in some of the radios being not assigned a channel. This problem is studied and resolved in [6]. All these works use POCs. Like in the previous work, [28] also orders the links but based on a ranking system and the rank of each node depends on the amount of aggregated traffic through each individual node, but also considers the distance of the node from the gateway and the number of the radios assigned on the node. Wang *et al.* [31] showed that POCs can also be assigned with a conflict graph approach where a channel with least conflict nature with its neighboring links is assigned as a channel on the link. A genetic algorithm based heuristic approach of channel assignment is proposed in [17] using POCs, where a channel is assigned on a link based on the link capacity parameter. Without any prior order, all nodes are being assigned a channel on its fixed radio and then the channel on the default radio and the procedure may gets triggered periodically based on the packet loss ratio in [18].

3.2.4 Scheduling Techniques

Scheduling in WMNs can be done either with TDMA framework or with the CSMA framework as mentioned in previous Chapter 2. The scheduling technique proposed in [17] is based on a TDMA framework where only the conflict free links can be scheduled in any time slot. They used genetic algorithm in determining the independent sets of links. Contrastly, CSMA framework only allows a node to transmit with some probability and the simulations in [6] use CSMA in delivering the traffic towards the receiver. Some of the works like in [17] do not perform the actual end-to-end delivery of the packets but instead only estimates the expected transmission count of packets delivery using some standards of routing protocols and calculates the throughput of the network. This type of calculation of the throughput does not correspond to the true scheduling.

It is often very difficut to develop a strategy which offers the best possible solution for every instance of wireless network, because every network instance has its own demands. Because of this, scheduling is a *combinatorial optimization problem.* Many existing works tried to develop the complex mathematical models for the problems of channel assignment and scheduling with routing and power control.

3.2.5 Exact Methods

Luo *et al.* [19] have developed a complex *mixed integer linear* problem to evaluate the quantitative measures of the impact of choices for the power control, routing and the physical interference model on a WMN. Since it is very complex by employing joint routing, power control and scheduling, this problem is broken down into master and pricing problem. Authors developed a column generation based greedy pricing tool to solve the pricing problem. Their results indicate that a WMN based on several choices like fewer power levels are sufficient to gain the maximum performance of the network. Multi-path routing is of not much advantage when compared with the single path routing and the independent sets leads to the spatial re-use of the network. A similar modeling work is also done in [8], [30]. Authors in [8] defined as a integer linear problem and from the results POCs perform better than OCs in one-hop and multi-hop networks. The concept of variable width spectrum is proposed in [30] and showed that the dynamic channel assignment with variable width spectrum improves the network capacity compared to the fixed bandwidth networks. However both works used *interference range* model to compute the interferences for channel assignment and link scheduling by allowing the node to parallely communicate no more than the number of radios assigned on it. The column generation problem to be solved in [30] is decomposed into a primal and dual problem. Since the dual problem is a hard ILP, a simulated annealing technique is proposed for the link scheduling in determining the transmission configurations.

3.2.6 Gateway Instances

Most of the previously mentioned work only considers only one gateway in their simulations, which is not the case in realistic networks, and they consider only one-way traffic that is either uplink or downlink for their simulations. However, the logic implies the same in transmitting the traffic in either way, but simulating one-way traffic and two-way traffic results in different levels of throughput increase because of the number of radios being active and the delay in the transmission. In [6], only one gateway is considered with a grid topology for their simulation, like [6], work in [32], [14], [6], [2] also considers only one gateway and all of these results only consider one way traffic. The outcome of these works do not correspond to the effective network. Because true WMN may have more than one gateway and the traffic flows in both uplink and downlink directions, which results in more activity of the links of the network. Employing multiple gateways is very difficult to handle with most of the proposed algorithms. In contrast to these works, we allow multiple gateways for realistic scenarios and conducted simulations taking into account two way traffic. Our algorithms are still capable to handle variable number of gateways without adding any additional constraint.

It is also a question on location of gateways in a WMN. The location of the gateway(s) depends upon handling more number of requests. He *et al.* [13] proposed algorithms on how to place multiple gateways in a WMN by breaking down the given network topology into a tree structure and restricted a node to communicate with only one gateway. This is not a good approach as a node should be able to connect to more than one gateway. Qin *et al.* [33] consider channel switching overhead as a measure to define the limited number of mesh nodes to be equipped with gateway functionality in WMN. However none of these works did exploit the end-to-end data transmission between nodes properly. We have developed several new strategies, so that a node be able to communicate with multiple gateways but only if it meets certain criteria which are explained in our algorithms. Some of the existing literature [32], [33], [17], [2] put effort on scheduling end-to-end data transmission in a TDMA approach by defining the transmission configurations of non-conflicting links. These independent set of transmission configurations are determined based on the interference models and by not allowing any interference in each configuration. In this work, we introduce transmission configurations, which allows a set of links able to transmit concurrently.

We believe that though there is a lot of existing literature on routing, channel assignment and scheduling of WMNs in both polynomial time algorithms and with complex optimization problems, to our best knowledge there is no such work which answers all these issues of the WMNs on a modular step-by-step approach in developing an efficient WMN from scratch by taking into account the realistic characteristics. In our work, we have proposed few polynomial time algorithms with each algorithm contributing to a development phase of the WMN by careful handling of the interference, routing, channel assignment and end-to-end delivery of packets in scheduling. The algorithms we have proposed correspond to a very fresh approach and we developed the transmission configurations which reduces delay and increases fairness when scheduling the packets and our results also indicate that the performance of the POC perform better than OCs.

Chapter 4

Assigning and Scheduling Partially Overlapped Channels in WMNs

In this chapter, we explain our contribution towards our thesis. In Section 4.1, we give the introduction about this chapter. Section 4.2 provides a very detailed step-by-step explanation of the physical interference modelling. In Section 4.3, we explain our channel assignment algorithm. In Section 4.4, we explain the scheduling algorithm we proposed and how all the algorithms are connected.

4.1 Introduction

The objective of this study is to evaluate the performance of the existing channels of IEEE 802.11 2.4 GHz by exploiting all the available channels to increase the spatial reuse and to increase the overall throughput of a WMN. In order to achieve this goal, we proposed several algorithms of polynomial time complexity for channel assignment and scheduling. We use the physical interference model for estimation of interferences and define transmisson configurations for TDMA scheduling. In addition, the proposed algorithms are developed on a layered approach, where the algorithms are independent of the outcomes of the other algorithms. This is an effort to build the system as close as possible for the design and management of WMNs.

4.2 Interference Model for Multi-Radio Multi-Chanel Wireless Systems

The wireless medium is omnipresent. When two nodes established a link, it means these two nodes are tuned to the same channel. From the background knowledge of Chapter 2 and from the previous work done by many researchers mentioned in Chapter 3, it is understood that most of the problems in WMN move around the spatial reuse of the wireless medium. An efficient system of WMN should allow more links to be operated at the same time. With more links active at the same time, it results in more transmissions resulting in higher throughput.

To build an efficient WMN, it is necessary to consider several realistic constraints. Interference is the most important factor in a WMN because of the overlapping channels. Even with a minor improvement in handling the interference, it results in larger levels of increase in throughput of a WMN. Given a WMN and given some traffic patterns, with proper scheduling techniques, the data has to be carried from the source to the destinations. Only with an efficient scheduling and interference technique, it is possible to increase the performance of the WMNs. The efficiency of the scheduling though depends on the interference, but still has to answer many challenges. Some of the challenges are *fairness* and *delay*. Fairness expresses the opportunity of a node to be able to transmit. If a node gets more opportunities to transmit, it means the node has a good amount of the share of the bandwidth. Delay is another factor which has huge impact on the throughput performance of the scheduling in WMN. With a less delay, a node is not required to wait too long in getting an opportunity to transmit. It is also possible to assign some priority on traffic at any node. So the traffic engineering in scheduling of WMNs should act accordingly depending upon the priority of the traffic. When acting upon the priorities of the traffic, it becomes a complicated problem in assigning the possible fair share of the bandwidth. In this work, we considered *fairness* and *delay* indirectly, which we explain it later in our algorithms.

In our earlier sections, we have given a brief introduction about the types of interferences and their impacts. Here, we model the physical interference model and introduce the definition of *affectance*. We use the affectance in our channel assignment algorithm for estimating the interferences among wireless links and assign a channel with least possible interference. We use SINR in defining transmission configurations.

Physical model

Under the physical model, a transmission is successful, if and only if SINR at the intended receiver exceeds a certain threshold so that the transmitted signal can be decoded with an acceptable bit error rate (BER). Physical model is widely considered as an accurate representation of physical layer behavior in real systems [27].

The modeling and estimation of interference is well explained in [10] and we represent it in the following steps.

Step 1:

The intensity of the signal received at the receiver is inversely proportional to the distance between the sender and the receiver, i.e., the more the distance between the sender and the receiver, more is the fall in the power levels of the signal. So, the relation of the power between the sender u and the receiver v is expressed as:

$$P_v = \frac{P_u}{d_{uv}^{\alpha}}. \tag{2}$$

Here, P_u is the power with which the sender transmits the signal and P_v is the power being received at the receiver, d_{uv} is the physical distance between nodes u and v. Parameter α is called the path loss exponent, which is a constant. The value of α depends on the various external conditions of the medium such as humidity, obstacles etc, as well as the exact sender-receiver distance. Experiments from previous work measure the value of α at various frequencies for both indoor and outdoor ranges from 1.6 to 6. According to [10], most of the previous works assume the value of α to be between 2 and 4. The term $d_{uv}^{-\alpha}$ is also called as the propagation attenuation or link gain on ℓ between the sender u and receiver v. This is the first step towards defining a physical interference model, however it only estimates the power level only one link.

Step 2:

In WMNs, many links can transmit at the same time. Since the radios are omnidirectional, the power from some non-intended sender s can still affect the total power received on an intended receiver v. A standard physical model needs to calculate the accumulated power dissipated from all other non-intended senders on the intended receiver. If there is a set L of links that can be active simultaneously (not including ℓ) along with the link $\ell = (u, v)$, then the total power received at the receiver v can be computed as,

$$P_v = \sum_{(\ell' \neq \ell) \in L} \frac{P_u}{P d_{u'v}^{\alpha}}. \tag{3}$$

Step 3:

We still need to consider the power of *ambient noise*, which is also called as background noise in calculating the interference, which usually exists in wireless medium. Let η be the power of ambient noise. Therefore SINR at the intended receiver v on link ℓ is calculated as:

$$\textsc{sinr}_v = \textsc{sinr}_v(S) = \frac{P_u}{\sum\limits_{(\ell' \neq \ell) \in L} \eta + P d^{\alpha}_{u'v}}. \tag{4}$$

Above are the detailed step-by-step approach in developing the physical interference model. The transmission is successful on a link at the intended receiver only if the power received at the intended receiver is above a certain threshold. We used the threshold values presented in [4].

Interference Model in Our Work:

According to the physical interference model, a transmission $\ell = (u, v)$, occurring simultaneously to a set L of other transmissions would be successful, if its associated SINR measured at the level of the receiver v is greater or equal to a threshold β. It is given by:

$$\textsc{sinr}_\ell(L) = \frac{P d^{-\alpha}_{uv}}{\eta + \sum\limits_{\ell' \in L} I_\ell(\ell')} > \beta \tag{5}$$

where P is the transmission power of node u, d_{uv} is the physical distance between nodes u and v, α is the path loss exponent (varies usually between 2 and 6), η is the power of the ambient noise. The values mentioned are for the outdoor settings of a WMN, which we use in our simulations. Note that all the nodes here are assumed to transmit with the same power level P. $I_\ell(\ell')$ represents the amount of interference caused by the link $\ell' = (u', v')$ on link ℓ. It is given by:

$$I_\ell(\ell') = P d_{u'v}^{-\alpha}. \tag{6}$$

The above equations are valid when the links are on the same channel. To address the case when nodes transmit concurrently on different but POC channels, Mishra *et al.* [20] introduce the notion of *I-factor*, denoted as $I_f(c_\ell, c_{\ell'})$, which measures the extent of overlap between channels c_ℓ and $c_{\ell'}$. The I-factor does not depend on the radio propagation properties of the environment and can be computed either analytically or empirically. It scales from 0 for completely orthogonal channels to 1 for similar channels. Table 1 from [20] shows the I-factor values in IEEE 802.11b/g as a function of channel separation.

Table 1: I-factor for possible channel separations in IEEE 802.11b/g

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

In general case, where links ℓ and ℓ' transmit on arbitrary channels c_ℓ and $c_{\ell'}$, respectively, $I_\ell(\ell')$ would be written as:

$$I_\ell(\ell') = P d_{u'v}^{-\alpha} I_f(c_\ell, c_{\ell'}). \tag{7}$$

According to [10], the relative interference of link ℓ' on link ℓ is the increase caused by ℓ' in the inverse of the SINR at ℓ, namely,

$$RI_\ell(\ell') = \frac{I_\ell(\ell')}{P d_{uv}^{-\alpha}} = I_f(c_\ell, c_{\ell'}) \frac{d_{uv}^{\alpha}}{d_{u'v}^{\alpha}}. \tag{8}$$

For convenience, $RI_\ell(\ell)$ is set to 0.

Affectance:

In [12], the authors introduce the notion of the *affectance* of a link ℓ, caused by a set S of other transmitting links. It is given by,

$$a_\ell(S) = \eta_\ell \sum_{\ell' \in S} RI_\ell(\ell') \tag{9}$$

$$\text{where} \qquad \eta_\ell = \frac{\beta}{1 - \dfrac{\beta\, \eta\, d_{uv}^{\alpha}}{P}}. \tag{10}$$

Intuitively, the affectance measures at what extent some link suffers from interference while considering also its own received power and the SINR threshold that it has to exceed. Moreover, it has the interesting property that a set of links S is SINR-feasible (the SINR at each receiving node is at least β) *iff* $\forall l \in S, a_\ell(S) \leq 1$.

Both SINR and *affectance* are the same in estimating the interference. *Affectance* is the inverse of the SINR. We use the concept of *affectance* in calculating the interference or affectance in assigning channels in our channel assignment Algorithm 3.

4.3 Channel Assignment

We define the notations in Section 4.3.1. We then discuss the channel assignment in the context of a multi-channel multi-radio wireless network in Section 4.3.3. The proposed channel assignment algorithm relies on an estimation of the traffic on each link, which we build in Section 4.3.2.

4.3.1 Notations

We consider a WMN represented as a graph $\mathcal{N}^{\mathrm{W}} = (V \cup G, L)$, where V is the set of MRs, simply referred to as nodes, G is the set of gateways, and L is the set of links. We assume that each node v has n_v^{RADIO} radios, and each gateway $g \in G$ has

n_g^{RADIO} radios. Each node or gateway can use its radios simultaneously to send or to receive data. We will use the generic index u, when we do not want to distinguish the router nodes from the gateways. Besides, each node v has a given volume of uplink traffic to transmit to Internet through one or several gateways, denoted by T_v^{UL}, and a given volume of downlink traffic to receive from the Internet through each gateway g, denoted by T_{gv}^{DL}. For each link $\ell \in L$, we assume an uniform transmission power P. Also, we assume n^{C} partially-overlapping available channels and R possible data rates. A transmission configuration T is defined as a set of transmission links $L' \subseteq L$ where $\forall \ell \in L', \text{SINR}_\ell(T \setminus \{\ell\}) \geq \beta$. Note that β denotes the SINR threshold associated with the lowest data rate in R.

Communications inside the network follows a TDMA access scheme, where each time frame is composed of a number of fixed-duration slots. Our target is to figure out the number of slots and the mapping between each slot and a transmission configuration for the overall throughput to be maximized. Our approach consist in solving the problem through a sequence of 4 stages, where each stage considers an individual aspect and involves a heuristic-based algorithm having as an input the results of the previous stage and producing an output for the next stage. These stages are described in the subsequent sections.

4.3.2 Stage 1: Routing and Traffic Estimation

This is the first stage in our scheduling of WMNs, where we define the routes and distribution of traffic. The goal of this stage is to determine the routes and evenly distribute the traffic onto the links. Our work assumes the traffic to be static and is known as input. Our motive is to always exploit the advantages with the information we have in hand at any stage as much as possible. To begin with, we define all the routes as a first step because we have the node positions and define the routes between all the MRs to the gateways and vice-verse and then explain about distribution of traffic. The shortest path defined in our algorithms is with the hop count but not with the euclidean distances. It is because, the maximum length of a link cannot be more than a fixed value and so the power. So, it makes easy to deal with the same power levels when assumed minimum hop count as the shortest routes. Our task is more about the planning of the WMNs, so we assume the traffic to be static. This is also due to the fact that most of the traffic instances in back-haul networks are static for particular duration of time [22]. Since we have the traffic information of each of the node, i.e., the amount of traffic it has to send, we use that information to distribute traffic. In our terminology, the *uplink* traffic is from all the MRs to the gateways (Internet), *downlink* traffic is from the gateways to the MRs.

Sub-stage 1: Routing

The routing technique we used in this work falls under the variety of *opportunistic routing* and is part of the network layer of the TCP/IP Internet model. With our routing technique, a MR can establish a route to all the gateways or a subset of gateways. The shortest paths from the MR towards gateways are considered as the uplink routes and the shortest paths from the gateways to the MRs are considered as the downlink routes. We use the *Dijkstra's* algorithm for computing the shortest paths. From Algorithm 1, we first compute a unique shortest path from each gateway to every MR. We assume that every gateway should be connected to every MR, because we believe every gateway provides some unique services which other gateway(s) may not provide. We assume that every MR should be receiving all services offered by all gateways. As a result, for downlink routes, every gateway has a unique downlink route to every other MR. For example, if there are 5 gateways and 50 MRs in a WMN, then every gateway has to compute a shortest path to all the MRs resulting in 50 ×

5 = 250 total downlink routes.

After the downlink routes, our algorithm computes *uplink* routes, we again use *Dijkstra's* algorithm in computing the shortest path from a MR to ever other gateway. Like in previous example, every MR has to calculate a shortest path to each of the 5 gateways resulting in 50 × 5 = 250 total uplink routes. But unlike in downlink routes, here not all the routes are feasible, and we developed a condition to ignore some of these routes which are unrealistic. With our condition mentioned in the Algorithm 1, a MR can exclude the uplink route to any gateway if the hop count on that route is more than m% to the route of its closest gateway. Indeed, we chose the value of m as 30% in our work, so the length of longer selected path between v and some gateway g do not exceed the length of a shortest path between v and any gateway from G by more than 30%. Clearly on the uplink side, our intention is to associate each node v only with the most closest gateways in terms of the number of hops, while ensuring a certain level of route diversity. By this we can avoid the congestion on the shorter path by also distributing some of the traffic over the longer path.

We are motivated by the fact that the Internet in real time consists of more than one gateway and so it is necessary to make sure *route diversity* exists among the uplink routes.

Sub-stage 2: Traffic Estimation:

After the routes are determined, this stage estimates how much traffic will be carried on each transmission link. The complete process is described in Algorithm 1. The basic idea is to strive to distribute each uplink traffic in an even manner among the selected paths to the gateways, but with minimizing at the same time the maximum amount of total traffic (uplink and downlink) that a link would carry. Algorithm 2, referred to as *water-filling*, gives a formal description of this. Each time an uplink traffic is distributed over a set of paths, this algorithm fills up the least loaded paths until they carry the same traffic as the next loaded ones. The process repeats until all paths will carry the same amount of traffic as the most loaded ones $T_p^{\max}$. At that point, the remaining traffic is distributed evenly over all the initially selected paths. The algorithm can stop whenever the remaining traffic to be distributed is equal to zero. Note that the amount of traffic T_p^{UL} carried on a path p is defined as the largest amount of traffic carried on an edge e on p, where e designates two links having the same endpoints but with opposite directions.

Example for Traffic Distribution and Routing (Algorithm 1)

Here, we will demonstrate the procedure of Algorithm 1 with a small example.

As shown in the Figure 8, we have a set of MRs, gateways, traffic demand for each MR as input. For simplicity, only one gateway is chosen. As a first step, we determine the neighboring MRs for each MR. Every MR has the information of its neighboring MRs. Find the downlink routes using the *Dijkstra* algorithm as shown in Figure 9. Distribute the downstream traffic on these links. After that, determine the uplink routes for every MR to each gateway again using *Dijkstra*. Filter the uplink routes for every MR by allowing a MR to send the upstream traffic only to the closest gateways possible. Distribute the upstream traffic on these links using Algorithm 2. At the end of the Algorithm 1, every MR knows about its neighbors, uplink and downlink routes for MRs and gateways are determined and the links are assigned the traffic on it. It is shown in Figure 11.

4.3.3 Stage 2: Channel Assignment

Here we explain the channel assignment (Algorithm 3) we propose.

Our intention is to provide the WMN the full flexibility of choosing a channel

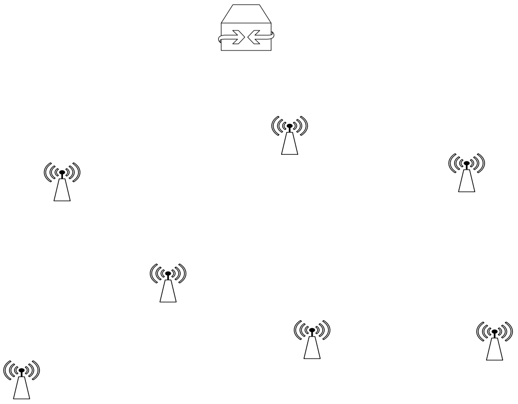


Figure 8: Procedure for Traffic Distribution and Routes - 1

and picks the best channel that can be well suited for its traffic demand on each of the link. Each link in the wireless radio transmission topology is assigned a channel which causes the least cumulative affectance (refer to Section 4.2) on the other already assigned links. The set C consists of all the 11 channels that are available in the 2.4 GHz spectrum band and the set L consists of all the virtual links in the WMN. The previous algorithm (Algorithm 1) tries to distribute the traffic evenly on all the links. Here, we use the outcome of the Algorithm 1 and try to assign channels onto the links in the decreasing order of the traffic demand on each of the link. In the *Initialization* step of Algorithm 3, we assign the link with the highest weight with one of the orthogonal channels, and in our simulations we assign 1. However, either 6 or 11 or any channel can also be assigned. We also define another set S, which stores the links that are already processed and are assigned a channel. These links are not considered again for the channel assignment procedure, though the interference from these links is considered when assigning a channel on a new link.

In the *Main Loop* of the algorithm 3, for every link, the affectance of each of the 11

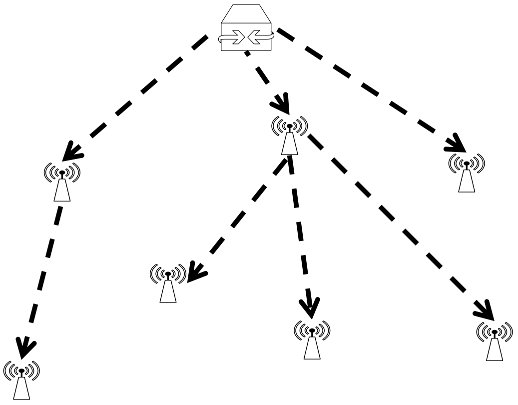


Figure 9: Procedure for Traffic Distribution and Routes - 2

channels is computed with respect to all the other links. The channel which results in the least affectance is assigned as the channel on the link ℓ. After the link is assigned with the channel then add the link to the set S to avoid considering it yet again as a candidate link for the channel assignment procedure. By assigning a channel of least affectance on any link, it brings on the minimum level of disturbance from the less loaded links on the more loaded ones and not the opposite. This allows the links with high traffic demand to be active simultaneously which results in a good performance of the WMN.

Example for Channel Assignment (Algorithm 3)

Here, channel assignment algorithm is shown with an example. As channels are assigned based on link weights, our framework uses the outcome of Algorithm 1 for assigning channels on the links. As shown in the Figure 12, links are labeled in decreasing order of the traffic amounts. For simplicity, only uplinks are chosen. As we can see, links adjacent to gateways carry the highest amount of traffic. For every link,

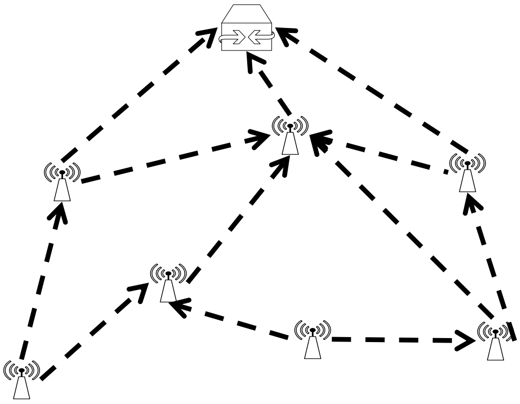


Figure 10: Procedure for Traffic Distribution and Routes - 3

the *affectance* for every channel is estimated and a channel with the least *affectance* is assigned on the link. In this example, 6 channels are considered out of 11 channels.

4.4 Scheduling Algorithm

At this point, we have each link assigned with a channel based on the information of the traffic estimation on the links. We propose a scheduling algorithm for multi-channel multi-radio wireless mesh network, that relies on ordering a set of transmission configurations, where each transmission configuration is a set of links which can simultaneously transmit during a given time slot. To achieve better spatial re-use, we use TDMA based link scheduling especially in case of WMNs, where the traffic requirements are relatively stable. We first describe the design of the transmission configurations in Section 4.4.1, and the scheduling of the configurations in order to maximize the throughput in Section 4.4.2.

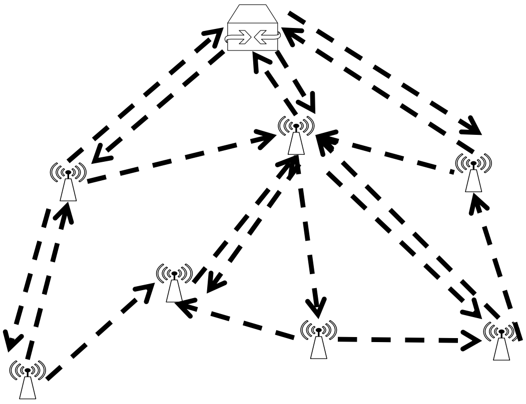


Figure 11: Procedure for Traffic Distribution and Routes - 4

4.4.1 Stage 3: Transmission Configurations

A transmission configuration (T) is a set of links, which can simultaneously transmit during a given time slot. These configurations are determined by taking into account physical interference model. An efficient scheduling algorithm needs efficient transmission configurations. Since configurations drive the performance of the scheduling, our Algorithm 4 develops configurations to answer several realistic characteristics like delay, throughput increase, etc., that may occur during scheduling. As mentioned earlier that we use layered approach in developing our algorithms, it is possible to replace our transmission configuration algorithm with a new one and everything else remains the same. Here, we use the outcome of the channel assignment and derive the configurations based on the logic defined in the algorithm 4.

According to Table 2, different threshold values apply depending on the modulation and the rate to be used.

For every T, we define a transmission capacity TCAP which is the sum of the data rates of all the links in that T. Since every link in a WMN has some amount of

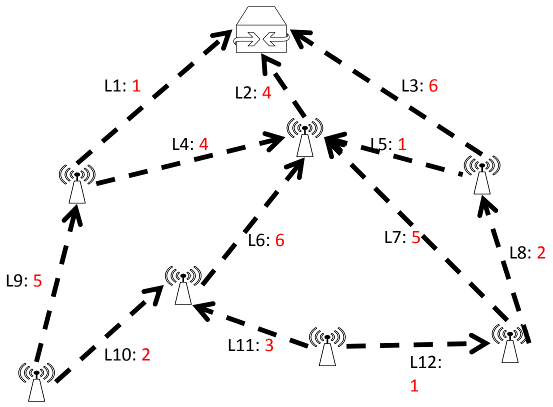


Figure 12: Procedure for Channel Assignment

interference, there is also an associated data rate that can be assigned to it from the Table 2.

$$\text{TCAP}(T) = \sum_{\ell \in T} \text{RATE}_{\ell}.$$

The logic for defining transmission configurations is divided into three steps and each of the step is explained detailedly below.

Step 1:

In the first step *Step 1: Building new configurations, covering all links* of the Algorithm 4, the algorithm starts building up the configurations by iterating all the links in decreasing order of weights. The link with the highest weight or TRAFFIC_{ℓ} is put into the T under construction. Then, we proceed iteratively in turn in the decreasing order of TRAFFIC_{ℓ} value and checking each link ℓ can be added to the configuration only if it satisfies few conditions like below.

Condition 1: The potential link if added to the existing configuration, then all the links in the configuration have to satisfy the SINR threshold condition.

Condition 2: This link if added to the configuration should not violate the condition on the number of radios for any of the corresponding end nodes. For example, if only two radios per node are allowed, then no more than two links that are incident onto the node can be put into the configuration.

Condition 3: If added to the configuration, then the new TCAP of the configuration should not be less than the current TCAP.

These three conditions are verified in the algorithm CHECK_ADD which is a subroutine of the Algorithm 4. Only if all these three conditions are satisfied by the link ℓ then it can be added to the configuration. By adding a new link, we do not want to disturb the links that are already in the configuration and because of this there is no surprise from the first condition that every link's SINR has to be above threshold for the successful reception of data at the receiver site. Since we know that the links in any T can be scheduled concurrently, from the second condition, we make sure we only allow the number of links of any node not more than the radios assigned to it. If more links of a node v are added into the configuration than the number of radios assigned to v, then those links cannot be scheduled. With the third condition, we try to maximize the amount of traffic to be moved in one time slot. If TCAP of a configuration is high, then if buffers also hold many packets, then a high amount of data is transferred from one hop to another, which may also result in the higher throughput. It is very easy to understand the outcome of the result of this type of setting when all the links in a T are transmitting data at the most possible rate then the throughput also leads to be very high.

During this step, if a link is added to any configuration, then it cannot be considered again for the next configuration. When building a new configuration, we first consider the links that are not yet embedded in the previous generated configurations again iterating the links in the decreasing order of the TRAFFIC_ℓ value. At the end of the first step, we have a set of configurations determined but with no two configurations can have a same link which shows there is still some more work to do as a link can be part of more than one configuration and is done in the following steps.

Step 2:

In Step 2 *Including at least one incoming link for each gateway* of the Algorithm 4, we try to improve the configuratons(T)s so that it tries to reduce the delay and increase the throughput during scheduling. It is further divided into two phases.

In *Phase 1* of the algorithm, we check if there is at least one incoming adjacent link(s) of each of the gateway (LAG) exists in every configuration. If no incoming link of any gateway is found in a T, then we just try to insert at least one incoming link ℓ of every gateway only if the link ℓ satisfies all three conditions mentioned above in Step 1.

If a LAG of any gateway cannot be inserted into any T, then we calculate SINR for evey link of the configuration by adding each LAG of the gateway. Do this for evey incoming link of the gateway. Now the SINR values of each of the configuration is computed for each of the gateway incoming link of the gateway. Among all these configurations, remove the links from the configurations, that which cause the least interference when trying to add a particular LAG and insert the LAG into the configuration. Do this for all the gateways whose LAG's are not embedded into T. If no link is found, then do not try to add the incoming link. In this case, we compromise the TCAP of the configuration i.e., we still try to add the incoming link even if the total TCAP may decrease. Allowing LAG's into each configuration is a greedy approach in increasing the throughput. Because of the existence of the LAG's in each of the configuration, these links can get a good share of bandwidth to transmit and as a result the throughout also increases because these links contain the highest amount of traffic.

Step 3:

Step 3 of Algorithm 4 is *Attempt to enlarge the configurations.* After the Step 1 and Step 2, we now try to check if we can enlarge any configuration T of the set $\mathcal{T}$. This is done by iterating all the links on each of the configuration T and check to see if a links can be part of the configuration by passing all three conditions mentioned above.

By the end of Step 3, we have a full fledged set of transmission configurations $\mathcal{T}$ and each configuration $T \in \mathcal{T}$ consists of a set of links which can be active simultaneously. Every link of a configuration also has an associated data rate based on its SINR value from other existing links of the configuration. We assign the data rates on the links much before the actual scheduling starts. We calculated the data rates by assuming all the links of a configuration are actively transmitting. The data rates assigned on the links is by assuming all the links of a configuration are active while transmitting, resulting in less SINR. These data rates assigned are lower bound. For example, if a link's SINR value is 10, then from Table 2, get the corresponding data rate (Mbps) assigned to this SINR (dB). So, for SINR value of 10, its corresponding data rate is 9 Mbps. The highest possible data rate can be assigned on a link is 54 Mbps and the lowest is 6 Mbps, which is well under the 802.11b/g standard.

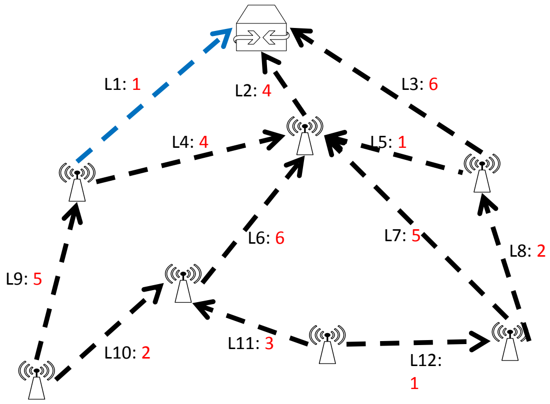
Example for Transmission Configurations (Algorithm 4)

In this Section, we describe a transmission configuration with a simple example. We use the outcome of the Algorithm 3 for defining the transmission configurations. The links are processed again in decreasing order of the traffic amounts. Insert the link with the highest weight into an empty configuration T1 as shown in Figure 13. Insert

802.11a/g (Mbps)	Modulation and Coding Scheme	Required SNR (dB)
6	BPSK 1/2	9.3
9	BPSK 3/4	10.3
12	QPSK 1/2	11.3
18	QPSK 3/4	13.3
24	16QAM 1/2	17.3
36	16QAM 3/4	21.3
48	64QAM 2/3	24.3
54	64QAM 3/4	26.3

Table 2: Link SINR parameters for 802.11a/g [4]

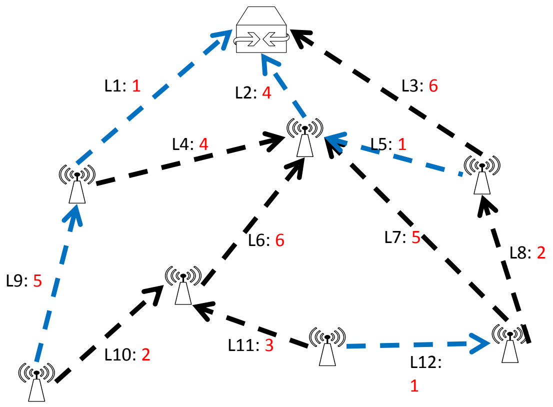
a link into the configuration by checking the SINR and TCAP of the configuration, i.e., a link can be added to the configuration only if all three conditions are satisfied. Figure 14 shows all the links labeled in blue color can transmit simultaneously in one time slot. Figure 15 has the links labeled in purple color can transmit simultaneously in another time slot. However, it is also possible that a link can be part of more than one configuration as shown in Figure 16, allowing multiple data rates for the links in different configurations. Ensuring a configuration contains at least one LAG is not shown in the example.



T1

LINK	THROUGHPUT (Mbps)
L1	36
TCAP	36

Figure 13: Procedure for Transmission Configurations - 1



T1

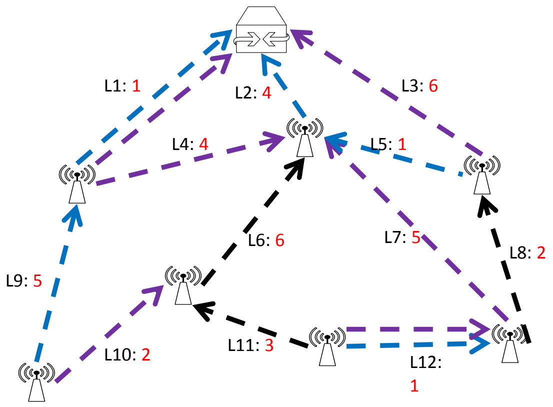
LINK	THROUGHPUT (Mbps)
L1	12
L2	12
L5	6
L9	36
L12	36
TCAP	102

Figure 14: Procedure for Transmission Configurations - 2

4.4.2 Stage 4: Scheduling

The scheduling algorithm (Algorithm 5) consists of determining the transmission configurations and mapping them to the time slots, so that the throughput is maximized, without letting the packets accumulating in the buffers (i.e., minimizing the delay indirectly). In order to do so, we assume that each node, whether associated with a wireless router or a gateway, has two types of buffers: the source buffers that contain the packets originating at that node, and the transit buffers that contain the packets on their way to their destination. Then, there is one source/buffer per outgoing link, taking into account the routing defined in Section 4.3.2.

Every packet contains the information of source, destination and the current node. After the execution of Algorithm 1, traffic is being distributed over all the source nodes buffers. The scheduling Algorithm 5 is of two phases: source buffer phase and transit buffer phase. During the source buffer phase it schedules the packets that belongs to the source packets and while in transit buffer phase, the packets belong to transit



T2

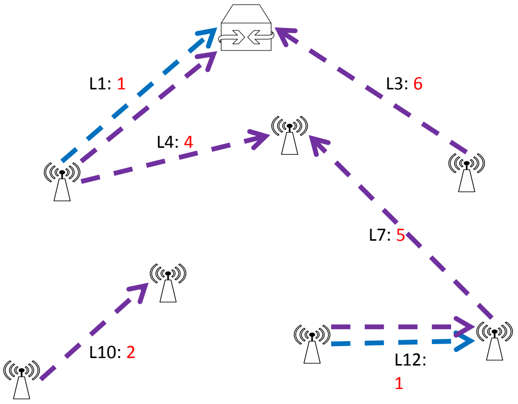
LINK	THROUGHPUT (Mbps)
L3	9
L4	6
L7	9
L10	12
L12	48
L1	12
TCAP	96

Figure 15: Procedure for Transmission Configurations - 3

buffers are scheduled. We define two strategies for choosing the buffers that can be scheduled.

- A set of buffers that hold the large amounts of traffic (packets) are served first, called as the BW (Bandwidth) technique
- A set of buffers that are far from the gateway are served first, called as the HOPS techniue

These above mentioned two strategies are used in both source and transit buffer phases. However, in transit buffer phase, we add another feature by also considering a buffer which was not visited for the long time. This is an attempt for *delay*, by considering a buffer of longest waiting for the opportunity to transmit. Because each phase can have two techniques, a total of 4 possible techniques can exist (BW & BW, BW & HOPS, HOPS & HOPS, HOPS & BW). After a group of buffers is chosen based on the above strategies, our algorithm tries to identify the minimum configurations which contain these buffers. Assign a time slot for each of the configuration and schedule the corresponding link. After a link is scheduled into the time



T2

LINK	THROUGHPUT (Mbps)
L3	9
L4	6
L7	9
L10	12
L12	48
L1	12
TCAP	96

Figure 16: Procedure for Transmission Configurations - 4

slot, then the packets are pushed to the next hop. The traffic is being moved on a hop-by-hop basis, until it reaches the destination. The maximum amount of packets being moved depends on the data rate of the link. The maximum number of packets that can be transmitted over the link cannot be more than the data rate the link supports. The same operations are being executed over source buffers and transit buffers interchangeably. These iterations keep executed by the scheduling algorithm until no more packets are available in any source or transit buffers of any node.

Example for Scheduling (Algorithm 5)

In this Section, we give a small flow diagram explanation for scheduling. By now, we have all the transmission configurations determined from the Algorithm 4, with each link is assigned a data rate. As shown in Figure 17, a link consists of two buffers, a source buffer and a transit buffer. We can see from the Figure 17 that L9 can contain its own packets to send but it do not receive packets from any other node and so the transit buffer size is null. On the other hand, L1 can receive packets from other nodes as well as contain its own packets to send. The flow diagram of scheduling is shown in Figure 18. It has two phases, source buffer phase and transit buffer phase. For every source buffer phase, a transit buffer phase executes and vice-versa. During source buffer phase, k buffers of maximum weight (BW) or maximum distance (HOPS) is chosen and find the minimum configurations which has all these buffers. Assign a time slot for each of the configuration and let the links be scheduled to push the packets forward by one hop. Update the contents of the buffers. Similar procedure is also for the transit buffer phase and in addition, also considers a buffer of the highest waiting time, by which we attempt to consider the delay indirectly. This procedure executes until all the buffers become empty.

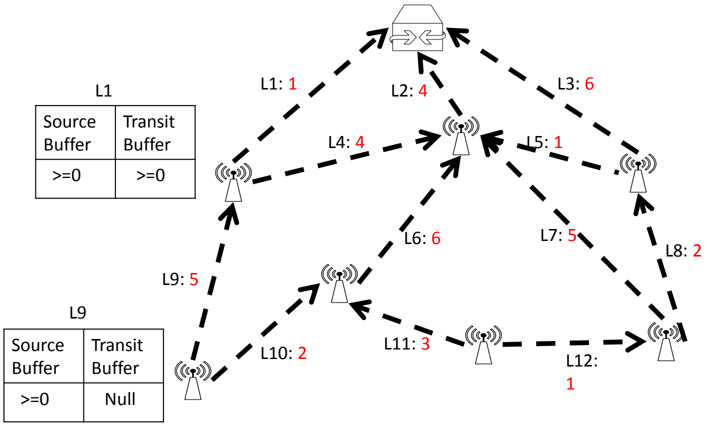


Figure 17: Source and Transit Buffer

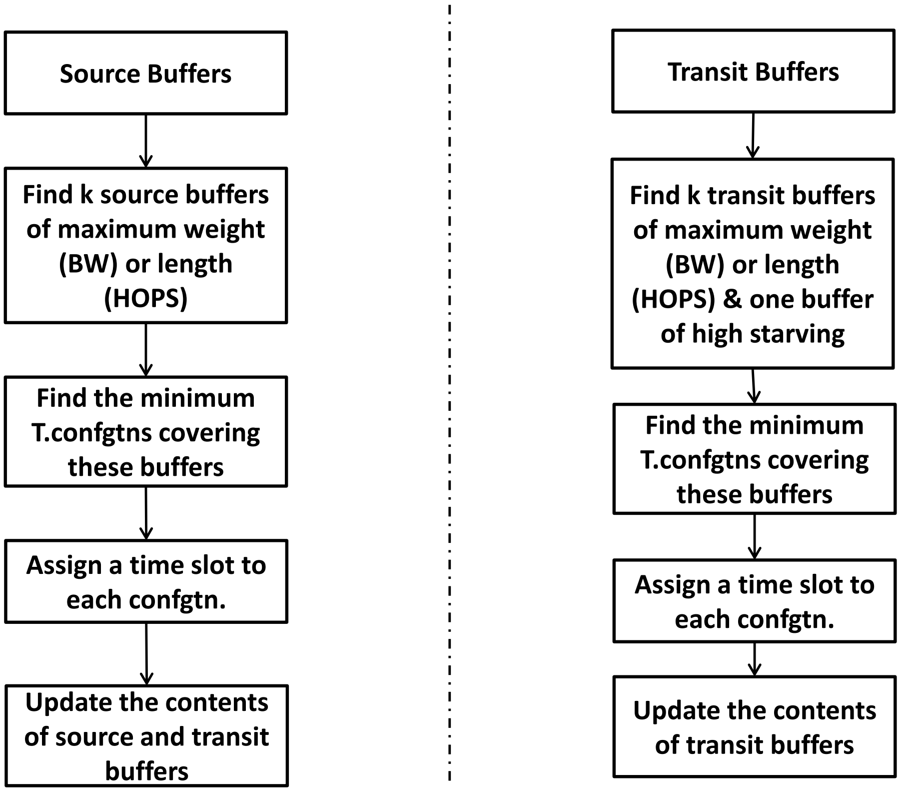


Figure 18: Flow Diagram of Scheduling

Algorithm	**Input**	**Output**
Algorithm 1	$\mathcal{N}^{\text{W}} = (V \cup G, L), T_v^{\text{UL}}, T_{gv}^{\text{DL}}$	TRAFFIC_ℓ, $\forall \ell \in L$; P_v^{UL}, P_{gv}^{DL}, $\forall v \in V$, $\forall g \in G$
Algorithm 2	T_v^{UL}, uplink traffic of v to be distributed over $p \in P_v^{UL}$	T_p^{UL}, the uplink traffic amount on path $p \in P_v^{UL}$
Algorithm 3	C : set of available channels L : set of all links	c_ℓ, $\forall \ell \in L$ Every link is assigned a channel $c \in C$
Algorithm 4	Set of links, each with an assigned channel n^{RADIO_u} : number of radios at node u	A set $\mathcal{T}$ of transmission configurations (indexed by T)
Algorithm 5	$\mathcal{T}$, L, TRAFFIC_ℓ, P_v^{UL}, P_{gv}^{DL}, k, $B_{v\ell}^S$, $B^T v\ell$, t^{LAST_ℓ}	$\text{TRAFFIC}_\ell \leftarrow 0$, $B_{v\ell}^S \leftarrow 0$, $B_{v\ell}^T \leftarrow 0$

Table 3: Input and output of Algorithms

Algorithm 1 *Estimating the Traffic to be Carried on each Link*

```
Input: $\mathcal{N}^{\text{W}} = (V \cup G, L), T_v^{\text{UL}}, T_{gv}^{\text{DL}}$
Output: $\textsc{traffic}_\ell$

  $\textsc{traffic}_\ell \leftarrow 0$ for all $\ell \in L$                         ▷ Initialization

                                       ▷ Downlink traffic contribution to $\textsc{traffic}_\ell$
  for $g \in G$ and $v \in V$ do
      $p_{gv} \leftarrow$ a shortest path from $g$ to $v$
      for $\ell \in p_{gv}$ do
          $\textsc{traffic}_\ell \leftarrow \textsc{traffic}_\ell + T_{gv}^{\text{DL}}$

  for $g \in G$ and $v \in V$ do                 ▷ Defining the set of uplink paths
      $p_{vg} \leftarrow$ the path in the opposite direction to $p_{gv}$
  $P_v^{\text{UL}} = \{p_{vg} : g \in G\}$
  $p \leftarrow$ the shortest path among the paths of $P_v^{\text{UL}}$
  $P' \leftarrow \{p\}$ ; $\textsc{more\_}p = .\ \textsc{false}.$
  if $|P_v^{\text{UL}}| \geq 2$ then
      $p' \leftarrow$ second shortest path of $P_v^{\text{UL}}$
      $\textsc{more\_}p = .\ \textsc{true}.$
  while $\textsc{more\_}p = .\ \textsc{true}.$ or
              $\dfrac{\textsc{length}(p') - \textsc{length}(p)}{\textsc{length}(p)} \leq 0.3$ do
      $P' \leftarrow P' \cup \{p'\}$ ; $p \leftarrow p'$
      if all paths of $P_v^{\text{UL}}$ have been explored then
          $\textsc{more\_}p \leftarrow .\textsc{false}.$
      else
          $p' \leftarrow$ next shortest path in $P_v^{\text{UL}}$
  $P_v^{\text{UL}} \leftarrow P'$

                                       ▷ Uplink traffic contribution to $\textsc{traffic}_\ell$
  for each node $v$ in decreasing order of $T_v^{\text{UL}}$ do
      for $g \in G$ do
          $T_{vg}^{\max} =$
              $\max_{(\ell,\ell') \in p_{vg} \times p_{gv} : \ell = \textsc{opp}(\ell')} \{\textsc{traffic}_\ell + \textsc{traffic}_{\ell'}\}$
          Let $\ell(vg)$ be such that:
              $T_{vg}^{\max} = \textsc{traffic}_{\ell(vg)} + \textsc{traffic}_{\textsc{opp}(\ell(vg))}$
      Call Algorithm 2 (Water Filling) on node $v$
      for $g \in G$ do
          for $\ell \in p$ for $p$ from $v$ to $g$ such that $T_p^{\text{UL}} > 0$ do
              $\textsc{traffic}_\ell \leftarrow \textsc{traffic}_\ell + T_p^{\text{UL}}$
```

Algorithm 2 *Water-filling at node v*

Input: T_v^{UL}, uplink traffic of v, to be distributed over $p \in P_v^{\text{UL}}$
Output: T_p^{UL}, the uplink traffic amount on path $p \in P_v^{\text{UL}}$

```
$T_v^{\max} \leftarrow \max_{g \in G} \textsc{traffic}_{\ell(vg)}$
if $T_v^{\text{UL}} \geq \sum_{g \in G} \left(T_v^{\max} - \textsc{traffic}_{\ell(vg)}\right)$ then
    $T_p^{\text{UL}} \leftarrow T_v^{\max}$ for each $p \in P_v^{\text{UL}}$
    $T_v \leftarrow T_v - \sum_{g \in G} \left(T_v^{\max} - \textsc{traffic}_{\ell(vg)}\right)$
    Add $\frac{T_v}{|P_v^{\text{UL}}|}$ to each path of $P_v^{\text{UL}}$
else                                              ▷ $P_v^{\text{UL}}$ contains at least 2 paths
    $\textsc{iter} \leftarrow 0$ ; $p \leftarrow$ shortest path of $P_v^{\text{UL}}$
    while no more path to consider in $P_v^{\text{UL}}$ or $T_v^{\text{UL}} = 0$ do
        $p'$ the next path in $P_v^{\text{UL}}$
        $\textsc{iter} \leftarrow \textsc{iter} + 1$
        for $p'' \in P_v^{\text{UL}} : T_{p''}^{\text{UL}} < T_{p'}^{\text{UL}}$ do
            $\delta \leftarrow T_{p'} - T_{p''}$
            if $\textsc{iter} \times \delta < T_v$ then
                $T_{p''}^{\text{UL}} \leftarrow T_{p''}^{\text{UL}} + \delta$ ; $T_v^{\text{UL}} \leftarrow T_v^{\text{UL}} - \delta$
            else
                $T_{p''}^{\text{UL}} \leftarrow T_{p''}^{\text{UL}} + T_v^{\text{UL}} / \textsc{iter}$
                $T_v^{\text{UL}} \leftarrow T_v^{\text{UL}} - T_v^{\text{UL}} / \textsc{iter}$
```

Algorithm 3 *Channel_Assignment*

```
$C$ : set of available channels
$L$ : set of links

$\ell \leftarrow= \arg\max_{\ell \in L} \textsc{traffic}_\ell$                    ▷ Initialization
Assign channel $c_\ell = 1$ to link $\ell$
$S = \{\ell\}$ ; $L' = L \backslash \{\ell\}$

                                    ▷ Main Loop: Channel Assignment to Links
for each link $\ell \in L'$ in decreasing order of $\textsc{traffic}_\ell$ do
    $c_\ell = \operatorname{argmin}_{c \in C} \sum_{\ell' \in S} a_{\ell'}(\{\ell\})$
    $S = S \cup \{\ell\}$
```

Procedure CHECK_ADD (ℓ, T, counter_g)

```
                    ▷ Adding One Yet Unconsidered Link in a Configuration
        under Construction
Input: Transmission configuration $T$ and link $\ell$
Output: Transmission configuration $T \cup \{\ell\}$ if $\ell$ can be
    added to $T$, $T$ otherwise
    For $\ell \in \omega^-(g), g \in G$, counter_$g$ =
     # of incoming links of $g$ that belongs to $T$

ADD ← . TRUE.
for each endpoint $u$ of $\ell$ do
    MARK[$u$] ← MARK[$u$] + 1
    if MARK [$u$] $> n_u^{\text{RADIO}}$ then
        EXIT the procedure

$T' \leftarrow T \cup \{\ell\}$ ; ADD ← .TRUE.
TCAP($T'$) ← 0

for $\ell \in T'$ do
    if SINR$_\ell(T' \setminus \{\ell\}) \geq \beta$ then
        Compute RATE$_\ell$
        TCAP($T'$) ← TCAP($T'$) + RATE$_\ell$
    else
        ADD ← .FALSE.
        EXIT from the for loop

if ADD = .TRUE. and TCAP($T'$) > TCAP($T$) then
    $T \leftarrow T \cup \{\ell\}$ ; $L^c \leftarrow L^c \cup \{\ell\}$;
    TCAP($T$) ← TCAP($T'$)
    if $\ell \in \omega^-(g)$ for some $g \in G$ then
        counter_$g$ ← counter_$g$ + 1
```

Procedure ENLARGE ($\mathcal{T}$)

```
▷ Attempt to expand the configurations, once all links are embedded in at least one configuration
for $T \in \mathcal{T}$ do
    for $\ell' \in L \setminus T$ do
        Let $u, u' \in V \cup G$ be the two endpoints of $\ell$
        MARK$[u] \leftarrow$ MARK$[u] + 1$
        MARK$[u'] \leftarrow$ MARK$[u'] + 1$
        if MARK$[u] \leq n_u^{\text{RADIO}}$ and MARK$[u'] \leq n_{u'}^{\text{RADIO}}$ then
            $T' \leftarrow T \cup \{\ell'\}$ ; ADD $\leftarrow$ .TRUE.
            $\hat{\ell} \leftarrow \ell'$
            while ADD = .TRUE. do
                if SINR$_{\hat{\ell}}(T' \setminus \{\hat{\ell}\}) < \beta$
                    or RATE$_{\hat{\ell}}$ has decreased then
                    ADD $\leftarrow$ .FALSE.
                else
                    Select the next $\hat{\ell}$ in $T'$
            if ADD = .TRUE. then
                $T \leftarrow T \cup \{\ell'\}$
```

Algorithm 4 *Transmission Configurations*

```
Input: Set of links, each with an assigned channel
  $n_u^{\text{RADIO}}$: number of radios at node $u$
Output: A set $\mathcal{T}$ of transmission configurations
            (indexed by $T$)

  $L^c$ : set of links which are in at least one configuration
  $L^c \leftarrow \emptyset$ ;    $c_\ell$ : channel assigned to link $\ell$
  counter_$g \leftarrow 0$ for all $g \in G$
  MARK$[v] \leftarrow 0$ for all $v \in V$; MARK$[g] \leftarrow 0$ for all $g \in G$

                              ▷ Step 1: Building new configurations, covering all links
  while $L^c \neq L$ do
      Select $\ell \in L \setminus L^c$ such that: $\ell = \arg\max_{\ell' \in L \setminus L^c} \text{TRAFFIC}_{\ell'}$
      for each endpoint $u$ of $\ell$ do
          MARK$[u] \leftarrow 1$
      $T \leftarrow \{\ell\}$ ; $L^c \leftarrow L^c \cup \{\ell\}$
      Compute $\text{SINR}_\ell$ and $\text{RATE}_\ell$ ; $\text{TCAP}(T) \leftarrow \text{RATE}_\ell$
      for $\ell' \in L \setminus L^c$ (in decreasing order of $\text{TRAFFIC}_{\ell'}$) do
          CHECK_ADD ($\ell', T$, counter_$g$)
      $\mathcal{T} \leftarrow \mathcal{T} \cup \{T\}$
                              ▷ Step 2: Including at least one incoming link for each gateway
  for $T \in \mathcal{T}$ and $g \in G$ do                                        ▷ Phase 1
      if counter_$g(T) = 0$ then
          for $\ell \in \omega^-(g)$ do CHECK_ADD ($\ell, T$, counter_$g$)
          If ADD = .TRUE. then go to next $g$
  for $T \in \mathcal{T}$ do                                                      ▷ Phase 2
      SINR_SMALL = .TRUE.
      while SINR_SMALL = .TRUE. do
          for $g \in G$: counter_$g(T) = 0$ do
              for $\ell \in \omega^-(g)$ do
                  $\mathcal{L}_\ell = \{\ell' \in T : \text{SINR}_{\ell'}(T \cup \{\ell\} \setminus \{\ell'\}) < \beta\}$
              if $\mathcal{L}_\ell = \emptyset$ then
                  SINR_SMALL = .FALSE. ; $T \leftarrow T \cup \{\ell\}$
              else
                  $\hat{\ell} \leftarrow \arg\min_{\ell' \in \mathcal{L}_\ell} \text{SINR}_{\ell'}(T \cup \{\ell\} \setminus \{\ell'\})$
                  $T \leftarrow T \setminus \{\hat{\ell}\}$ ; $L^c \leftarrow L^c \setminus \{\hat{\ell}\}$

                              ▷ Step 3: Attempt to enlarge the configurations
  ENLARGE($\mathcal{T}$) ; if $L^c \neq L$ then Go back to Step 1
```

```
                                        ▷ Step 4: Compute the rates of the links
for $T \in \mathcal{T}$ and $\ell \in T$ do
    Compute $\textsc{sinr}_\ell(T)$ and $\textsc{rate}_\ell$ accordingly,
        using Table 2
```

Algorithm 5 *Scheduling*

```
Input: $\mathcal{T}$, $L$, $\textsc{traffic}_\ell$, $P_v^{\text{UL}}$, $P_v^{\text{DL}}$, $k$
Output:
  $t$ : time slot index
  $B_{v\ell}^S$: buffer at node $v \in V \cup G$ for the packets having $v$ as a source to be sent on outgoing link $\ell$
  $B_{v\ell}^T$: buffer at node $v \in V$ for the packets transiting through $v$ to be sent on outgoing link $\ell$
  $t_\ell^{\text{LAST}}$: last time slot where the link $\ell$ was scheduled.

  $t \leftarrow 1$ ; $t_\ell^{\text{LAST}} \leftarrow 0$ for each $\ell \in L$
  Distribute the source packets on each $v \in V$ over the buffers
    $B_{v\ell}^S$ according to $\textsc{traffic}_\ell$ for the uplink traffic $T_v^{\text{UL}}$,
    where $\ell$ is the first link on the route $v \rightsquigarrow g, g \in G$
  Set $B_{g\ell}^S$ to $T_{gv}^{\text{DL}}$ for the downlink traffic,
    where $\ell$ is the first link on the route $g \rightsquigarrow v$

  while $\exists$ at least one non-empty buffer $B_{u\ell}^S$ or $B_{u\ell}^T$ do
                                        ▷ Step 1: scheduling the packets from the sources
    Select the maximum number up to $k$ of non-empty
      buffers from $B_{u\ell}^S$ such that:
      in round-robin or $\sum_{\text{selected}} |B_{u\ell}^T|$ or $\sum_{\text{selected}: B_{u\ell}^T \neq \emptyset} \textsc{length}(p_{u \rightarrow \text{DST}})$
    Find a minimum set $\mathcal{T}' \subseteq \mathcal{T}$ of configurations
      containing these $k$ buffers
    Update the contents of the buffers $B_{u\ell}^S$ and $B_{u\ell}^T$
      according to $P_v^{\text{UL}}$, $P_v^{\text{DL}}$, and the rates of the links
      used in $\mathcal{T}'$
    for $T \in \mathcal{T}'$ do
        Assign $T$ to time slot $t$
        $t \leftarrow t + 1$
                                        ▷ Step 2: scheduling in-transit packets
    Select the maximum number up to $k$ of non-empty
      buffers from $B_{u\ell}^T$, $u \in V \cup G$ such that:
      $\sum_{\text{selected}} |B_{u\ell}^T|$ or $\sum_{\text{selected}: B_{u\ell}^T \neq \emptyset} \textsc{length}(p_{u \rightarrow \text{DST}})$
      is maximum,
      including one buffer with a minimal $t_\ell^{\text{LAST}}$
    Find a minimum set $\mathcal{T}' \subseteq \mathcal{T}$ of configurations
      containing these $k$ buffers
    Update the contents of the buffers $B_{u\ell}^T$ according to
      $P_u^{\text{UL}}$, $P_u^{\text{DL}}$, and the rates of the links used in $\mathcal{T}'$
    for $T \in \mathcal{T}'$ do
        Assign $T$ to time slot $t$
        $t \leftarrow t + 1$
```

Chapter 5

Simulation

In this chapter, we discuss the results of the simulations conducted on the algorithms proposed in Chapter 4. These algorithms are proposed towards increasing spatial reuse of all the channels and to increase the throughput of the WMNs. The performance of these algorithms is verified through various experimental settings, which we further explain this chapter. We have analyzed the results in terms of the throughput for various traffic and WMN network instances over the variable number of channels and the radios. Section 5.1 define several parameters for network topology instances and traffic instances we use for our simulations. Section 5.2 shows the comparison of throughput of various channel scenarios. We then examine the characteristics of the transmission configurations in Section 5.2.2. Section 5.2.3 validates the links adjacent to gateways (LAGs) in every configuration and distribution of the channels in the channel assignment in Section 5.2.4 respectively. Section 5.2.5 explains and compares the results of each of the scheduling techniques.

5.1 Data Instances

In this section, we define the data instances we use for our simulation environment. Our settings correspond to the outdoor WMN settings and with more realistic parameters which many existing works have not considered. Table 4 gives the details of the parameters we use in our simulations.

5.1.1 Network Topology Instances

We next describe the various instances of topology, traffic, radio and channels.

Topology Scenarios

We consider a 2-dimensional square topology with a 1km side length (0, 1000) × (1000, 0). We assume up to 4 gateways for any given topology instance. If 4 gateways are considered, they are located in positions (200,800), (800, 200), (800, 800), (200, 200). However, the position of the gateways is not restricted and can be placed anywhere. For the locations of the MRs, we examine two location scenarios: a grid location distribution, and a random location distribution. In the grid MR location scenario, a network of lines cross each other to form a series of squares. A MR is placed at every corner of this square. In a grid topology of size 6 horizontal lines × 6 vertical lines, the number of nodes or MRs generated are 36 including the gateways. In the uniform random MR location distribution, 170 MRs are generated (including gateways). The transmission range of a MR is kept to 200m and, in the generation process, we make sure that each wireless MR has at least one routing path towards at least one gateway.

Traffic Instances

Simulations were conducted over several traffic instances. In all traffic instances, uplink traffic is the traffic from the MRs to the gateway(s) and the downlink traffic is from each gateway to the MRs. A random traffic generator is used to generate traffic at every MR. At every MR, uplink traffic (T_v^{UL}) and, at gateways downlink traffic (T_{gv}^{UL}) is generated between [30, 50] Mbps.

Radio and Channel Scenarios

We use 2.4GHz spectrum, which consists of only 3 orthogonal channels of 11 channels. Since we can use at most 3 orthogonal channels, it can be argued that a maximum of 3 radios can be allowed on any MR or gateway. It is possible to equip a MR with more radios but then the throughput per radio may get saturated. Channel scenario denoted by 1,..,x means we consider all channels between 1 and x. For all the experiments, every MR (resp. gateway) is equipped with the same functionality, i.e., 2 (resp. 3) radios that are omni-directional and with constant power. We use a constant power value of 20mW for all wireless MRs and gateways. In all algorithms, we use the value of $\beta = 8.51$ for SINR threshold, and the scheduling algorithm with the buffer bandwidth criterion. Most of the parameters we used in our simulations are from [4].

5.2 Results

In this section, we explain the results of our algorithms. We have evaluated the average throughput upon several traffic instances.

5.2.1 Throughput vs. Number of Overlapping Channels

In each time frame of the TDMA based scheduling, one transmission configuration per time slot can be scheduled. It allows all the links of the configuration to transmit concurrently and pushes the traffic to the next hop of each link. The next hop can

Topology Settings	
Dimension	2D
Side length	1 KM
Gateways	≤ 4
If 4 gateways	(200,800), (800,200), (800,800), (200,200)
If 1 gateway	(500,500)

Node & Traffic Settings	
Range	200m
Power(P)	20mW
SINR threshold	8.51
Path loss exponent(α)	4
Noise(η)	10^{-9}
Radios of a MR	[2,3]
Radios of gateways	[2,3]
Traffic instances	[30, 50] Mbps
Packet size	1 Mbps
Time slot size	2 sec

Table 4: WMN simulation settings

be the destination node or only a transit node, but we consider only the traffic that is received at the destination(s) as the throughput of that time slot. The sum of the individual throughput of all the time slots over total time slots is the average throughput of the WMN. We do not eliminate any warm up time slots but considers all time slots, which includes the warm up and the steady state for estimating the throughput. Our observation by excluding and not excluding warmup time slots is the final behavior of the throughput comparison remains almost the same. So, we only present the throughput of all channel scenarios including the warmup time slots.

$$Throughput\_of\_time\_slot = \frac{Traffic\_reached\_destinations}{Time\_slot\_duration} \tag{11}$$

$$Average\_throughput = \frac{\sum Throughput\_of\_time\_slots}{Total\_time\_slots} \tag{12}$$

In Figures 19 and 20, we plotted the average throughput of the wireless network

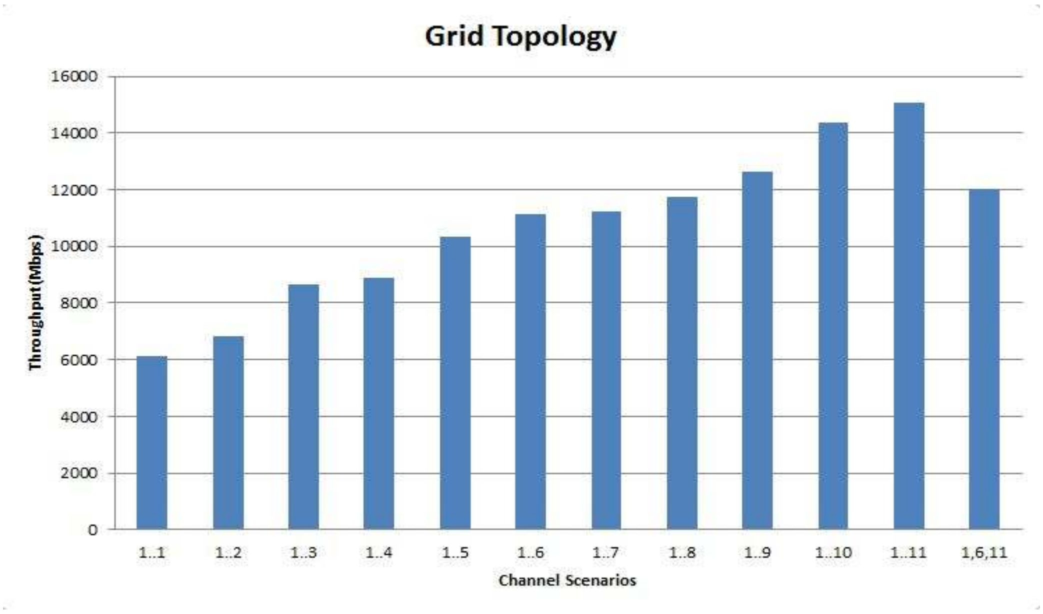


Figure 19: Average Throughput vs. Channel Scenarios - Grid Topology

for different channel scenarios.

We are interested in the average throughput for each of the channel scenario. The average throughput must increase gradually as more channels are considered for scheduling. The results from Figures 19 and 20 indicate that POCs perform always better than OCs. From grid topology scenario, there is a gain of up to 25% over OCs in using POCs. Figures 19 & 20 shows the throughput comparison for only one strategy of scheduling (BW & BW). However, though it is not mentioned here, but the final throughput comparison using other strategies also represents in a similar fashion like in Figures 19 and 20.

5.2.2 Characteristics of the Transmission Configurations

In Figure 21, we present characteristics of the transmission configurations. The left vertical axis corresponds to the TCAP of the transmission configurations (Mbps), while the right vertical axis expresses the number of links in a given configuration. The horizontal axis lists the set of transmission configurations by their generated order.

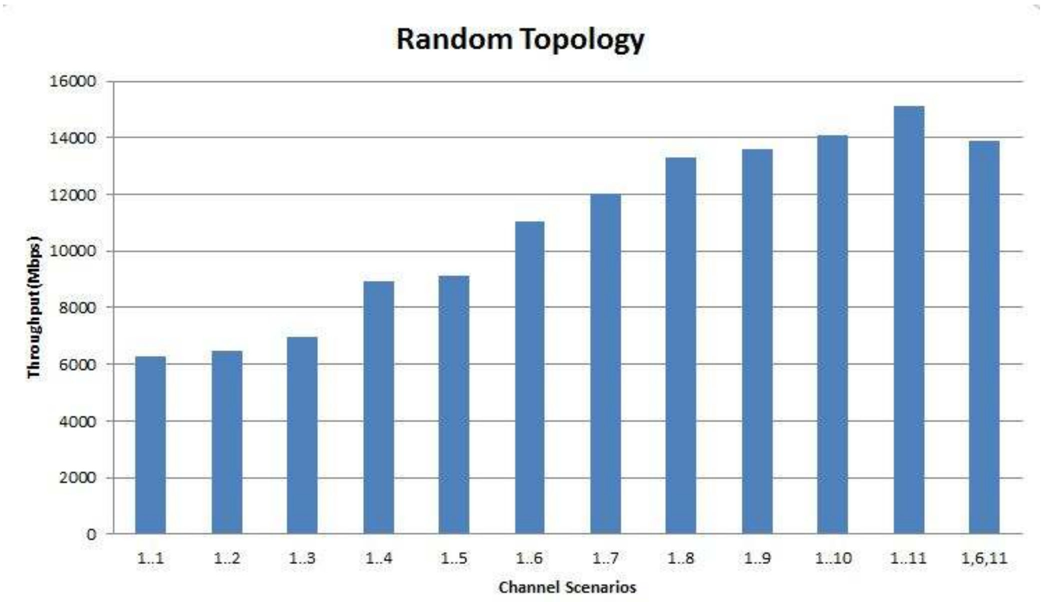


Figure 20: Average Throughput vs. Channel Scenarios - Random Topology

Figure 21 represents the transmission configurations of a randomly generated WMN instance consists of 170 MRs with 800 links.

The TCAP is calculated as the sum of the data rates of all the links in configuration. We observe that TCAP varies from 100 to 520 Mbps per configuration, while the number of links vary from 10 to 30. The highest data rate that can be assigned to a link is 54 Mbps from Table 2. From Figure 21, it can be seen, that the configuration with the highest number of links has the highest TCAP and configuration with the minimum number of links has the least value of TCAP. This cannot be the case always because few configurations though consists of least number of links can still have average TCAP, when all the links are assigned with highest possible data rate.

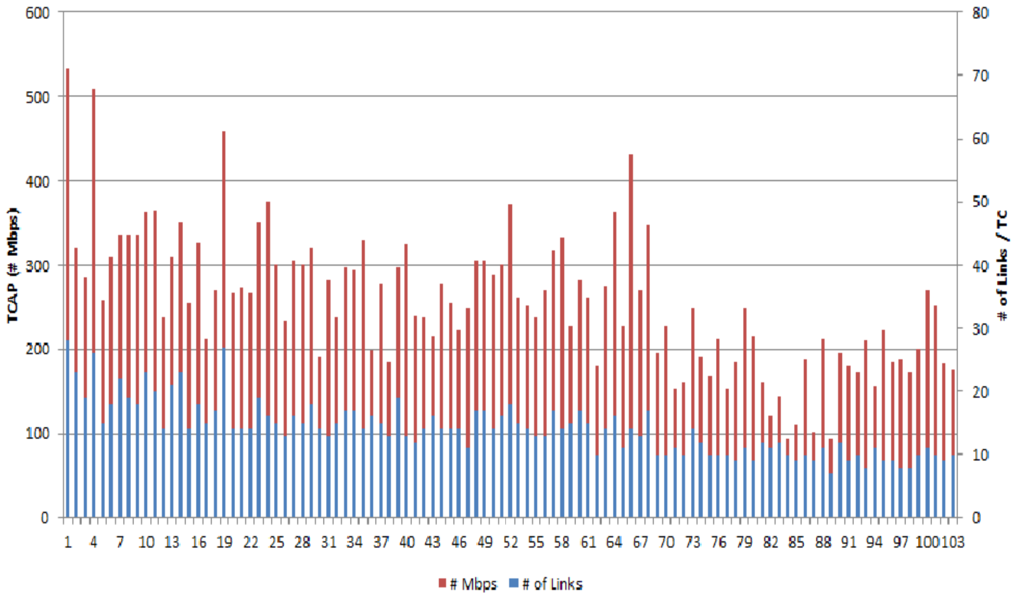


Figure 21: Set of Configurations & TCAP - Random Topology

5.2.3 Links Adjacent to Gateways for Transmission Configuration

Link adjacent to gateway (LAG) are the incoming links adjacent to gateways. In Algorithm 4, we try to add at least one incoming link of each of the gateway into every transmission configuration. This is the result of Step 1 and Step 2 of the Algorithm 4. Figure 22 depicts the result of LAGs for a WMN instance of 4 gateways equipped with 3 radios and randomly generated 170 MRs with 2 radios. The horizontal axis represents the configurations by their generated order and vertical axis represents the number of LAGs for each configuration. Gateways are distinguished by the colors. Our algorithm does the best effort in including the LAGs. The result indicates that 90% of the configurations consists of the LAGs and very few configurations do not contain any LAG. Some configurations can contain more than one LAG of the same gateway, it occurs when the LAGs are assigned non-interfering channels. Some configurations do not contain LAGs, because Step 2 of the algorithm do not find any

LAG(s) that can be embedded into configuration. This occurs if the LAG's SINR is less than threshold when inserted into the configuration.

From our observations, if gateways are assigned 3 radios while MRs with 2 radios, there is a negligible increase in throughput amounts when compared to scenario of WMN with gateways (2 radios) amd MRs (2 radios) for some of the traffic instances. We also conclude that, for a MR the throughput gets saturated after 2 radios and for gateways it is with 3 radios.

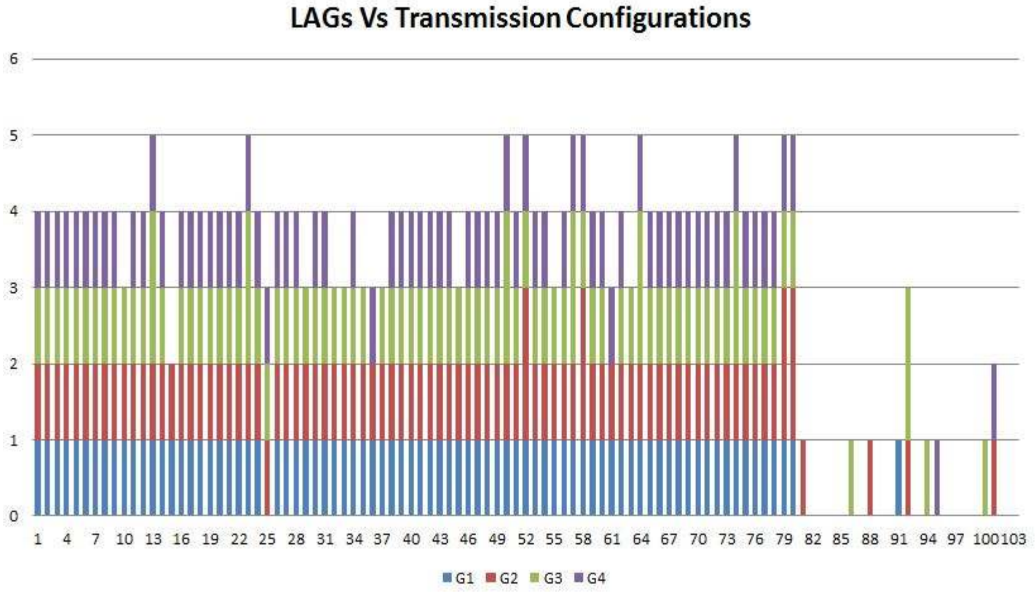


Figure 22: LAGs for each Transmission Configuration (Multiple Gateways)

5.2.4 Distribution of the Channels in the Channel Assignments

In this section, the performance of the channel assignment algorithm is represented by the distribution of channels on wireless links. Figure 23 indicate the channel distribution when used all 11 channels. Figure 24 represents for orthogonal channels.

Affectance is used for assigning the least interfering channels on a wireless link. Indeed, the largest channel occurrences correspond to the channels which are the least pairwise overlapping, while the smallest ones are associated with the most overlapping channels. When all 11 channels are used, 60% of the links are assigned with orthogonal channels. While remaining 40% of the links are assigned with overlapping channels, allowing more links to be active as in Figure 23. When only orthogonal channels are used, all three channels are used almost in same proportions.

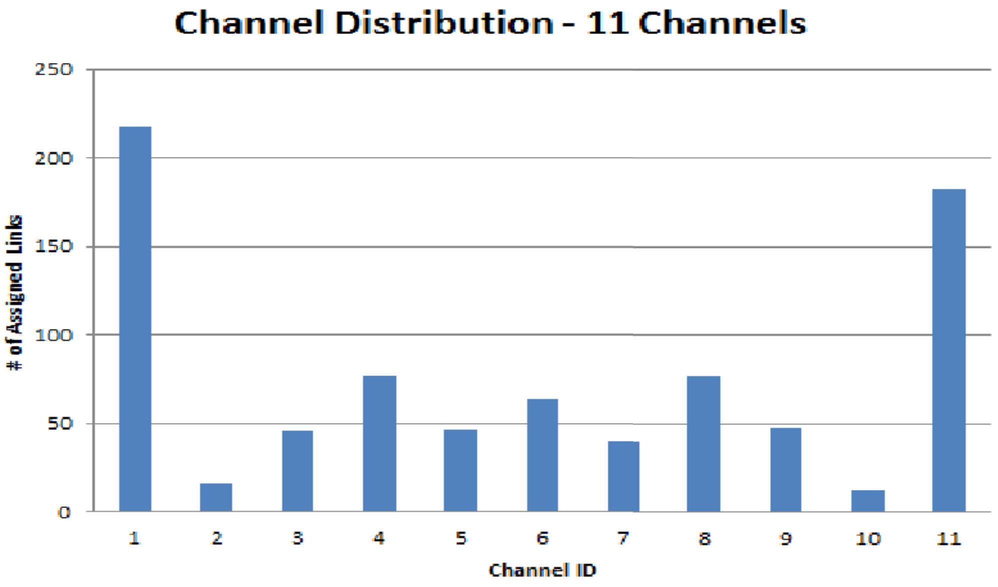


Figure 23: Channel Distribution - 11 Channels

5.2.5 Throughput Behavior

In this section, we discuss the behavior of the scheduling algorithm (Algorithm 5), which has two phases: one phase for source buffers and another phase for transit buffers. Every link consists of two buffers: source buffer which contains the MR's own packets to be pushed onto the link, and a transit buffer which stores the transit packets. During the source buffer phase, the packets are moved from the source buffers to the next hops' transit buffer. In transit buffer phase, packets are moved

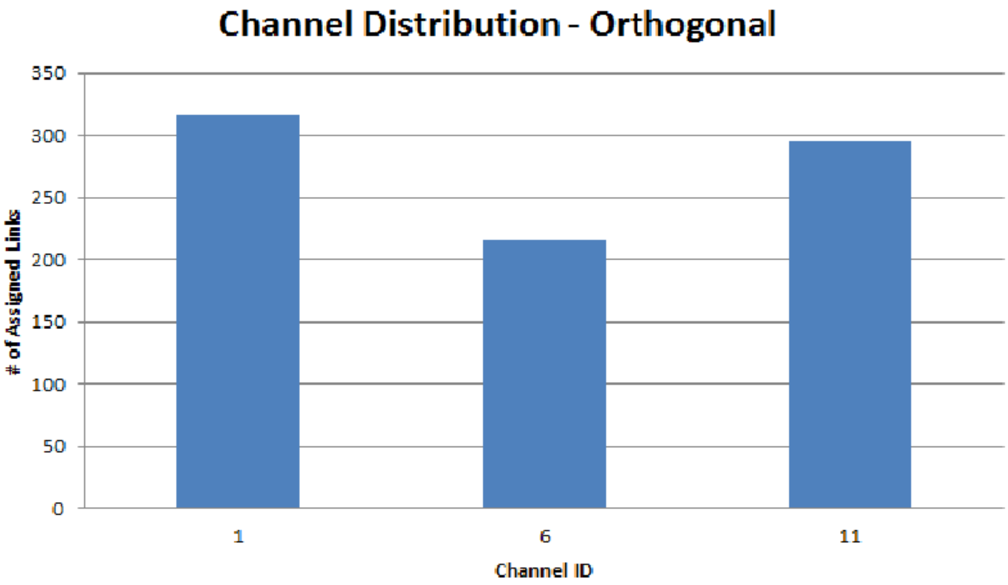


Figure 24: Channel Distribution - Orthogonal

from transit buffers to next hops' transit buffer. If throughput from the source buffer phase is non-negative, it means that a MR whose source buffer has packets also has the destination in its next hop, otherwise throughput of source buffer phase is zero.

Since the scheduling algorithm has two techniques called BandWidth (BW) & Hops (HOPS) in both the source and the transit buffers as mentioned before in Algorithm 5, we have conducted simulations on all the possible combinations of the techniques. A total of 4 possible combinations can exist,

1. BW & BW
2. BW& HOPS
3. HOPS & BW
4. HOPS & HOPS

If BW & HOPS is used, BW technique is applied for source buffers where buffers are processed in decreasing order of the total number of packets they contain. HOPS is used for transit buffers, where buffers are processed in the decreasing order of the distance to gateways. The following sections describe the behavior of each of the combination.

BandWidth & BandWidth

Figure 25 explains the scheduling behavior when BW & BW scheduling strategy is implemented. With this technique, buffers are processed in the decreasing order of the number of packets in both phases. During the initial time slots, the links adjacent to gateways are active most of the time because of their heavy link weights assigned on it. This is because the gateway source buffers contain very high traffic to send in their source buffers as a downlink traffic to all MRs. The links adjacent to gateways carry the highest traffic and are always processed before any other link. Another reason for the high throughput is because a MR can have paths to more than one gateway, it is faster for the MRs which are near gateways to push the traffic to gateways on more than route. Because many links can be active any time, the packets are also pushed from the farther MRs to the transit buffers of the next hop. During this time, throughput reached at the destinations maintains a steady state. After a while many packets being accumulated at those nearest MRs to gateways and are pushed to the gateways during the final time slots. The throughput from the source buffer phase becomes 0 when no more packets are left in any source buffer of the links. The throughput behavior for both multiple gateways Figure 25(a) and 1 gateway Figure 25(b) are also shown in the figure.

BandWidth & Hops

Figure 26 explains the behavior of the BW & HOPS technique of the scheduling algorithm. With BW in source phase, buffers are chosen and scheduled in decreasing order of the maximum number of the packets. The throughput from the source phase is positive if the packets of the MRs adjacent to gateways is pushed as the uplink traffic or vice versa. The transit buffers on the other hand schedules the buffers in the decreasing order of distance from gateway(s). In downlink traffic, this results in considering the transit buffers which are farther before the buffers which are near gateways. This technique leads to accumulation of packets after a while, and are pused towards the destinations. Since the buffers are served on the distance, it needs a very long steady state, resulting in less throughput during the steady state. After the accumulation of packets in intermediate hops and by the time the MRs adjacent to gateways are served, there is huge amounts of data to be pushed to gateways which is the reason for the high throughout during the final time slots as mentioned in the Figure 26(a) for 4 gateways and Figure 26(b) for 1 gateway.

Hops & BandWidth

Figure 27 represents the scheduling nature of the HOPS & BW technique. This technique seems to be the best of all the other techniques in having the highest throughput. During the source buffer phases of the scheduling, buffers are scheduled in the decreasing order of the distance from the gateways which helps in packets to be pushed from farther routers and while in transit buffer phase, buffers are scheduled to maximize the throughput by iterating over the buffers which has the maximum number of packets. Among all our scheduling strategies, this strategy leads to the highest throughput, because source buffers do not contain high amounts of packets unlike in transit buffers which are responsible for the transiting traffic. Processing source buffers allows the farthest MRs source packets to be moved to the next hop. On the other hand, transit buffers are served in the order of the maximum packets. With these policies steady state is effectively used for the packet transmission and is clearly shown in Figure 27(a) for 4 gateways and Figure 27(b) for 1 gateway.

Hops & Hops

Figure 28 explains the scheduling behavior of the HOPS & BW technique. With this technique, buffers are processed in decreasing order of the distance in both source and transit buffers. This results in accumulation of the packets from the farthest buffers to the intermediate and then to the destination. As a result, most of the steady state involves the data accumulation and during the final time slots, the throughput is very high as shown in the Figure 28.

From all our scheduling strategies, the major concern we observed is with stability of the steady state. With all our scheduling strategies, the throughput is not very high during the steady state but only at the beginning or final time slots. We still have a few ideas to increase the throughput and maintain a stable steady state. Some of the possible ideas are,

> Our current work consider BW and HOPS. By iterating over buffers that holds maximum traffic and the buffers which holds minimum traffic alternatively, can be a postive sign for increasing the throughput.
>
> Making sure that all the transit buffers contain a similar amounts of packets in it. It then leads to have a possible steady state.
>
> Instead of iterating source and transit buffers alternatively, define a criteria which allows the transit buffers executes more number of times than the source buffers.
>
> Allow only outgoing LAG into the configurations, or both incoming and outgoing LAGs.

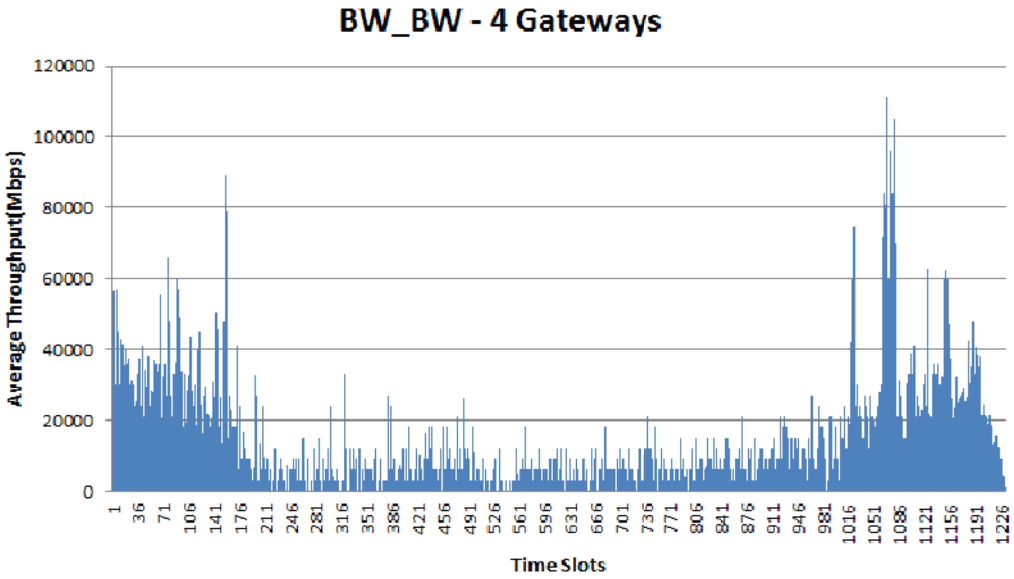
While choosing the minimum number of configurations, choose them by both the presence of links along with the data rate. In our current work, we choose the configurations only by the links existence but we do not consider the data rate of the links in the configurations.

5.2.6 Comparison of Scheduling Techniques

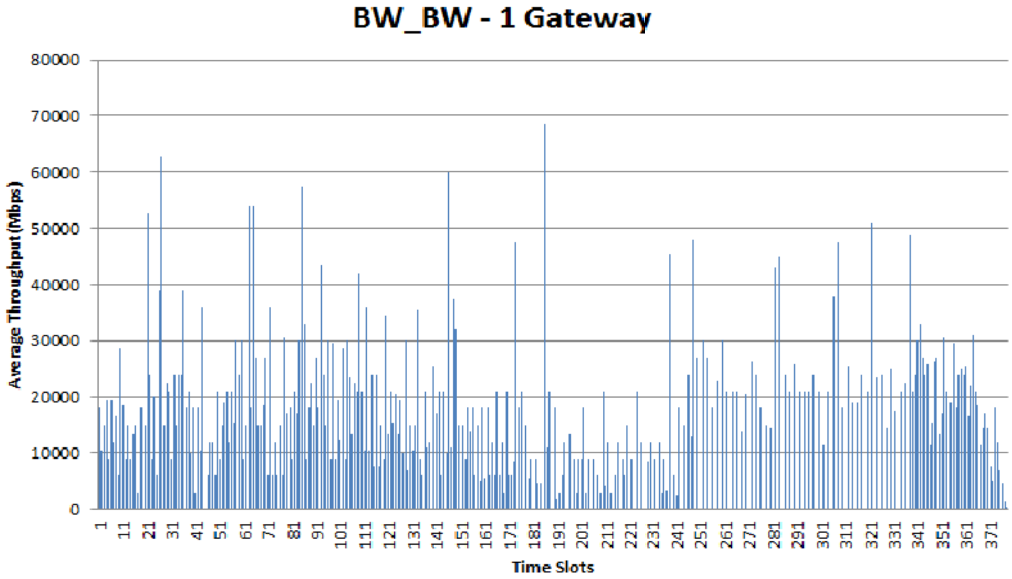
In the above Section 5.2.5, the behavior of the individual scheduling technique is depicted and explained. The throughput comparison of each of the scheduling technique is explained in this section by using the same results as before.

Figure 29 compares the throughput for each of the scheduling technique for two topology instances of 1 gateway and 4 gateways. It can be identified that HOPS_BW yields maximum throughput than other scheduling techniques. It is because, the traffic originated at MRs far from gateways is served in prior, which results in less delay, and serving all the transit buffers for maximizing the throughput. The alternating BW_HOPS results in the least throughput of all the techniques, explains the fact the delayness though handled but maximizing throughput factor applied for source phase does not have much impact after the source buffers become empty of the MRs or gateways.

Figure 29 plot throughput using 4 gateways and 1 gateway when considered both uplink and downlink traffic. The throughput for 1 gateway is a bit higher when compared to 4 gateways is because with one gateway the downlink traffic is only from one gateway resulting in less time slots, where as with four gateways the traffic is much higher because of the downlink traffic from each gateway to all other nodes resulting in more traffic and more time slots.

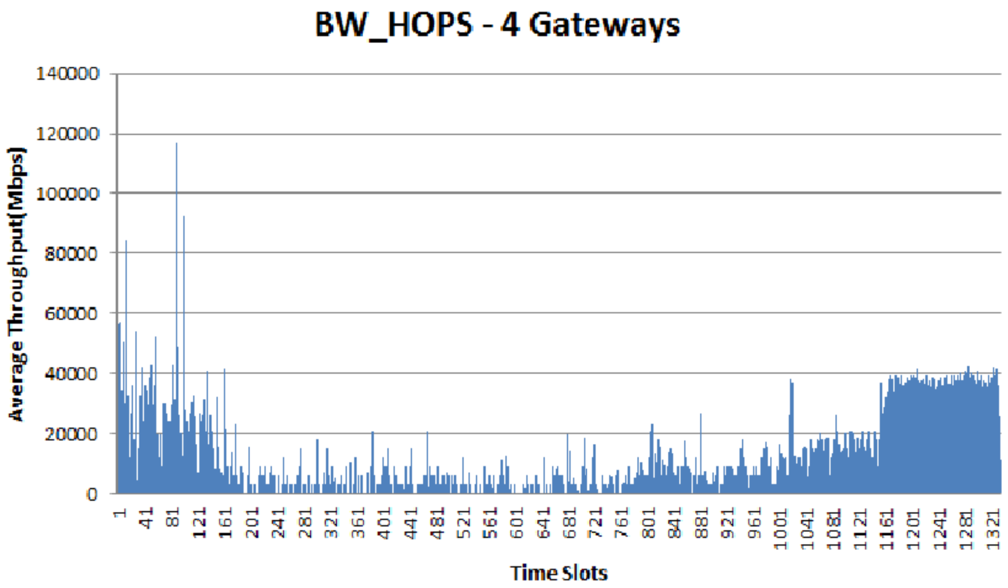


(a) Scheduling Behavior - 4 Gateways

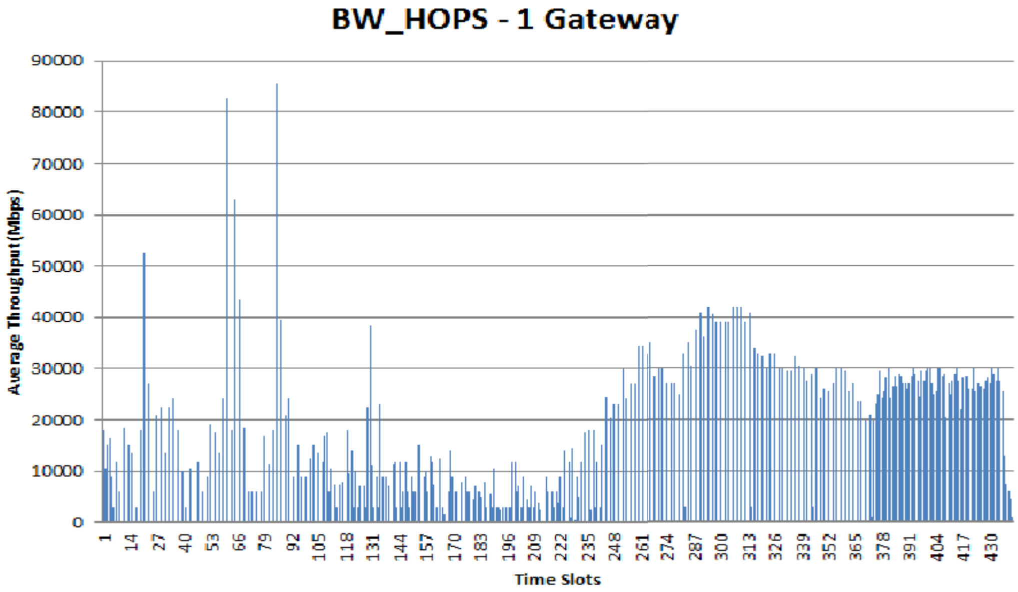


(b) Scheduling Behavior - 1 Gateway

Figure 25: Scheduling Behavior - BW & BW

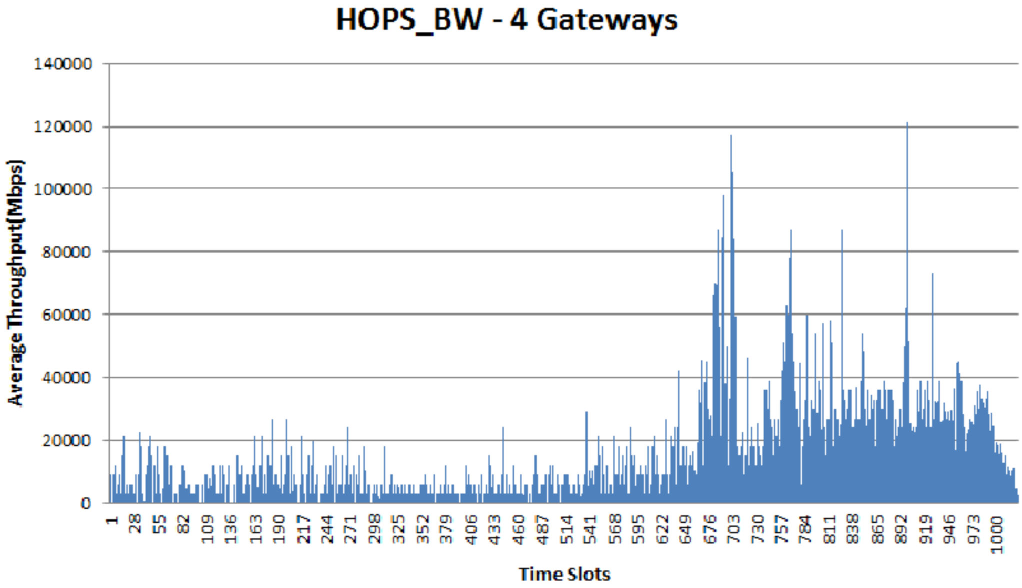


(a) Scheduling Behavior - 4 Gateways

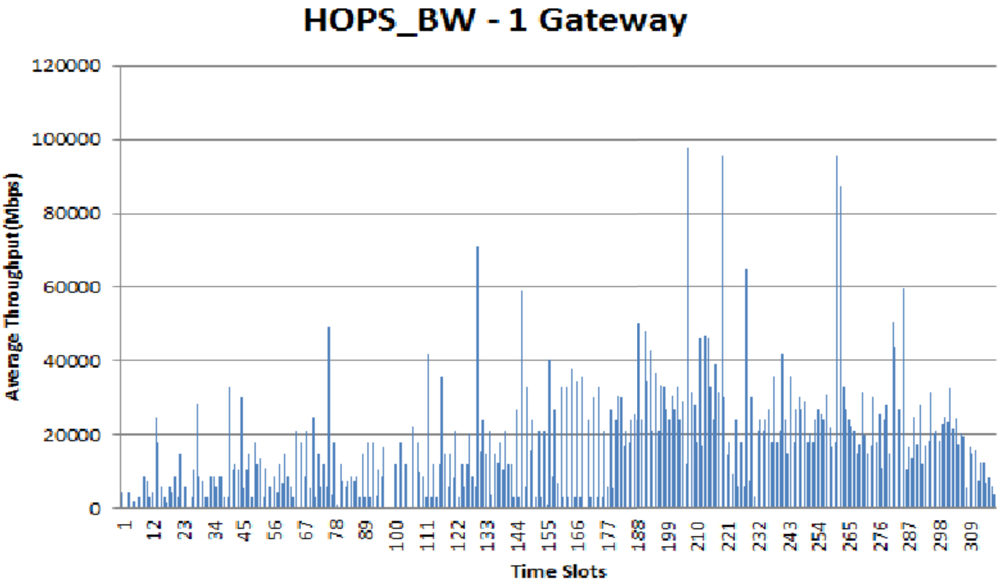


(b) Scheduling Behavior - 1 Gateway

Figure 26: Scheduling Behavior - BW & HOPS

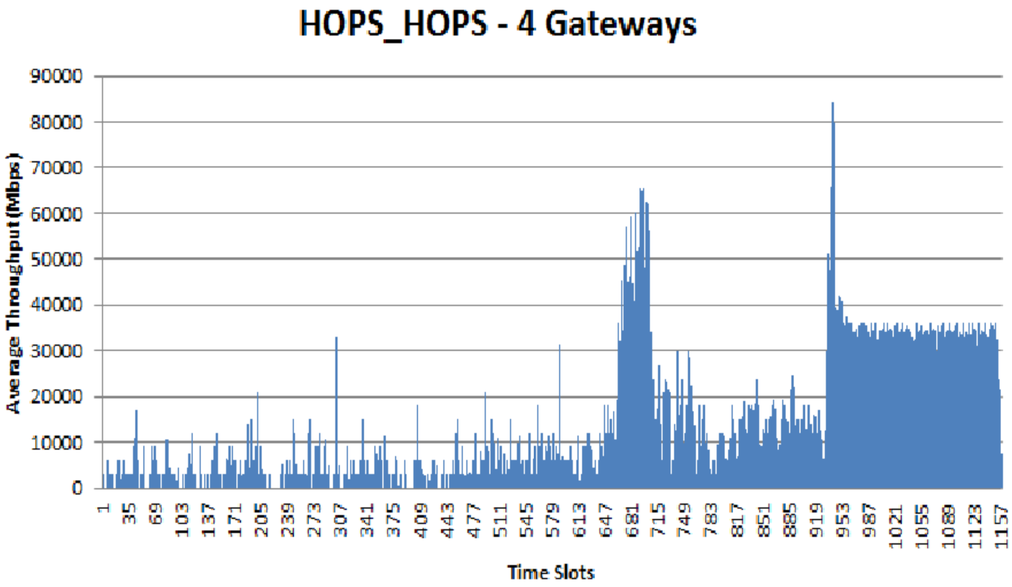


(a) Scheduling Behavior - 4 Gateways

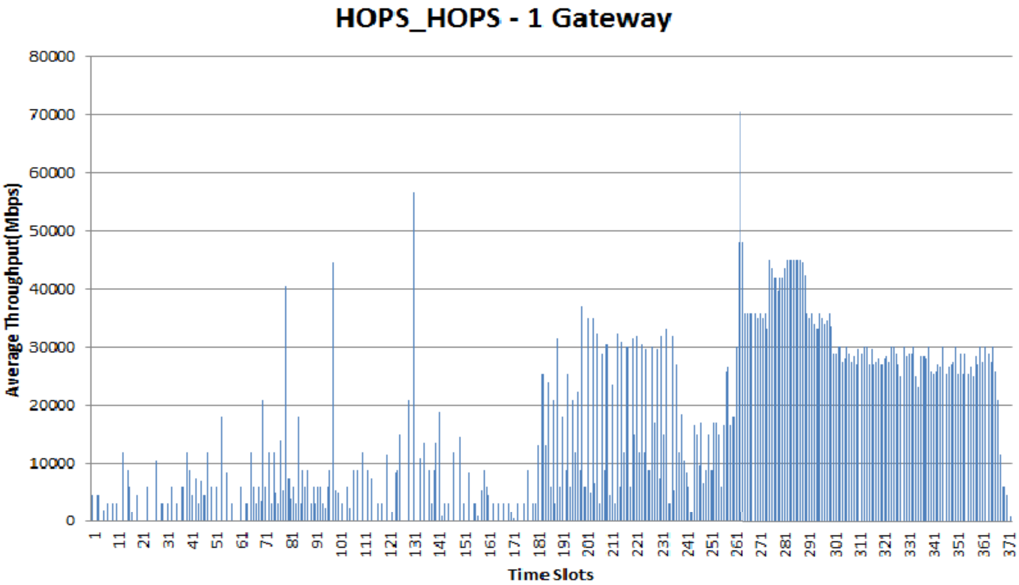


(b) Scheduling Behavior - 1 Gateway

Figure 27: Scheduling Behavior - HOPS & BW



(a) Scheduling Behavior - 4 Gateways



(b) Scheduling Behavior - 1 Gateway

Figure 28: Scheduling Behavior - HOPS & HOPS

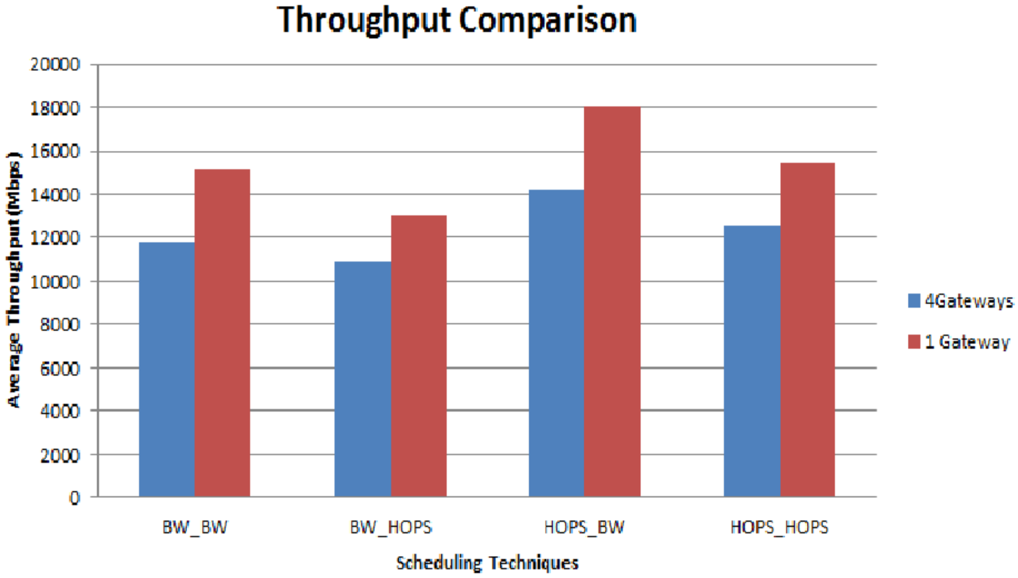


Figure 29: Scheudling Techniques - Throughput Comparison

Chapter 6

Conclusion

In this chapter, we summarize the work done on the channel assignment and scheduling algorithms we proposed in Section 6.1. We then also provide some challenges and related extensions of this work in Section 6.2.

6.1 A Summary

We have proposed scalable heuristic algorithms for channel assignment and scheduling of WMNs. The channel assignment algorithm includes determining the uplink and downlink routes. Downlink routes are unique. On the uplink side, our intention is to associate each node only with closest gateways in terms of number of hops, while ensuring certain level of route diversity. We then distribute the traffic evenly on the links. First downstream traffic is distributed and then upstream traffic is distributed among the links in an even manner among the selected paths to the gateways but with minimizing at the same time the maximum amount of total traffic (uplink and downlink) that a link would carry. We use the notion of *affectance* [10] for calculating the interference in our channel assignment algorithm. A link is assigned a channel which causes the least cumulative affectance on other already assigned links.

We then proposed a TDMA based scheduling algorithm. A large time frame is divided into time slots and each time slot can transmit a subset of links concurrently. We define transmission configuration, which is a set of links which can simultaneously transmit during a given time slot. Transmission configurations are mainly defined by considering SINR threshold and increase in transmission capacity. We also make sure that each configuration contains one incoming link for each gateway in order to maximize the throughput. We then schedule the links to transmit the data from the source to destination. It is done by properly mapping the transmission configurations among time slots. Our scheduling algorithm assumes that a link consists of two types of buffers, source and transit buffers. Source buffers contain the packets that the corresponding MR needs to send and the transit buffers contain the packets to be sent by MR on their way to destination. These buffers operate interchangeably, allowing the packets to move from one hop to another so that we maximize the throughput, without letting the packets accumulating in the buffers (i.e., minimizing the delay indirectly).

We then conducted several experiments to evaluate our algorithms Our results represents that we can gain up to 25% increase in throughput, which shows that POCs on WMNs perform better than using only OCs.

6.2 Future Work

There are still several challenges and problems that can be explored to increase the performance of the WMNs. Several problems such as, allowing variable power levels for MRs, dynamic channel assignment and scheduling algorithms as seen as immediate goals of this continuing work. More importantly, by allowing quality of service (QoS) issues in scheduling can make the objective of this work even more realistic.

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