Efficient Use of Partially Overlapping Channels in WMNs

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Abstract

There has been growing interest in using Wireless Mesh Networks (WMNs) because of their advantages such as easier to scale up and self-organization. We instigate whether increasing the number of available channels through the use of Partially Overlapping Channels (POCs) is always useful for improving the Quality of Service (QoS) of WMNs namely the throughput or delay. For the purpose of this thesis, we design a set of algorithms for: *i*) Channel assignment; *ii*) Transmission Configurations (TCs) which is a set of links with the ability of sending data simultaneously; *iii*) power control; and *iv*) delivery of packets to their destination in order to take advantage of POCs in WMNs.

We evaluate our proposed algorithms by a comprehensive set of numerical experiments. Numerical experiments indicate that using POCs leads not only to increase throughput of networks, but also it can decrease delay of packet delivery.

Acknowledgment

I owe my deep gratitude and respect to my supervisor Prof. B.Jaumard whose wisdom, knowledge and experiences shape numerous insightful conversations, without which many ideas in our research would have not been well developed. Her understanding, support and guidance helped me to make this thesis possible.

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Abbreviations

AP Access Point.

BA Building Automation.

BACnet Building Automation and Control Network.

BHN Broadband Home Network.

BPA Back-Pressure Algorithm.

CA Channel Assignment.

CAA Channel Assignment Algorithm.

CCA Common Channel Assignment.

CDMA Code Division Multiple Access.

CNN Community and Neighborhood Networking.

COMPOW Power Common Protocol.

CP Channel Partitioning.

CSMA Carrier Sense Mltiple Access.

CSMA/CA Carrier Sense Mltiple Access with Collision Avoidance.

DCA Dynamic Channel Assignment.

DSL Digital Subscriber Line.

DTG Dynamic Traffic Generator.

EN Enterprise Networking.

FCC Federal Communications Commission.

FDMA Frequency Division Multiple Access.

GBA Greedy-Based Algorithm.

GSM Global System for Mobile Communications, originally Groupe Spcial Mobile.

HCA Hybrid Channel Assignment.

HMS Health and Medical System.

ICB Interface-to-Channel Binding.

ISRO Ideally Scheduled Route Optimization.

LAN Local Area Network.

MAC Media Access Control.

MAN Metropolitan Area Network.

MBF Maximum-Buffer-First Algorithm.

Mbps Mega Bits Per Second.

MCHT Multi-Channel Hidden Terminal.

MIMO Multiple-Input and Multiple-Output.

MPM Multi Point to Multi-Point.

MRMC Multi-Radio Multi-Channel.

NIB Neighbor-to-Interface Binding.

NIC Network Interface Card.

NOC Non-Overlapping Channel.

OC Orthogonal Channel.

PBA Pattern-Based Algorithm.

PCA Power Control Algorithm.

PDA Personal Digital Assistant.

PFT Perron-Frobenius Theorem.

POC Partially Overlapping Channel.

PTM Point to Multi-Point.

PTP Point to Point.

QoS Quality of Service.

RAP Random Access Protocol.

RF Radio Frequency.

SB Source Buffer.

SCA Static Channel Assignment.

SRSC Single-Radio Single-Channel.

SSS Security Surveillance System.

STG Static Traffic Generator.

TB Transit Buffer.

TC Transmission Configuration.

TCP Transmission Control Protocol.

TDMA Time-Division Multiple-Access.

VCA Varying Channel Assignment.

VPN Virtual Private Network.

WEP Wired Equivalent Privacy.

WLAN Wireless Local Area Network.

WMC Wireless Mesh Client.

WMG Wireless Mesh Gateway.

WMN Wireless Mesh Network.

WMR Wireless Mesh Router.

Chapter 1

Introduction

This chapter begins by laying out the general background of Wireless Mesh Networks (WMNs) in Section 1.1 and motivation of this thesis in Section 1.2. Finally, key contributions of this thesis are described in Section 1.3.

1.1 General Background

All nodes contribute to the distribution of data in mesh networks. A WMN is made of links connecting routers, gateways and clients. According to Figure 1.1, clients of WMNs such as laptops and smartphones can connect to wireless routers by wireless Network Interface Cards (NICs); moreover, the responsibilities of the gateways are either to connect a WMN with other WMNs or to the Internet. In WMNs, responsibilities of each node are either hosting data or forwarding data to its neighbors. It is possible that all nodes cannot be directly reachable from every node in the WMNs because each node has a different transmission range. Hence, it is necessary to employ a routing mechanism to forward packets from their source to their destination. The most important features of WMNs are being self-organized and self-configured. When a node fails, its neighbors perform its responsibility for delivering packets to the other nodes. As a result, WMNs dynamically handle and maintain node connectivity.

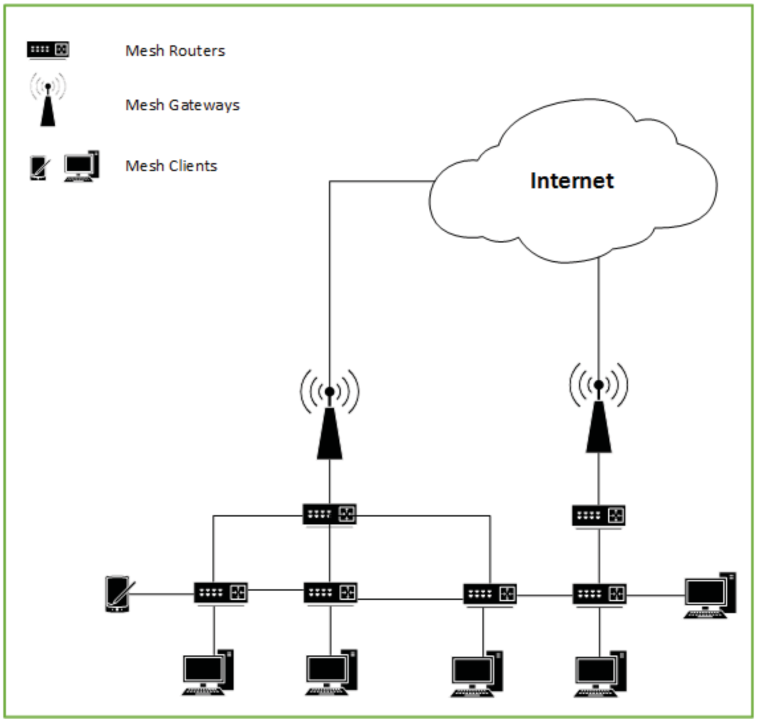


Figure 1.1: Overview of WMNs

WMNs have an enormous tendency to extend themselves after a period of time; this is made possible by extending the coverage range of wireless networks. Routers have minimal mobility; however, clients can be either immobile or mobile nodes. WMNs can easily connect to other WMNs; moreover they also support peer-to-peer communications. Applications of WMNs may vary based on their characteristics [5].

IEEE 802.11b/g is a well-known standard. The first WMNs' architecture is Single-Radio Single-Channel (SRSC). In SRSC, Wireless Mesh Routers (WMRs) can only communicate with one router at a specific time slot. In other words, if node A communicates with node B in time slot x, it cannot communicate with node D during the same time slot. Multi-channels with separated frequency are available in IEEE 802.11 standard. IEEE 802.11a standard provides 12 Non-Overlapping Channels (NOCs). In contrast, IEEE 802.11b/g offers only three NOCs. However, IEEE 802.11a has a shorter range because it works on higher frequency spectrum (5GHz) than IEEE 802.11b/g (2GHz) [10] . Partially overlapping channel mechanisms are proposed due to the limited number of non-overlapping channels.

1.2 Description of Thesis

Many studies have already been done on channel assignment, which is one of the challenging issues in WMNs. The ultimate aim is the improvement of the throughput. However, throughput strongly depends on several factors such as topology, traffic patterns, channel assignment strategy and delivery packets strategy [5]. Recently, the improvement of WMN' Quality of Service (QoS) is getting a higher attention among researchers. Consequently, the Multi-Radio Multi-Channel (MRMC) architecture was proposed to elevate the WMNs' QoS such as throughput and delay of packet delivery [39]. After a while, WMNs' devices can simultaneously communicate with two or more different devices when WMNs' components are equipped with two or more radio interfaces.

The effect of channels' interference declines dramatically the throughput of networks. Several researchers have proposed to use Orthogonal Channels (OCs) since they do not have any interference with each other. Hence, they can decrease the interference among the channels of the spectrum [24, 36]. However, the limited number of OCs in IEEE 802.11b is a key drawback. Partially Overlapping Channels (POCs) can boost the throughput of networks according to several studies [19, 35, 48]. It is necessary to find a comprehensive way to assign the channels to the links. Time-Division Multiple-Access (TDMA) is applied in WMNs in order to decease interference and boost the throughput [24]. A set of links with minimum possible interference can simultaneously transmit data in TDMA based networks.

Power control can optimize WMN capacity by reducing interference among nodes [5]. The battery-life of nodes can be enhanced by minimizing the nodes' power; moreover, using a suitable mechanism to assign a proper power to nodes can improve the QoS of networks [37].

Scheduling in WMNs refers to how packets can find their ways through the networks. A WMR establishes a stable connection between other routers if they are in the same transmission range. Hence, packets find their way through the network by using links between WMNs' nodes. Scheduling algorithms directly affect network throughput and delay of packet delivery. Against real world scenarios, all the previously methods suffer from some serious limitations. These gaps lead us to focus on channel assignment and scheduling problems.

1.3 Contributions

We investigate on how POCs, power control, different scheduling strategies can affect the QoS of WMNs. Our numerical experiments are based on a MRMC architecture with a Dynamic Traffic Generator (DTG). Several algorithms for building Transmission Configurations (TCs) are provided. A TC is a set of links which can send data simultaneously in a time slot. TCs are used to simulate a TDMA based WMNs. After creation of all TCs, our application assigns the actual power to each link with a Power Control Algorithm (PCA). In addition, two different algorithms that deliver traffic to their destination are suggested. Scheduling algorithms directly affect the throughput and delay of packet delivery.

Finally, numerical results show the effect of algorithms on the throughput and delay of packet delivery. We also compare the improvement of throughput and declining of delay in all combinations of our proposed algorithms.

1.4 Organization of Thesis

This dissertation is organized into six chapters. Chapter 1 provides an introduction to WMNs. The basic conceptions of WMNs are expressed in detail in Chapter 2. Subsequently, Chapter 3 summarizes the most recent works. In Chapter 4, all our algorithms namely channel assignment, definition of transmission configurations, scheduling and power control are described. The results of our experiments are discussed in Chapter 5. The conclusion of our study and possible opportunities for future work are expressed in Chapter 6.

Chapter 2

Background

In this chapter, an overview of WiFi networks is provided in Section 2.1. Then, WMNs and its significant properties are described in Section 2.1.5. After, the advantage of POCs and its challenges are discussed in Section 2.2. Next, Section 2.3 includes a discussion on Channel Assignment (CA). Scheduling mechanism is explained in Section 2.4. Finally, Section 2.5 gives a formal statement of the problem studied in this thesis.

2.1 Wireless Networks

2.1.1 Introduction

A Wireless Local Area Network (WLAN) is any Local Area Network (LAN) that a mobile user can connect to by using a wireless connection. Wi-Fi is a specific type of WLANs that uses specifications in the IEEE 802.11 wireless protocols as shown in Figure 2.1 [47]. WiFi stands for Wireless Fidelity. It is also the name of WiFi Alliance for a wireless standard. The WiFi Alliance organization's responsibility is to certify the interoperability of wireless devices [9]. WiFi is the common name for wireless local area networks based on IEEE 802.11b standard. It is one of the brightest areas of the communication business [17].

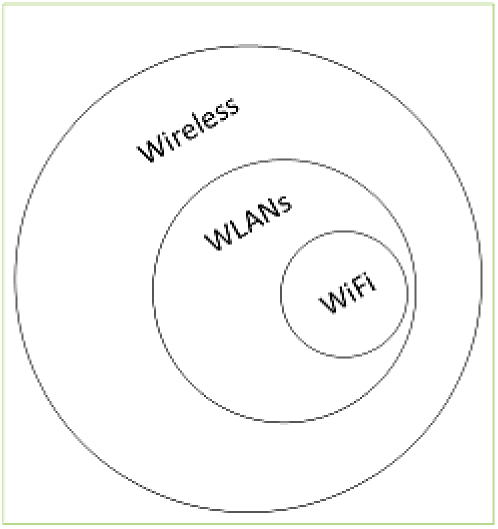


Figure 2.1: WiFi vs. WLANs

2.1.2 Standards

IEEE 802.11 [2] is a set of specifications for implementing WLANs with different sub-standards. IEEE 802.1a [3] is the first sub-standard of IEEE 802.11. It also operates in the 5GHz band. However, the drawback of IEEE 802.11a is that the signal traveling distance is dramatically decreased because of solid obstacles and walls according to its high frequency of the signal. In addition, the high cost of IEEE 802.11a based devices is an important disadvantage. Sending data with maximum speed (54 Mega Bits Per Second (Mbps)) is the key advantage of IEEE 802.11a standard.

IEEE 802.11b [4] is a new sub-standard to improve the distance of spectrum traveling. IEEE 802.11b is based on 2.4 GHz frequency band; as a result, signal can travel a longer distance. However, the weakness is the interference between on IEEE 802.11b based devices. The maximum data rate in IEEE 802.11*b* is 11 Mbps.

IEEE 802.11g came on stage by using the advantage of other standards in early 2000s. IEEE 802.11g not only operates in 2.4GHz band but also it can transmit data with 54 Mbps like IEEE 802.11a. Moreover, IEEE 802.11g devices are compatible with IEEE 802.11b devices; although, the interference with other devices is a key disadvantage of IEEE 802.11b based devices.

WiFi offers free broadband Internet access to any WiFi-capable devices such as laptops or smartphones [17]. Wireless networks are classified based on their characteristics and type of connectivity namely Point to Point (PTP), Point to Multi-Point (PTM), and Multi Point to Multi-Point (MPM). The advantage of PTP networks is reliability; however, they cannot expand easily. PTM has an acceptable level of scalability, but they suffer from low reliability. MPM overcomes the other two categories' limitation by providing high reliability and scalability to a significant number of users [40].

Nowadays, WiFi plays a main role of connecting tools and devices. Security, mobility, and ease of use are noticeable WiFi's characteristics [17]. We will briefly outline these characteristics, although the features will not be included in the context of this research project.

2.1.3 Security

Apparently, the most vital feature for WiFi networks is security because WiFi is available everywhere. In addition, access to WiFi in most of the cases is free and public. The dark side is a hacker just sitting on a chair in the park, listening to the WiFi communications of a grocery store, and capturing the credit card number of its clients. Life of WiFi can be endangered by the previously scenario. Wired Equivalent Privacy (WEP) can help traditional networks to become more secure; however, the key of encryption can recover with a simple amount of effort. still today, there is no final and comprehensive solution for security issues. WEP provides an easy-to-use and simple mechanism for securing traditional wired networks in acceptable level. Enhanced WEP(EWEP) provides security for WiFi networks [5, 17].

2.1.4 Mobility

Mobility is an essential and primary feature of WiFi networking. Several factors help to provide mobility to WiFi. Technology is the first stop on the ”mobility” road. There should be some devices to help users to connect WiFi networks and establish a stable connection between users and Access Points (APs). Typically, mobility is achievable based on Mobile-IP approach. Hence, a central mobility manager is required to keep track of mobile users. Moreover, IP routing can handle the details of the mobile connection. Mobile-IP and Virtual Private Networks (VPNs) can provide a desirable solution for a mobile and secure environment [17]. However, all networks components' positions are fixed in this study.

2.1.5 Wireless Mesh Networks

WMNs consist of Wireless Mesh Clients (WMCs), WMRs and Wireless Mesh Gateways (WMGs). Each WMN element can forward data to some of the next nodes. In other words, each node operates not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations [5].

A WMR contains additional routing functions to support mesh networking. To further improve the flexibility of mesh networking, a mesh router is usually equipped with multiple wireless interfaces built on either the same or different wireless access technologies [5]. A WMG is a WMR with additional functionality in connecting a WMN to the Internet or other WMNs. WMCs are users of WMNs such as laptops, smartphones, and Personal Digital Assistants (PDAs). Moreover, developing WMNs follows a simple bottom-top mechanism.

WMNs provide several significant advantages in wireless networks, which are described in detail in the following.

1. **Self Organization and Self Configuration:** There are no implementation constraints or mandatory protocols for building a WMN; in addition, the cost and time of their set-up is low because of self-healing and self-configuring abilities of WMNs. The QoS of WMNs is boosted because of these features.

2. **Low Deployment:** Using WMRs lead WMNs to deploy easily. In multi-hop networks, WMRs can expand the network step-by-step in time.

3. **More reliability:** There are several paths between routers and gateways in mesh topologies. Hence, there is an alternative way to reach destination if some middle nodes fail. This feature also results in decreasing the number of bottleneck links.

WMNs are used in different technologies which are explained in the following:

1. **Broadband Home Network (BHN):** There are many dead zones in any home. The expensive solutions such as site survey and installing multiple access points are not an

appropriate solution. WMNs replace APs with WMRs. There are several solutions for removing the dead zones such as adding a new WMR, changing the position of a WMR and adjusting the power of a WMR.

2. **Community and Neighborhood Networking (CNN):** Internet connected Digital Subscriber Line (DSL) or cable is the common architecture for network access in the community. This type of architecture serves several drawbacks such as network resource utilization is reduced because all traffic must pass through Internet, a high cost of network services, and homes have only a single bottleneck path for accessing the Internet. WMNs enlighten the disadvantage of DSL or cable architectures; in addition, they can serve some additional applications such as distributing file access and video streaming.

3. **Enterprise Networking (EN):** ENs refer to a wide range of networks. Nowadays, IEEE 802.11 is the most applicable standard in practice. ENs can be several medium-size networks for all offices in a building or a large network among offices in several buildings. However, these networks act like several isolated islands where connections among them can be achieved by wired Ethernet connections. Wired Ethernet connections is the key reason for increasing the cost of this type of networks. In order to overcome those disadvantages, Ethernet connections can be removed by replacing the access points with mesh routers to help boost the robustness and resource utilization of ENs.

4. **Metropolitan Area Network (MAN):** Using MANs in metropolitan areas serve several advantages namely transmitting data which can be done with much higher speed than other cellular networks, the WMNs do not depend on the wired backbone, and the cost of MANs is highly economical. WMNs cover much larger areas than home or companies building.

5. **Building Automation (BA):** There is an increasing interest in order to control electronic devices in houses because of the popularization of smart houses. Wired networks provide an expensive solution for smart houses due to the complexity in

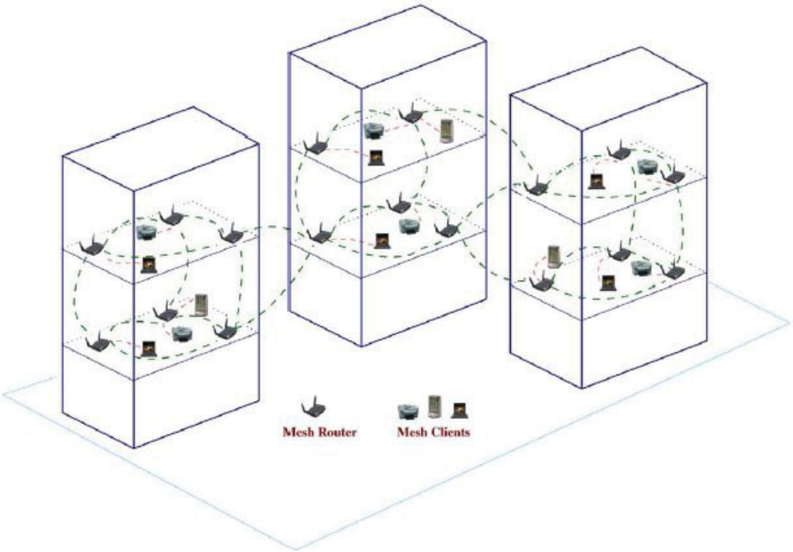


Figure 2.2: Enterprise WMN example [5].

installing and maintenance. Moreover, WiFi networks are still an expensive solution for this specific application due to wiring of Ethernet. The cost of building automation decreases dramatically by replacing the Building Automation and Control Network (BACnet) access point with WMRs.

6. **Health and Medical System (HMS):** Transferring data from a room of a hospital to other rooms like doctors' rooms seems a vital need. The traditional solution is wired based networks which is more expensive than WMNs in installing and maintaining networks. The WiFi solution is also expensive because of the existence of Ethernet connections. In contrast, these issues are properly solved by WMNs.

7. **Security Surveillance System (SSS):** Surveillance systems become a significant necessity for building, shopping malls because security is a key concern of users. WMNs provide a comprehensive and reliable framework to reach a stable system for security.

Several factors can affect the performance of networks namely radio techniques, security, and mesh connectivity. They are explained in detail in the following.

1. **Radio techniques** rely on the rapid development of semiconductor, Radio Frequency (RF) technologies, and communication theory. Smart antennas, Multiple-Input and

Multiple-Output (MIMO) systems, MRMC systems are developed to boost the capacity of wireless networks. Nowadays, multi-radio chipsets are available in the market.

2. **Scalability** is referred to the multi-hop aspect of the WMNs. In multi-hop networks, the performance of huge networks declines dramatically because the routing protocol may not be able to find an alternative path when a link fails. In other words, the node-to-node reliability strongly depends on the scale of the network; in addition, when node-to-node reliability improves, the size of the network declines. Applying a centralized multiple access scheme such as TDMA and Code Division Multiple Access (CDMA) is challenging because of their complexities and their requirements. A hybrid multiple access scheme with Carrier Sense Mltiple Access with Collision Avoidance (CSMA/CA) and TDMA can improve the scalability of WMNs. Hybrid multiple access schemes use TDMA for a part of topology which bottlenecks links exist. In addition, the rest of network operating in Carrier Sense Mltiple Access (CSMA) [31]. In this study, we use TDMA for raising the performance of networks.

3. **Mesh connectivity:** Many advantages of WMNs originate form mesh connectivity. Mesh connectivity is a significant necessity for Media Access Control (MAC) and routing protocols. In our research, the scheduling algorithms can manage each request and prevent any collision.

4. **Broadband and QoS:** Most applications of WMNs are broadband services with different QoS requirements. Consequently, different metrics for evaluating the performance of WMNs such as delay, fairness, delay jitter, node's throughput, and packet loss ratios are required. We use the average throughput and the average delay for evaluating the output of our simulation.

5. **Compatibility and inter-operability:** Supporting conventional and mesh clients are the most desirable aspects of WMNs. As a consequence, for dealing with conventional clients, WMNs need to have a backward compatibility. Integrating WMNs with another wireless network is possible by adding inter-operation functionality to some specific WMRs.

6. **Security** is the main concern for every user. The security mechanism is completely different from other ad hoc networks due to the topology differences. In addition, the security solutions, which are proposed for ad hoc networks are not adapted for WMNs.

2.2 Partially Overlapped Channels

Most of WMNs' MAC layers are created based on the IEEE 802.11 standard. IEEE 802.11b and 802.11g provide 14 frequency channels in 2.4GHz range. However, only 11 channels are allowed for unlicensed use by the Federal Communications Commission (FCC) in North America. Figure 2.3 illustrates the frequency of 2.4GHz band where each channel maps to its corresponding center frequency. The bandwidth of the channels is set to 22MHz and center frequency of each channel is separated from the next channel by 5MHz. Thus, some channels fall in the frequency range of their neighbors.

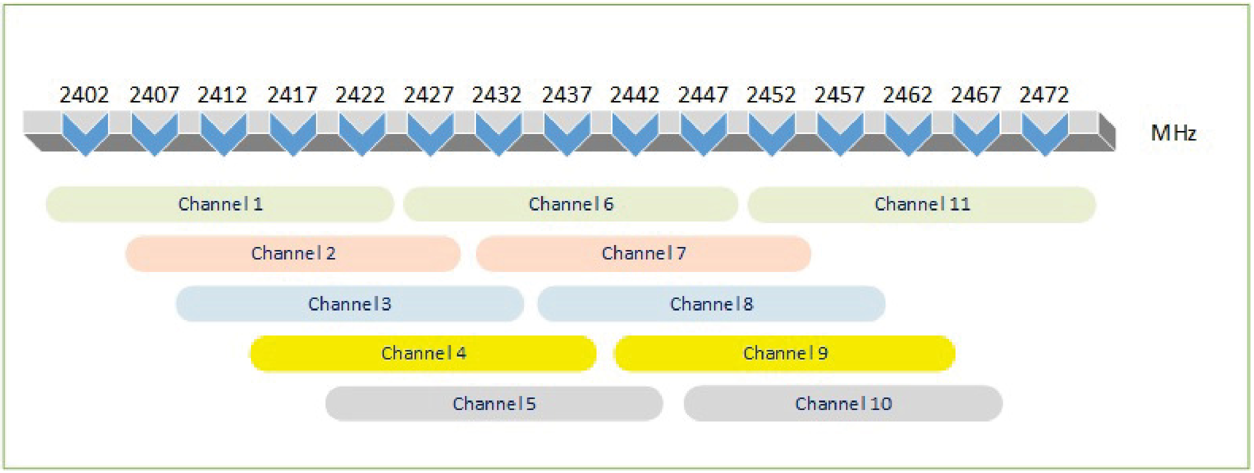


Figure 2.3: Frequency Spectrum of 2.4GHz Band

2.2.1 Interference

Regarding interference issues in WMNs, it is worth mentioning that interference plays an important role in the degradation of the network performance. To talk about interference, let u, u', v, and v' be a set of nodes in our network. u and u' are introduced as the senders and v and v' as the receivers. Assume that all four nodes are within interference range of each other. Interference is classified into co-channel interference, adjacent channel interference and self-interference. These main types of interference are next explained.

2.2.1.1 Co-channel Interference

Co-channel interference occurs whenever two neighboring pairs of nodes transmit using the same channel simultaneously. In Figure 2.4, the same channel number, i.e., channel 6, is assigned to the two pairs $u - v$ and $u' - v'$. Suppose u has data to send to v. u senses the wireless medium working on a particular channel, e.g., channel 6. If the channel is idle, it can send its data. Otherwise, it waits for a back-off period and keeps trying until the channel becomes idle. Also, the same scenario happens for the second pair.

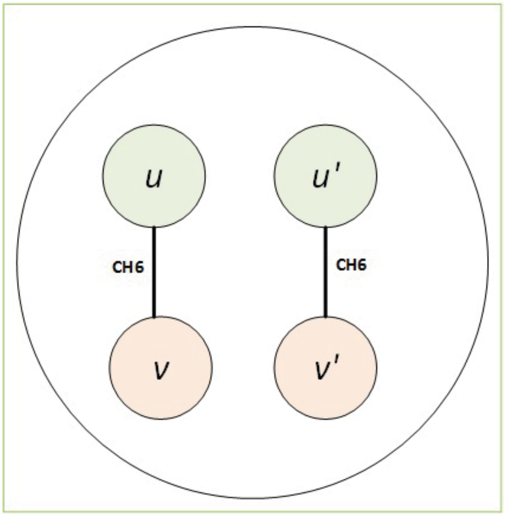


Figure 2.4: Co-channel Interference

2.2.1.2 Adjacent Channel Interference

This type of interference happens when the frequency of a pair overlaps with the frequency of the neighboring pair. Suppose the channels assigned to the pairs $u - v$ and $u - v$ are 6 and 8 respectively, as illustrated in Figure 2.5. u sends data on channel 6 to v. These simultaneous transmissions cause a transmission error because the channel 6 and 8 overlap each other. Hence, v and v' cannot decode the packets properly because of adjacent channel interference. Thus, adjacent channel interference severely degrades network capacity. It is worth mentioning that in this type, the interference range has an inverse relation to the channel separation.

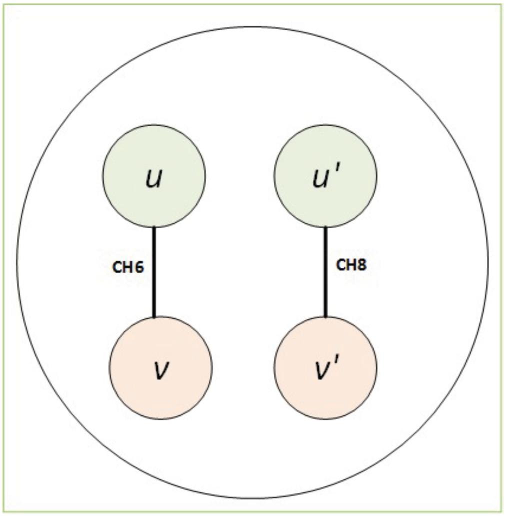


Figure 2.5: Adjacent Interference Channel

The severity of the adjacent channel interference is closely related to the geographical location of two nodes. When two nodes are close to each other, the level of severity of adjacent channels interference is immense. Therefore, the assignment of overlapping and non-overlapping channels in WMNs should be done intelligently for improving the throughput of networks.

2.2.1.3 Self-Interference

Self-interference is defined as interference caused by a node itself due to one of its transmissions. It happens when two different nodes connect to a common node with the same channel. In Figure 2.6, u is a common node with two radios. It connects to two nodes v and v'. If two radios work with the same channel, e.g., channel 6, simultaneous transmission of both radios causes interference and marked degradation regardless of the distance of the receivers.

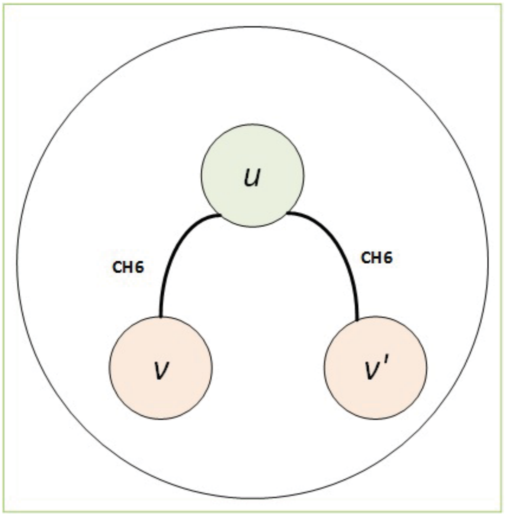


Figure 2.6: Self Interference

2.2.2 Interference Models

Interference directly affects the throughput by reducing the amount of transmitted data in a specific time slot. The key question is what communication throughput can be achieved under existence of interference. In addition, the answer depends on which devices can transmit concurrently without any interference. Hence, it is necessary to develop a transmission model to find an acceptable answer.

In the following, two interference models, that are widely used, are explained:

2.2.2.1 Protocol Interference Model

Each radio has a transmission range and an interference range. A transmission is successful if a particular receiver is in the transmission range of the sender and not in the interference range of other senders. For example, node u sends data over the ith channel to node v. The connection between u and v is a stable connection if Equation (2.1) is satisfied for every other nodes like u', which transmits data concurrently over the same channel [15].

$$|u' - v| \geq (1 + \Delta)|u - v|, \Delta > 0. \tag{2.1}$$

The quantity $\Delta > 0$ indicates situations where a secure zone is specified to prevent a neighboring node form sending data on the same channel in the same time slot.

2.2.2.2 Physical Interference Model

In the physical interference model, the transmission is successful if the Signal to Interference to Noise Ratio (SINR) of the sender's signal at the receiver node is larger than a threshold (β) that depends on the rate [14,45]. The amount of SINR indicates whether the transmitted data can be decoded at the receiver node or not. The physical model is more complex and more accurate than the protocol model.

$$\textsc{sinr}_\ell(L) = \frac{P d_{uv}^{-\alpha}}{\eta + \sum\limits_{\ell' \in L} I_\ell(\ell')}. \tag{2.2}$$

SINR is formulated in Equation (2.2) where P is defined as the transmission power of node u, d_{uv} is the distance between node u and v, α is the path loss exponent, L is a set of links, and η is the power of ambient noise. Under fixed power assumptions, P is a constant; however, under power control management, P corresponds to the power of ℓ. We will propose in Chapter 4, Section 4.4, an algorithm for the management of the power control. A closer look reveals the inverse relation between SINR and $I_\ell(\ell')$ where $I_\ell(\ell')$ is the interference of link ℓ' on link ℓ. $I_\ell(\ell')$ is calculated by the following equation:

$$I_\ell(\ell') = P d_{u'v}^{-\alpha}. \tag{2.3}$$

Equation (2.3) assumes implicitly that transmissions take place on the same channel. To address the situation when nodes transmit on different channels, Mishra *et al.* [27], introduced the notion of Interference-factor or simply I-factor denoted by $I_f(c, c')$. It measures the extend of overlap between channel c and c'. Moreover, I-Factor does not depend on the environmental factor or radio propagation characteristics. It scales from 0 for orthogonal channels to 1 for similar channels. Table 2.1 shows the IEEE 802.11b and 802.11g channel separation factor. Therefore, by using I-Factor in Equation (2.3), we obtain Equation (2.4) where c_ℓ is the channel of link ℓ.

$$I_\ell(\ell') = P d_{u'v}^{-\alpha} I_f(c_\ell, c_{\ell'}). \tag{2.4}$$

In addition, the notion of Relative Interference (IR) of link ℓ' on link ℓ is written:

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

Table 2.1: I-factor in IEEE 802.11b/g

$$RI_\ell(\ell') = \frac{I_\ell(\ell')}{Pd_{uv}^{-\alpha}} = I_f(c_\ell, c_{\ell'})\frac{d_{uv}^\alpha}{d_{u'v}^\alpha}. \tag{2.5}$$

Consequently, the notion of *affectance* of a link ℓ for set S of interference links is as follows:

$$a_\ell(S) = \eta_\ell \sum_{\ell' \in L} RI_\ell(\ell'), \tag{2.6}$$

where the value of η_ℓ is defined as:

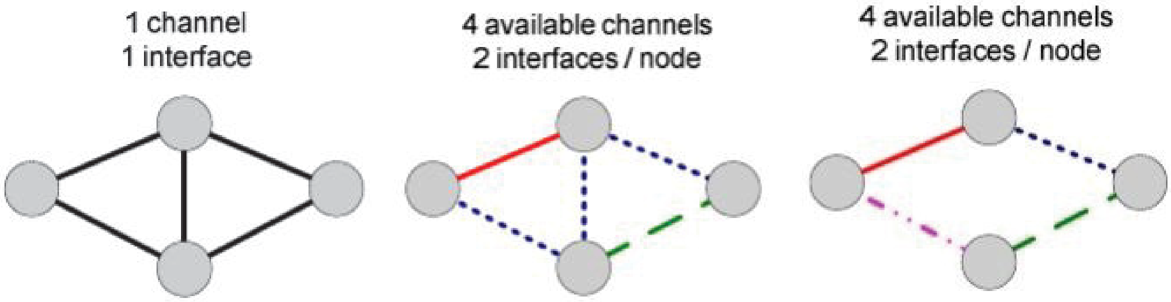
$$\eta_\ell = \frac{\beta}{1 - \frac{\beta \eta d_{uv} \alpha}{P}}. \tag{2.7}$$

Both *affectance* and SINR are equivalent in expressing the interference. The connection between two nodes is established whenever the SINR becomes greater than β under fixed rate assumption or *iff* $\forall \ell \in S, a_\ell(S) \leq 1$.

2.3 Channel Assignment

The aim of many studies is to improve the WMNs' QoS such as throughput or to decrease the delay of packet delivery. At the beginning of the wireless paradigm, most of the off-the-shelf devices were equipped with a single radio. These type of devices can negatively affect the QoS of the networks because the adjacent channel interference in networks is increased. Nowadays, many off-the-shelf devices are equipped with multiple radios. This technology improvement can increase the networks' throughput. As was mentioned in the previous section, IEEE 802.11b and IEEE 802.11g provide three non-overlapping channels. In addition, they can transmit data simultaneously.

In practice, the number of available channels is much less than the number of nodes' radios in a network. As a result, assigning the same channel to several links is unavoidable.



(a) Single Channel (b) Max connectivity (c) Minimum Interference

Figure 2.7: Tradeoff between connectivity and interference [7]

In addition, reusing of radio spectrum is the most effective way for increasing the QoS of WMNs and decreasing the effect of interference. Finally, assigning channels in an efficient way is the main issue in MRMC architecture [7].

There is a trade-off between increasing the network connectivity and declining the interference as illustrated in Figure 2.7. When a single channel is available, it is assigned to all nodes; hence, both connectivity and interference are maximized as shown in Figure 2.7a. In the next two scenarios, there are four non-overlapping channels and each node is equipped with two radios. In Figure 2.7b, maximum connectivity is achievable by assigning one channel to two links. As a result, the interference increases dramatically because of high interference of the same channel. In contrast, the interference is decreased, as well as the connectivity of the network when a link is removed as shown in Figure 2.7c.

We will next discuss three commonly used strategies for assigning channels to the radios.

2.3.1 Static Channel Assignment

Channels are permanently assigned to the transmission interface of a node in Static Channel Assignment (SCA). Common Channel Assignment (CCA) and Varying Channel Assignment (VCA) are two different strategies of SCA. CCA is the simplest strategy for assigning channels in a static way. It assigns the same set of channels to the nodes' interface. Consequently, high connectivity of the network is a key benefit of CCA strategy. In VCA nodes' interface assign to the different set of channels. The major drawback of this approach is that the throughput of networks is decreased after a while because the network topologies are changed [33].

2.3.2 Dynamic Channel Assignment

In Dynamic Channel Assignment (DCA), channels can change after several time slots. In addition, when a node needs to communicate with other nodes, there is a mechanism to ensure both of them have the same channel. The advantage of DCA is the ability of switching to any channel for any node. The challenging part of DCA is the delay of channel assignment mechanism [33].

2.3.3 Hybrid Channel Assignment

Hybrid Channel Assignment (HCA) is the combination of both static and dynamic channel assignment strategies. In HCA strategy, there are two types of nodes namely *fixed* and *flexible* nodes. Thus, a fixed set of channels is assigned to *fixed* nodes; moreover, channels are assigned dynamically to *flexible* nodes [25]. This strategy can inherit the advantage of both SCA and DCA.

2.4 Scheduling

Scheduling mechanisms deliver packets to their destination. Scheduling strategies can directly impact on throughput and fairness. The lack of an appropriate scheduling strategy can increase the delay of packet delivery.

Wireless channels are shared among multiple nodes. If more than one node sends data at a time on shared media, a collision may happen. Media Access Control (MAC) is an important aspect when a share medium is used to communicate between network nodes. MAC protocols define rules for orderly access to the shared medium with respect to fairness sharing and efficient sharing of bandwidth [44]. Three broad classes of MAC protocols are Random Access Protocol (RAP), Channel Partitioning (CP), and Taking Turns (TT). RAP and CP are explained below.

2.4.1 Random Access Protocol

Random Access MAC protocol specifies how to detect collisions and how to recover from collisions. Random Access Protocol allows all nodes to start transmitting if they have packets to send. The first mechanism of random access protocol is ALOHA [6]. In ALOHA, every node starts transmitting as soon as they have some data. As a result, if more than one node sends data, collision may happen. If a collision occurs all senders needs to try resending later. ALOHA cannot use of channels' capacity completely. The second mechanism of random access protocol is CSMA. A node first listen to the medium. Then, if the medium is idle, the node can send data. The corrupted message is sent when a collision of data happens. In CSMA/CA, when there is a collision, the transmission is stopped for several time slots.

2.4.2 Channel Partitioning

In practice, each carrier has only a limited number of radio frequencies. Carriers have to assign their radio frequencies to users whenever users want to send the data. Hence, there is a way to divide the total of radio frequencies into small portions. Indeed, frequency division was done to divide the spectrum into small portions [46]. Key techniques in the CP strategies are next explained in detail.

2.4.2.1 Frequency Division Multiple Access

The frequency band is broken down into a number of slots and they are assigned to each user. In a typical Frequency Division Multiple Access (FDMA) system, the total bandwidth is divided into slots with $25kHZ$ wide as shown in Figure 2.8. The problem of FDMA lies in the fact that the transmitted power when plotted against bandwidth is not an idealized rectangle [46]. Consequently, there is a marked interference between two adjacent channels. In addition, the need of using power amplifiers before transmitting data with an antenna is another marked disadvantage of FDMA. In summary, it is very difficult to get away from simple implementation of FDMA. By contrast, the loss of efficiency is the main drawback of FDMA [46].

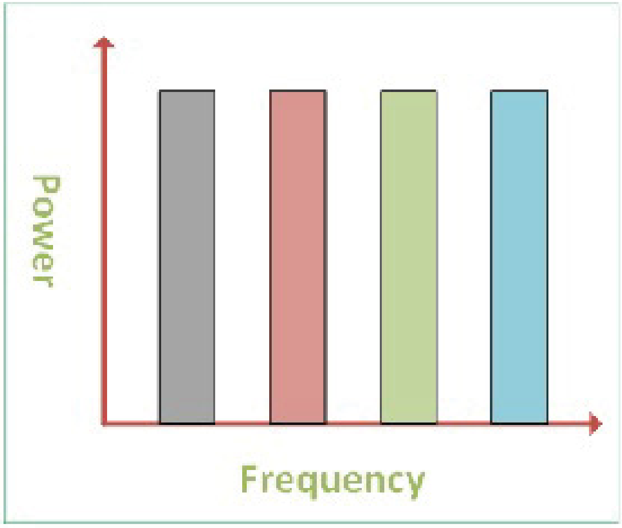


Figure 2.8: FDMA

2.4.2.2 Time-Division Multiple-Access

In this approach, each user can access to the total frequency, but in a limited time as shown in Figure 2.9. For example, an active user has access to 200kHZ of bandwidth for 577μs every 4.6ms in Global System for Mobile Communications (GSM) [46].

An idle device wants to transmit data in a limited period. At the beginning, the power of a device is zero and it should be increased to a specific amount of power. Hence, if duration of TDMA is not sufficient for boosting the power, the device cannot shift to sending data mode. *Ramping up* means that wireless devices must increase their power when they want to transmit data to other nodes. *Ramping down* refers to the idle time of a wireless device after sending data is terminated. In addition, if the duration of TDMA is not enough for ramping up and down, undesired channel interference is increased dramatically. For preventing the unwanted interference, TDMA introduces the guard band. The guard band is a specific time in which ramping up and down are permitted. TDMA based systems also need additional time in order to send timing information to the subscriber for specifying transmission time.

TDMA solves the main disadvantage of FDMA by assigning a user to a signal in a time slot. Thus, only one amplifier is needed at the base station. In addition, the cost of TDMA is less than FDMA because of the number of amplifiers. The drawback of TDMA is its complexity [33]. We will propose transmission configuration in Chapter 4. A TDMA based

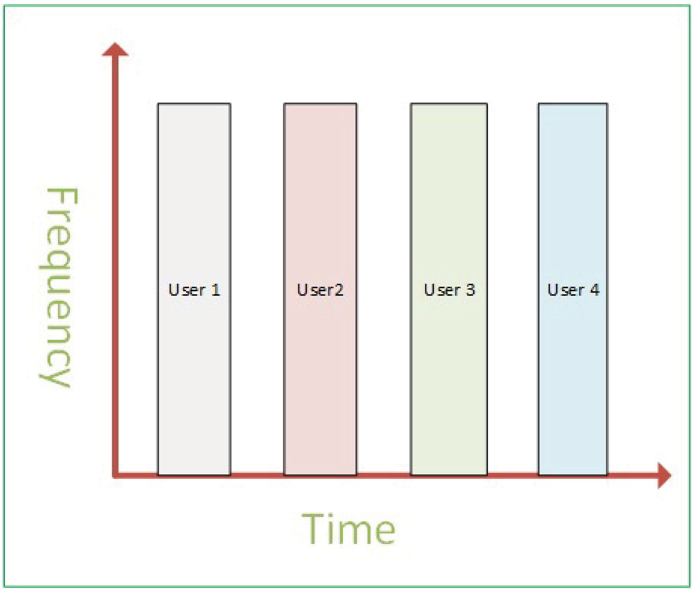


Figure 2.9: TDMA

network simulates by transmission configuration.

2.5 Statement of Problem

We consider a wireless mesh network represented as a graph $\mathcal{N} = (V \cup G, L)$, where V is the set of mesh routers, simply referred to as nodes, G is the set of gateways, and L is the set of transmission links. We assume that each node or gateway may have a different number of communication interfaces.

The inputs are a set of gateways and routers, a set of links, and traffic assigned to and from each node. Assigned channels to links, a set of transmission configurations, the throughput of the network, and the average delay in the packet delivery define the output.

Our goal in this thesis is to maximize the throughput of a WMN and to minimize the delay of packets delivery using all 11 channels of the 2.4 GHz spectrum. We also break down the problem into following sub-problems:

- Generate a valid random topology.
- Find the best possible uplink and downlink paths.
- Generate dynamic traffic for each time slot.

- Assign channels to links.
- Model a TDMA based network with transmission configurations.
- Assign power to links in each transmission configuration.
- Deliver packets to their destinations.

Chapter 3

Literature Review

3.1 Introduction

Wireless Mesh Networks (WMNs) are converged networks because they do not provide a unique and new standard. Network convergence refers to the provision of telephone, video and data communication services within a single network. They are built based on useful features of previous standards such as mobile ad hoc networks and Wireless Local Area Networks (WLANs) [42]. Nowadays, WMNs technology has became a reliable and highly efficient technology because a lot of effort has been done in academia and industry. However, there are still several issues that need further investigation. As explained earlier, channel assignment refers to mapping a link to a channel so that the interference of a link to other links remain minimal. In addition, scheduling method addresses the process of transmitting data from the source to its destination. However, these two problems are NP-hard problems. Many related works introduce heuristic algorithms, which are not the best solution, but they can run in polynomial time. In addition, most of researches address only Orthogonal Channels (OCs) to mitigate interference in WMNs [24,36]. However, due to the limited number of OCs, Partially Overlapping Channels (POCs) emerged as a promising alternative [13, 27, 28].

In this chapter, we will explain several related studies that have been done in different aspects of WMNs.

3.2 Single-Radio Single-Channel (SRSC)

In [43], So *et al.* used multiple channels dynamically as a Media Access Control (MAC) protocol to boost WMNs' throughput. The MAC protocol is designed only for using a single radio in IEEE 802.11 standard. However, the usage of a single radio MAC protocol leads to losing the capacity of networks because of Multi-Channel Hidden Terminal (MCHT) problem [15]. When a node is listening to the media on a specific channel, it cannot also listen to the media on different channels. As a result multi-channel hidden terminal happens based on this scenario. Their proposed solution is to use multi-channel by switching dynamically between different channels. Their protocol only needs one radio per node. In addition, they claim their solution can solve MCHT by temporal synchronization.

3.3 Multi-Radio Multi-Channel (MRMC)

Multi-Radio Multi-Channel (MRMC) WMNs emerged rapidly to enhance the quality of Internet access [33]. The results showed that using MRMC instead of a single radio and a single channel can improve the network throughput up to a factor of seven; however, an industrial document reports that MRMC solution boosts networks' capacity only up to a factor of five [41]. In [41], the authors categorized the channel assignment algorithms in MRMC architectures based on their characteristics as shown in Figure 3.1.

Channel Assignment (CA) mechanisms are categorized into two categories: centralized and distributed. The central control has all knowledge about mesh networks [33]. Hence, all calculations for CA problem are performed in a single place. Afterwards, the result is distributed to all nodes of the network. In contrast, there is no single place for calculating the CA problem in distributed mechanisms. Each node executes its own algorithm to assign the channels instead of a center place.

CA problem may be classified in term of traffic pattern into gateways and peer oriented. In gateways oriented networks traffic is to or from the gateway; however, a pair of nodes can send or receive the traffic to or from other nodes in pair oriented networks [41].

In [11], the authors categorized channel assignment algorithms in both omni-directional

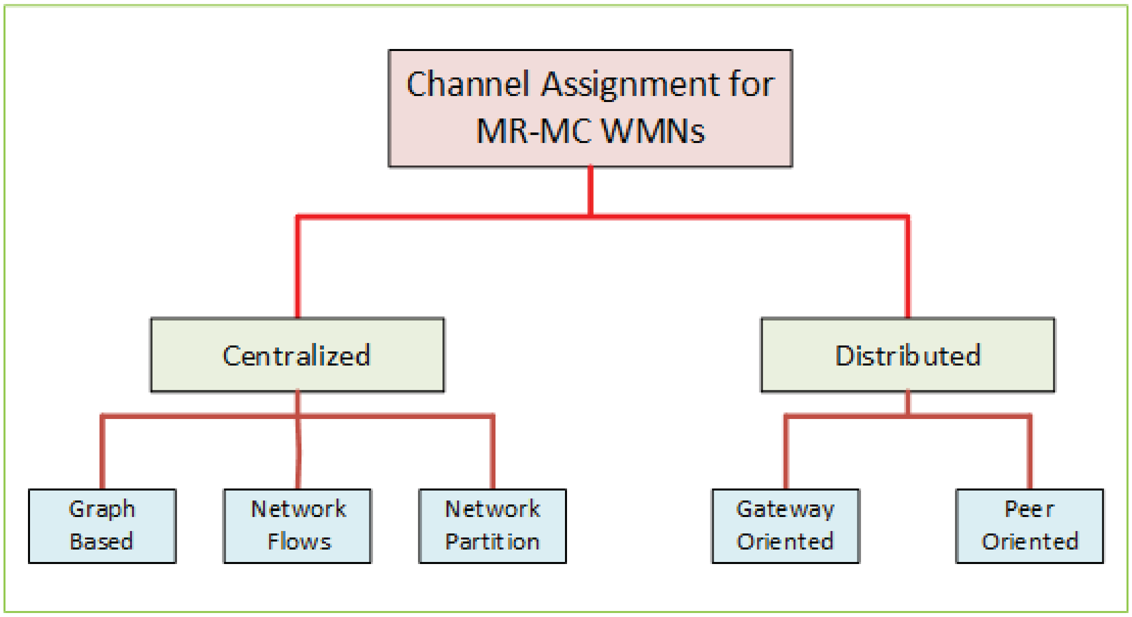


Figure 3.1: CA Algorithms classification.

and directional antenna networks. They focus on dynamic and static channel assignment strategies. Static channel assignment strategies have lower overhead because the interfaces of nodes cannot switch between different channels. However, dynamic channel assignment strategies are suitable when pattern of traffic is frequently changed.

In [19], Iyengar *et al.* model the CA as a graph edge coloring which colors present different assigned channels to the adjacent links in a graph. Moreover, they use SINR to calculate the interference in each link. In addition, they also propose a routing algorithm based on SINR. They simulate the model with NS2 in $1Km$ square as an environment with 16 routers and 2 gateways. The range of routers is $250m$ and the distance between routers is $200m$. They conclude that networks throughput is improved when the number of available channels and number of radios are increased.

In [39], Raniwala *et al.* introduce *Hyacinth* as a MRMC in WMN with fixed gateways. Routing protocols are designed to find the paths to the gateways with a minimum number of hops. They also divided the CA problem into two sub-problems: Neighbor-to-Interface Binding (NIB) and Interface-to-Channel Binding (ICB). Each Network Interface Card (NIC) are classified into two categories: UP-NICs and DOWN-NICs. UP-NICs's responsibility is connecting to parent and DOWN-NICs is used for connecting to children. By this classification, each node has to assign the channel only to DOWN-NIC, and the channel of UP-NIC is the same as the parent's DOWN-NICs as shown in Figure 3.2. For choosing the best possible channel for a node's DOWN-NIC, each node calculates the traffic loads on all channels and shares it with other nodes. Moreover, each node has different privileges to use a channel based on a priority. The priority is calculated by hop distance to the gateway. The smaller number refers to a node near the gateway. The close nodes have more priority over other nodes.

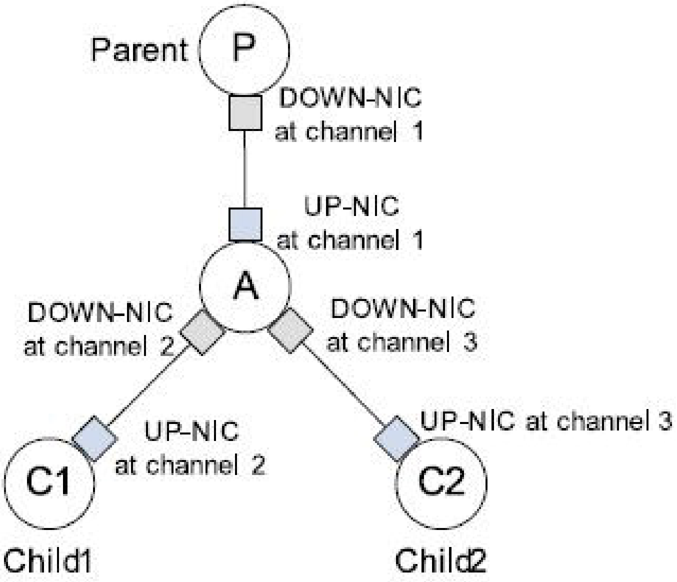


Figure 3.2: CA in Hyacinth [41].

Modeling the interference has been a well-known research area for a long time. In [27,28], Mishra *et al.* showed that the network throughput can be improved by using POC. They introduced *Interference-factor* or simply *I-factor* as a new interference measurement. It represents an overlapping parameter between two radio channels with $I(i, j)$ as the notation. $I(i, j)$ presents the overlap between channels i and j. Moreover, it shows the portion of power of the signal on channel j that will be received on channel i.

In [18], Hoque *et al.* proposed *I-matrix* as a new interference model. *I-matrix* helps select channels with minimal interference by comparing a channel's interference with all other channels in the current node's radio.

In [25], Liu *et al.* introduced a channel assignment method called CAEPO. It considers interference between channels and packet loss ratio as the main factors. In their scheme, the receiving radio is tuned to a fixed channel while the transmitting radio can be switched on different channels. They proposed an exact method using a mixed integer linear problem. They tried to figure out the impact of different combinations of physical interference model, power control and routing on a WMN. Based on the complexity of the problem the authors proposed a column generation pricing for solving this problem. The result illustrates that multiple-path routing cannot help to boost the throughput; however, single-path routing leads to a better result.

In [35], Mohsenian *et al.* employed a peer-oriented and distributed approach without assumptions on the traffic pattern. The proposed solution tries to optimize the performance of Transmission Control Protocol (TCP) congestion control on a network of 15 routers with three radios. The results showed that using POCs instead of only using OCs raises the network capacity by 93%. In [13], Feng *et al.* found that POCs can improve throughput by 50 to 80% over OCs. Recently, Xiang *et al.* revisited the joint channel assignment and link scheduling problem considering the physical interference model in [48]. They tested the proposed model in a network of 45 nodes with a gateway in the center. The generated traffic is only a one-way traffic. They concluded that applying POC needs to receive more attention in practice because of the trade-off occurring between the complexity of assigning 11 channels and the improvement of network capacity.

3.4 Gateways Issues

In [25] and [48] a set of Transmission Configurations (TCs) formed by non-conflicting links is defined to enable concurrent transmissions in Time-Division Multiple-Access (TDMA) networks . Most of the works are using one gateway in their research; however, in practice, there are several gateways in a WMN. The location of gateways is another consideration because the gateways should handle many requests. In [16], He *et al.* show that finding the optimal gateways' position for WMN in an NP-hard problem. Then, they formulate the problem as a linear program issue. In addition, they also recommend dividing the network topology into a tree structure and force the topology to communicate with only one gateway.

Livingston *et al.* [26] proposed Ideally Scheduled Route Optimization (ISRO) as a mechanism to optimize gateways selection, routing, and scheduling. The approach relies on finding an optimized solution for routing of gateway traffic by interference-free scheduling. The next step is to produce an interference-free schedule to figure out capacity of links; In addition, ISRO uses the extracted information that is obtained from previous levels as constraints to optimize the route.

3.5 Power Control

In [38], the authors formulated the power control problem as an optimization problem with connectivity and bi-connectivity as two constrains. They mentioned that power control in multihop wireless network can build an appropriate topology. A wrong topology can decline the Quality of Service (QoS) of networks. They illustrated a topology control mechanism under a power adjusting mechanism can boost the capacity of wireless networks.

In [29], the authors introduced a Power Common Protocol (COMPOW) for improving the capacity of networks. In addition, their proposed protocol can maximized the throughput, boosting battery life, and decrease the contention at the MAC layer. Their solution also provides a power aware route mechanism.

In [22], Kawadia *et al.* identified transmit power control as a cross-layer problem. Transmit power control can affect the physical layer, network layer, and transport layer. At the beginning, they identified several criteria for guiding their design process. Afterwards, they implemented several power control protocol namely COMPOW [29], CLUSTERPOW [21], and MINPOW [21]. They also simulated the power control protocols in N2R simulator. Finally, they presented several software architecture considerations for implementing their protocols.

In [32], Pathak *et al.* shows that in TDMA based system, increasing the level of power can positively impact on the performance of networks. They present boosted throughput is achievable by increasing the amount of power in node-to-gateway traffic pattern. They also proved that wireless mesh networks can achieve per node throughput of $O(1/\sigma)$ where σ is a factor which depends on the longest path form a gateway to a router. Previous research has indicated that the upper bound of per node throughput is $O(1/n)$ where n is the number of nodes in the networks [20].

3.6 Conclusion

Previous studies simplify tested conditions in terms of number of nodes, type of traffic and power control mechanism. We proposed several algorithms with polynomial running time which make a framework for a well-design, modular and step-by-step approach for recreating a WMN behaviors. In this study, the creation of random topologies, managing interference, calculating appropriate paths for each node in the topologies, and assigning channels are handled in an end-to-end manner. Moreover, two comprehensive algorithms for creating TCs are provided. Adjusting links' power is applied in this study for improving the capacity of TCs.

Chapter 4

Assigning and Scheduling Partially Overlapped Channels

In this chapter, we explain all proposed algorithms in detail. Dynamic Traffic Generator is explained in Section 4.1. Then, the channel assignment mechanism is discussed in Section 4.2. In Section 4.3, our approach for scheduling packets is explained. Afterwards, we discuss how power control algorithm manages the power of links in Section 4.4. Finally, we conclude this chapter by providing the complexity of all algorithms.

4.1 Dynamic Traffic Generator

There are two ways for generating traffic in network simulation. On one hand, the Static Traffic Generator (STG) generates the whole traffic for all nodes of a network in time slot zero. When the scheduling algorithms start to deliver packets to their destination, the network is full of traffic. In other words, all source buffers in a network are saturated by the *uplink* or *downlink* traffics at the time slot zero.

On the other hand, traffic may be generated for a specified period of time. The term DURATION refers to a period of time that Dynamic Traffic Generator (DTG) generates traffic for a network. In each time slot in DURATION, the generator engine decides to whether produces traffic or not. Hence, the network is not saturated in time slot zero.

Algorithm DyTr (Duration)

```
Input:
  Duration: Traffic is generated during this period of time(second)
  $downOverup$: the ratio of downlink traffic over uplink traffic

Output:
  $\text{traffic}^n$ which is indexed by $\text{traffic}^n_t$, $t$ is a time slot, $n$ is a node index.

  $G$: set of gateways in the network.
  $R$: set of routers in the network.
  $\lambda_n$: rate of node $n$

  for $n \in \mathcal{N}$ do                                                    ▷ Step 1
      $\lambda_n \leftarrow$ a random number between $[\lambda_{\max}, \lambda_{\min}]$
  end for
  TimeSlot $\leftarrow 0$
  $\mathcal{N} \leftarrow \{G \cup R\}$
  while Duration $> 0$ do
      for $n \in \mathcal{N}$ do
          if $n \in r$ then
              $\#packets \leftarrow$ getPoissonArrival($1$, $\lambda_n$)
          else
              $\#packets \leftarrow$ getPoissonArrival($downOverup$, $\lambda_n$)
          $\text{traffic}^n_{\text{TimeSlot}} \leftarrow (\#packts * 12000)/10^6$        ▷ Convert to Mega bits
      end for
      Duration $\leftarrow$ Duration $- 1$
      TimeSlot $\leftarrow$ TimeSlot $+ 1$
  end while
```

It is possible that there is no traffic for some nodes in a network at many time slots. Dynamic Traffic Generator (DTG) is coded in Algorithm DyTr. The output of Algorithm DyTr refers to traffic of each time slot for all nodes of a network. Procedure PoArr generates a number of Poisson arrivals based on Knuth algorithm [23]. The first step in Algorithm DyTr is to specify the average of generated traffic for each node(λ_n) in a network. Then, the number of generated packet in each time slot is discovered by calling Procedure PoArr. The amount of *downlink traffic* and *uplink traffic* are varied based on networks. For example, almost 40% of the whole traffic in a P2P file sharing network is the uplink traffic [12]. Algorithm DyTr controls the gap between downlink and uplink traffic with *downOverup*. According to [8] the size of a packet in wireless networks is 1500 bytes which equals to 12000 bits. As a result, Algorithm DyTr obtains the size of generated packet by multiplying the size of a packet and the number of generated packets.

Procedure PoArr (*downOverup*, λ)

Output: number of packets

```
$\#packets \leftarrow 0$
$a \leftarrow$ random number $[0.1, 1.0]$
$\lambda \leftarrow \lambda * downOverup$
$p \leftarrow e^{-\lambda}$
while $a > p$ do
    $\#packets \leftarrow \#packets + 1$
    $a = a - p$
    $p = p * \lambda / \#packets;$
end while
RETURN $\#packets$
```

As shown in Figure 4.1, data in a packet indicates the source of packet, its destination, packet's path, its size, time of birth and time of death. When a packet is created, DTG sets the time of birth. Scheduling algorithms set time of death for a packet when the packet reaches its destination. On the one hand, if the size of a packet is more than the capacity of the corresponding link, the packet can be broke down into smaller packets. On the other hand, when two similar small packets arrive at a buffer, they can merge and establish a bigger packet. Two packets are equivalent if their destination, source, path and time of birth are the same.

In this study, each link has a Source Buffer (SB) and a Transit Buffer (TB) in a network. SBs are filled by packets that the current node is their source. In contrast, packets go to TBs if the current node is an intermediate node on their way. Scheduling algorithms check the availability of the traffic in both buffers in each time slot and they deliver packets to their destination. Figure 4.2 presents a small network with available traffic. SB of ℓ_1 contains 50b traffic; in addition, source and transit buffer of ℓ_2 contain 20b and 10b traffic. In Figure 4.2, transit buffer of link ℓ_2 contains packet P_4 because the source node of link ℓ_2 is not the destination of packet P_4.

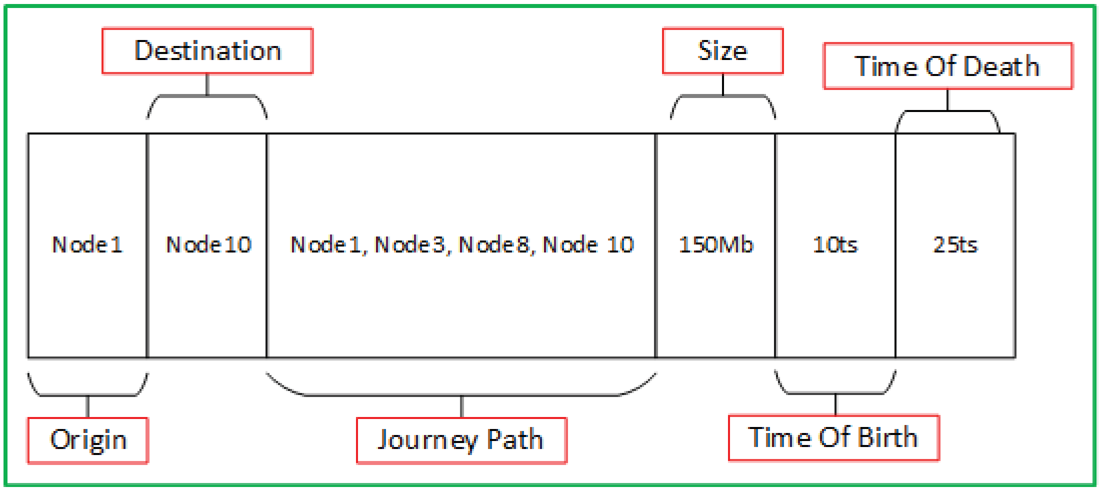
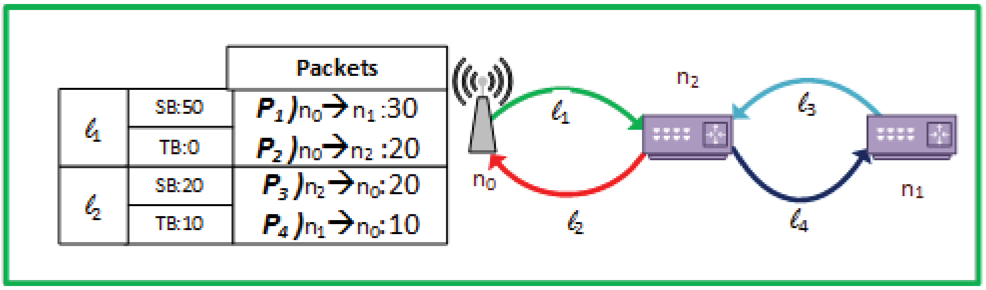


Figure 4.1: A Packet



		Packets
l_1	SB:50	P_1) $n_0 \rightarrow n_1$:30
	TB:0	P_2) $n_0 \rightarrow n_2$:20
l_2	SB:20	P_3) $n_2 \rightarrow n_0$:20
	TB:10	P_4) $n_1 \rightarrow n_0$:10

Figure 4.2: Transit and Source buffers

4.2 Channel Assignment

As was pointed out in Section 2.2.2.2 to this study, SINR is the foundation of assigning channels to links in WMNs. In this section, the steps of assigning appropriate channels to links are described and discussed. In Section 4.2.1, the procedure of routing is explained. Then, the traffic estimation mechanism is described in Section 4.2.2. Finally, Channel Assignment Algorithm (CAA) is explained in detail in Section 4.2.3.

4.2.1 Routing

We build a graph in which nodes are associated with gateways and routers. In addition, there are two arcs in opposite directions between two nodes if they can send data to each other.

Each router or gateway has a coverage range. If the range of a receiver and transmitter overlaps each other, the sender can transmit data to the receiver. In the graph, we express this fact by connecting the network elements with links. Figure 4.3 shows how a gateway and routers can reach each other and establish stable links.

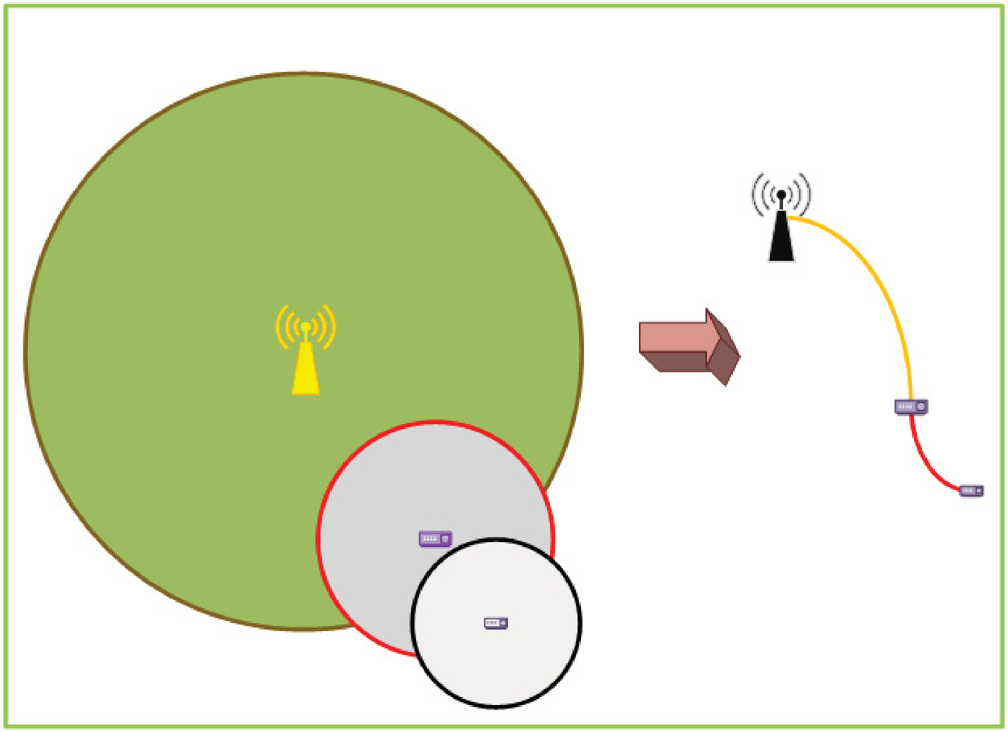


Figure 4.3: Establishing links among routers and a gateway

The number of gateways can vary in WMNs. In our routing mechanism, each router establishes a route to a gateway or a set of gateways based on their coverage area. First, all possible shortest paths from all gateways to each router are calculated by *Dijkstra* algorithm. Then, if there are two or more gateways in the network, the existence of several path from a router to different gateways is possible. In order to recognize the best possible paths from a router to only one gateway, the main factor for finding it, is the number of hops. However, it is possible that several paths for a router to different gateways have equal length. In Figure 4.4, P_1 and P_2 connect n_1 to the to different gateway. P_2 will be deleted because P_3 connects router n_2 to another gateway with only one link but the number of links in P_2 is 2(dotted lines are paths).

Two types of paths are distinguished in this study. A *downlink path* is a path from a

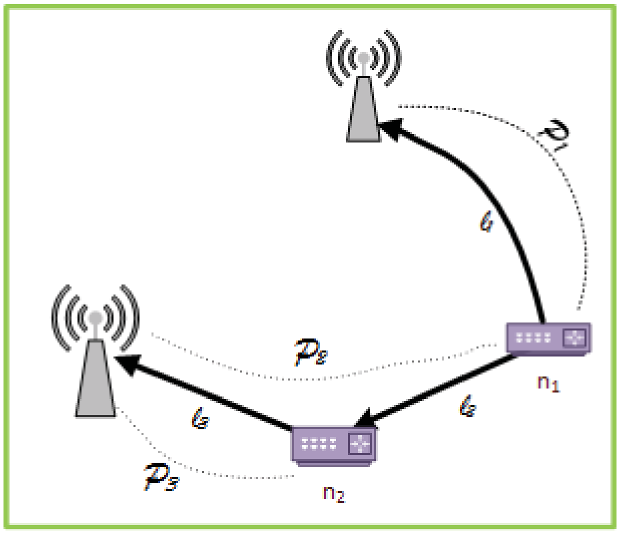


Figure 4.4: Deleting a Path

gateway to a router with P_{DL} as the notation. *Downlink paths* can be obtained by *Dijkstra*'s algorithm. The second type of path is *uplink path* or P_{UL} which is a path from a router to a gateway. *Uplink paths* are obtained by reversing *downlink paths*.

4.2.2 Traffic Estimation

Estimating the amount of traffic that goes through each link helps Channel Assignment Algorithm (CAA) to assign channels accurately. It is necessary to find links with maximum traffic because they are bottlenecks in the network. Gateway links may be bottleneck links because of the enormous amount of both *downlink traffic* and *uplink traffic* may be passed through them. Bottleneck links can deeply affect the QoS of WMNs. Moreover, links without traffic, they are not part of any shortest paths, are removed because they do not participate in scheduling phase which will be explained in Section 4.3.

Traffic of each time slot for routers and gateways was generated by Dynamic Traffic Generator (DTG). In addition, bottleneck links may be changed when pattern of traffic is changed in a time slot. In a specific period of time slots, amount of traffic of each link in a network is estimated based on the remaining traffic in both buffers and traffic in the next time slots.

Figure 4.5 illustrates the remaining traffic at time slot 10. Only source buffer of link ℓ_1

and transit buffer of link ℓ_2 contain traffic at time slot 10. The next generated traffic for next 10 time slots is presented in Table 4.1 for different nodes.

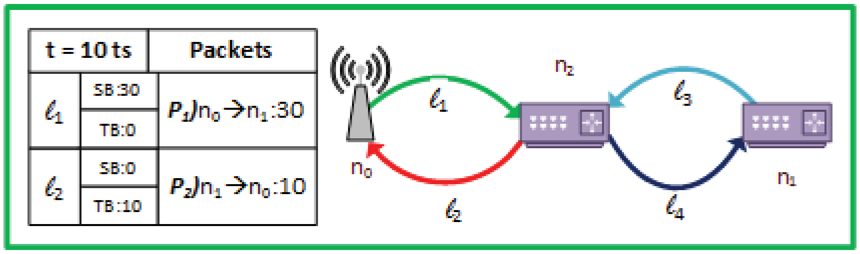


Figure 4.5: Remaining Traffic at time slot 10

Time Slot	Node	Packet	Size
15	0	P_3) $0 \to 1$	10Mb
20	2	P_4) $2 \to 0$	15Mb

Table 4.1: Generated traffic in the next 10 time slots

Table 4.2 presents the estimated traffic load according to Table 4.1 and Figure 4.5. When n_0 sends data to node n_1, traffic will pass through both ℓ_1 and ℓ_4. In addition, packet P_2 is in transit buffer of ℓ_2 which means it already passed through link ℓ_3. Finally, ℓ_3 is removed from optimal links set because there is no packet which will pass through ℓ_3 in the next 10 time slots.

Link	Traffic
ℓ_1	40Mb
ℓ_2	25Mb
ℓ_3	0
ℓ_4	40Mb

Table 4.2: Traffic Estimation

4.2.3 Channel Assignment Algorithm (CAA)

Responsibility of Algorithm ChanA is to assign an appropriate channel to links. The aim of the algorithm is to assign a well-suited channel to a link with respect to its traffic demand. L is the set of links in decreasing order of traffic demand. Let C be the set of available channels in the 2.4 GHz spectrum band. C may contain from 1 up to 11 channels. $\textsc{traffic}_\ell$ is equal to the traffic amount of link ℓ. Algorithm ChanA assigns channel 1 to the first link (the link with the maximum traffic) at *Initialization* phase. In the *Main Loop* phase, it calculates the *affectance* of each available link with regard to all considered links. Finally, it selects the channel with the minimum amount of *affectance* as shown in Figure 4.6. After the channel of a link is specified, the link is inserted in S to avoid assigning a new channel to it again.

Algorithm ChanA allows the high loaded links to be active simultaneously in more time slots to improve the QoS of networks.

```
Algorithm ChanA  ChannelA($C$,$L$,$\textsc{traffic}_\ell$, $c_\ell$, $S$)
    $C$ : set of available channels
    $L$ : set of links
    $\textsc{traffic}_\ell$: traffic on link $\ell$
    $c_\ell$: appropriate channel for $\ell$
    $S$: set of links with an assigned channel

    $S \leftarrow \emptyset$
    $\ell \leftarrow \arg\max_{\ell \in L} \textsc{traffic}_\ell$        ▷ Initialization
    Assign channel $c_\ell = 1$ to the first link $\ell$
    $S \leftarrow S \cup \{\ell\}$

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

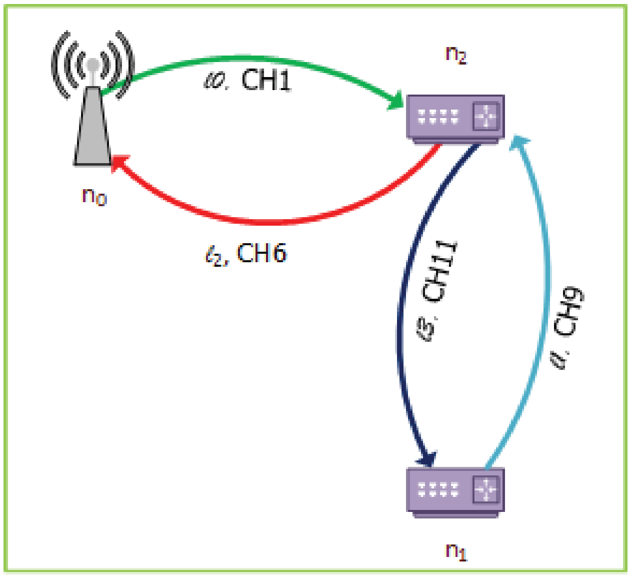


Figure 4.6: Channel Assignment

4.3 Scheduling

This section will study scheduling in WMNs. Our scheduling mechanism for MRMC WMNs encompasses creating transmission configurations and packet delivery.

Modeling a TDMA based system is achievable by transmission configurations. In Section 4.3.1, two proposed algorithms for creating transmission configuration are explained. Packets reach their destination by two algorithms which are explained in Section 4.3.2.

In this study, *downlink traffic* is set of packets such that their sources are gateways. Moreover, *uplink traffic* is set of packets such that their sources and destinations are routers and gateways respectively.

4.3.1 Transmission Configuration

A TC is a set of links that can be activated concurrently during a single time slot. As a result, it can directly affect the networks' performance. Our algorithms create several TCs with respect to the physical interference model. These algorithms use the result of Channel Assignment Algorithm (CAA) (Algorithm ChanA) for checking the interference between

802.11a/g (Mbps)	Modulation and Coding Scheme	Required SNR (dB)	Required SNR Absolute Value
6	BPSK 1/2	9.3	8·51(β)
9	BPSK 3/4	10.3	10·71
12	QPSK 1/2	11.3	13·48
18	QPSK 3/4	13.3	21·37
24	16QAM 1/2	17.3	53·70
36	16QAM 3/4	21.3	134·89
48	64QAM 2/3	24.3	269·15
54	64QAM 3/4	26.3	426·57

Table 4.3: Link SINR parameters for 802.11a/g [1]

links. In addition, both algorithms use Table 4.3 not only for pointing out the data rate of each link in a TC but also for indicating whether a link can be added to a TC or not. SINR with dB unit can be converted into absolute value of the SINR by Equation (4.1). It is necessary here to clarify that the absolute value of SINR is used in this study.

$$\textsc{sinr}(db) = 10 * \log(\textsc{sinr}). \tag{4.1}$$

4.3.1.1 Principles of Transmission Configuration

Procedure CanAdd shows how a link can be added to a TC. The β threshold, capacity of transmission configuration (TCAP), and the number of available radios are our three criteria.

```
Procedure CalcRate CalcDataRate ( T )
Input: : $T$: current transmission configuration
Output: : Assign an appropriate data rate to each link in transmission configuration
  for each $\ell \in T$ do
      $rate_\ell \leftarrow ComputeRate(\textsc{sinr}_\ell(L \setminus \{\ell\}))$        ▷ According to Table 4.3
  end for
```

Principle 1: Each router and gateway has a number of interfaces for establishing a connection to other network components. Principle 1 verifies that the endpoints of a link has at least one available radio. In Procedure CanAdd, the number of radios for a node is denoted by n_v^{RADIO}.

Principle 2: β is a constant with the value of 8.51. It is associated with the smallest possible rate, with which ℓ can transmit. If the SINR between two links is less than β, a stable connection between them cannot be established. In other words, if the SINR is more than β, the receiver can obtain the data from sender.

Procedure CanAdd *CanAdd*(ℓ, T)

```
Input: a link $\ell$ and a transmission configuration $T$
Output: the transmission configuration $T \cup \{\ell\}$ if $\ell$ can be
        added, $T$ otherwise

$o(\ell)$ and $d(\ell)$ are the origin and destination of link $\ell$, respectively.

$\forall \ell \in L$ MARK $[o(\ell)] \leftarrow 0$ ; MARK$[d(\ell)] \leftarrow 0$
ADD $\leftarrow$ . TRUE.
if MARK $[o(\ell)] < n_{o(\ell)}^{\text{RADIO}}$ and MARK $[d(l)] < n_{d(l)}^{\text{RADIO}}$ then
    $T' \leftarrow T \cup \{\ell\}$ ; TCAP$(T') \leftarrow 0$
    for $\ell' \in T'$ do
        if SINR$_{\ell'}(T' \setminus \{\ell'\}) \geq \beta$ then
            CalcDataRate$(T')$
        else
            ADD $\leftarrow$ .FALSE.
    end for

    if ADD = .TRUE. and TCAP$(T') \geq$ TCAP$(T)$ then
        return TRUE
return FALSE
```

Principle 3: The value of absolute SINR is not a sufficient requirement for adding a link to the current transmission configuration. Hence, the capacity of a transmission configuration is defined by summation of all links' data rate in a TC as shown in Equation (4.2) and Procedure CalcRate. The term TCAP(T) has come to be used to refer to the capacity of a transmission configuration. The current transmission configuration is denoted by T. After ℓ meets the two previous principles, it is nominated for insertion in the current TC; however, the capacity of a TC can be reduced after ℓ is added. As a result, ℓ cannot be added to the current transmission configuration.

$$\textsc{tcap}(T) = \sum_{\ell \in T} \textsc{rate}_\ell. \tag{4.2}$$

For example, Figure 4.6 illustrates four links with their channels. The identity of links indicates the order of links in terms of traffic. We also assume that SINR criteria meets for each pair of links. On other words, SINR for each pair of links is more than β. The first link (ℓ_0) is added to T according to Figure 4.7.

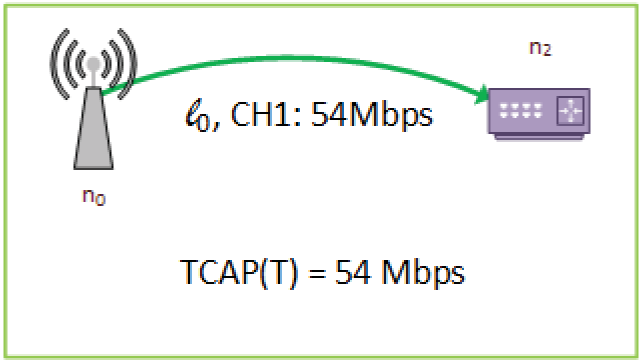


Figure 4.7: Accept: The first link is added to T

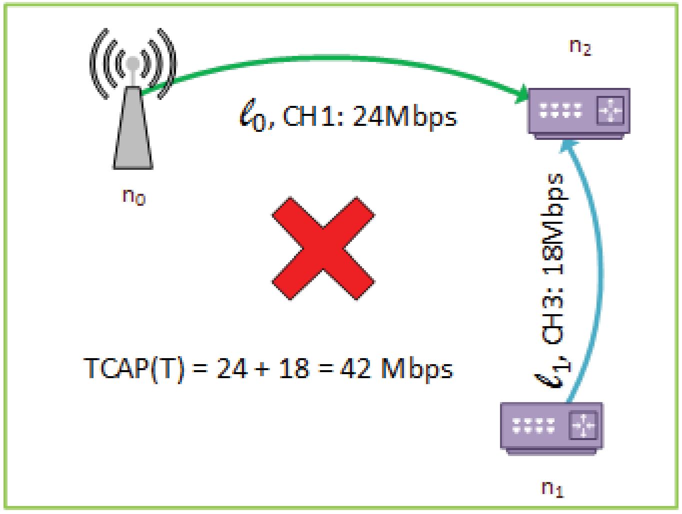


Figure 4.8: Reject: ℓ_1 cannot be added to T

ℓ_1 cannot be added to the current TC because the capacity of transmission configuration (TCAP(T)) is decreased after ℓ_1 was added to the current transmission configuration. As a result, Procedure CanAdd rejects the insertion of ℓ_1 to T. ℓ_2 can be added since it positively changes capacity of the transmission configuration as shown in Figure 4.9.

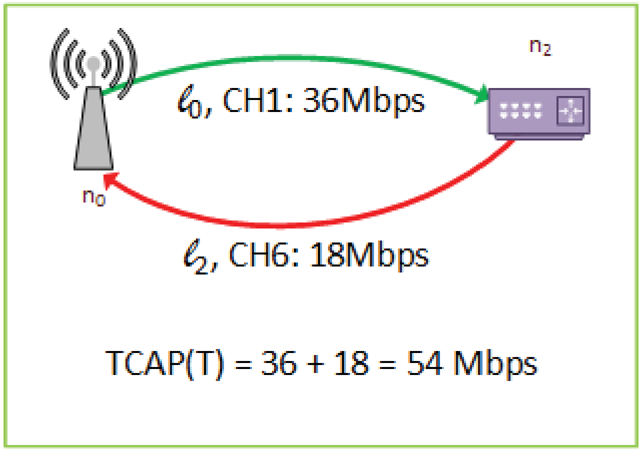


Figure 4.9: Accept: ℓ_2 is added to T

4.3.1.2 Greedy-Based Algorithm vs. Pattern-Based Algorithm

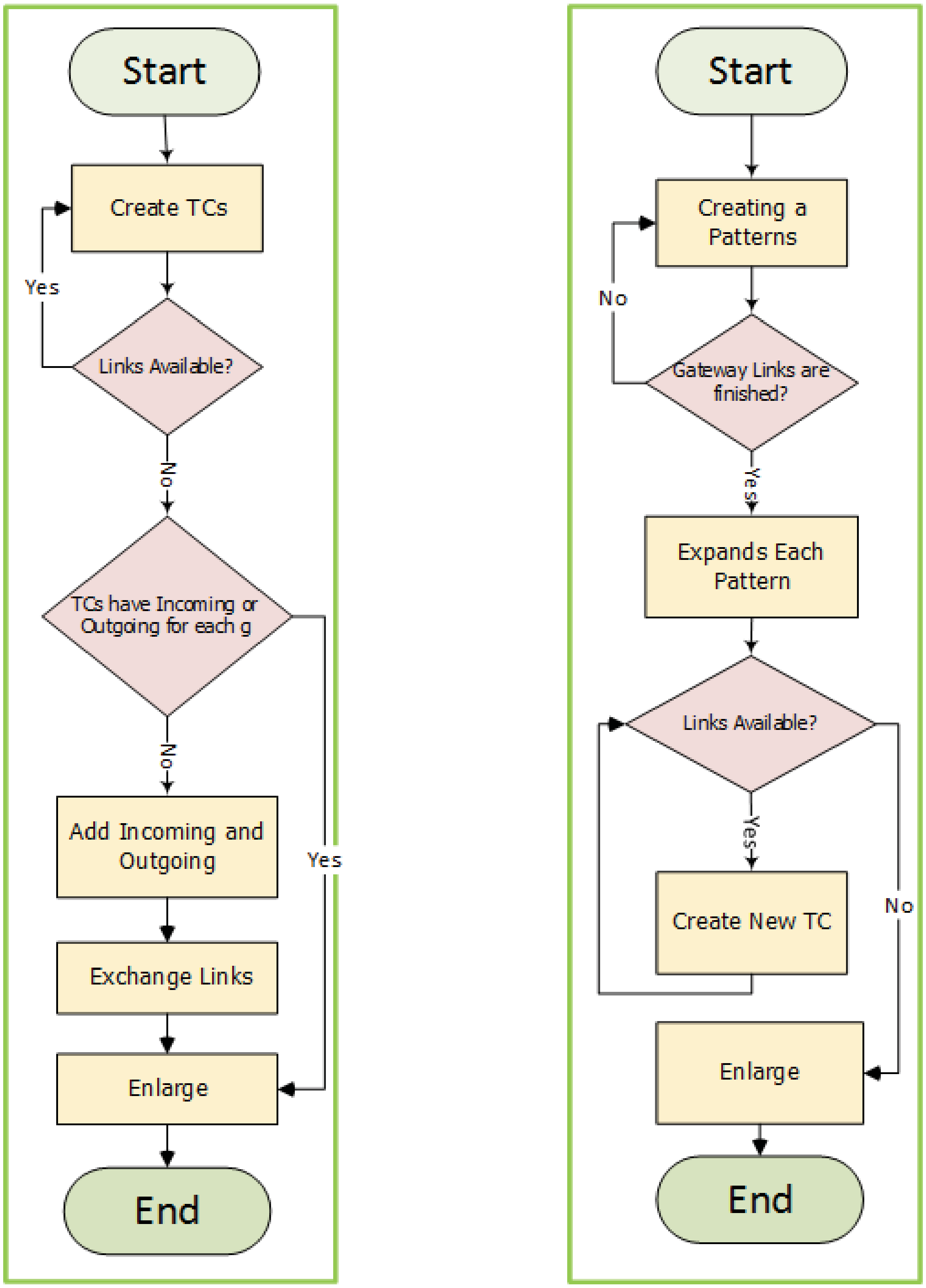
Greedy-Based Algorithm (Algorithm TCGBA) builds all TCs in an iterative manner. In contrast, Pattern-Based Algorithm (Algorithm TCPBA) creates multiple patterns of transmission configuration in the beginning and then extends them by adding new links. The structure of transmission configuration (T_i), pattern of transmission configurations (T_{p_i}), and final TCs are shown in (4.3). Therein, Algorithm TCPBA creates several patterns (T_{p1}, T_{p2}, T_{p3}). All links in the patterns are gateways links. Then, a transmission configuration becomes mature by adding new links to a pattern ($T_1 = T_{p1} \cup \{\ell_9\}$). Finally, it establishes the set of transmission configurations ($\mathcal{T}$) by unifying all TCs.

$$\begin{aligned}
&T_{p1} = \{\ell_1, \ell_3, \ell_5\}; T_{p2} = \{\ell_5, \ell_6, \ell_8\}; T_{p3} = \{\ell_2, \ell_4, \ell_7\};\\
&T_1 = T_{p1} \cup \{\ell_9\}; T_2 = T_{p2} \cup \{\ell_{10}, \ell_{11}\};\\
&T_3 = T_{p3} \cup \{\ell_{12}\}; T_4 = \{\ell_{13}, \ell_{14}\};\\
&\mathcal{T} = \{T_1, T_2, T_3, T_4\}.
\end{aligned} \tag{4.3}$$

In addition, Algorithm TCPBA builds patterns based on the type of links and traffic. However, the Greedy-Based Algorithm (GBA) appends links based on only their traffic. For instance, Pattern-Based Algorithm (PBA) tries to insert more outgoing links than incoming links if r is more than 1. In contrast, in the GBA, links are tested based on their traffic before joining the current TC. The structure of transmission configuration (T_i) and all transmission configurations ($\mathcal{T}$) for GBA are shown in (4.4). Algorithm TCGBA creates a transmission configuration (T_1 or T_2 or T_3) from scratch.

$$\begin{aligned} T_1 &= \{\ell_1, \ell_3, \ell_5\} \\ T_2 &= \{\ell_5, \ell_6, \ell_8\} \\ T_3 &= \{\ell_2, \ell_4, \ell_7\} \\ \mathcal{T} &= \{T_1, T_2, T_3\}. \end{aligned} \tag{4.4}$$

Figure 4.10 describes the flowchart of both algorithms. The number of steps in Algorithm TCPBA is smaller than in Algorithm TCGBA. In addition, in Section 4.5, we will see the performance of Algorithm TCGBA is better than Algorithm TCPBA in terms of throughput.



(a) Flowchart of Algorithm TCGBA (b) Flowchart of Algorithm TCPBA

Figure 4.10: Flowcharts of TC algorithms

4.3.1.3 Greedy-Based Algorithm

Greedy-Based Algorithm (Algorithm TCGBA) is the first method for creating TCs. All transmission configurations are denoted by $\mathcal{T}$. At the first step, the algorithm tests all existing links to insert in the current transmission configuration (T) based on their SINR. Procedure CanAdd confirms the principles of adding a link to a transmission configuration according to Section 4.3.1.1. After adding a link to the TC, the radios of the link's endpoints are filled because the connection between two nodes within reach of each other is established. $o(\ell)$ and $d(\ell)$ are the origin and destination of link ℓ. MARK $[d(\ell)]$ and $[o(\ell)]$ keep the number of occupied communication interfaces for endpoints of link ℓ. The responsibility of $counter^{g}_{in|out}(T)$ is to keep an eye on the type of links. Type of links is depend on the links' endpoints. If the source of a link is a gateway, the $counter^{g}_{out}(T)$ is increased by one unit. We use $counter^{g}_{in|out}(T)$ in the next step for improving the performance of networks. An enormous amount of traffic is passed through the gateways' links. Hence, it is necessary to add links of gateways to each TC as much as possible. L^C contains links that already belong to at least one TC; consequently, they cannot be considered again for a new TC. The primary *While loop* iterates until the number of links in L^C will be equal to the number of all available links.

In Step 2, first, the existence of outgoing or incoming links for each gateway is checked. Then, if there is no incoming link (ℓ') to a gateway (g), the algorithm tries to insert an incoming link by using Procedure CanAdd. The mechanism of step 2 is also repeated for outgoing links of each gateway.

```
Algorithm TCGBA ()
Input:
  Set of links $L$ with their assigned channel
Output: A set $\mathcal{T}$ of transmission configurations
            (indexed by $T$)
  $n_u^{\text{RADIO}}$: number of radios at node $u$
  $L^c$ : set of links in at least one configuration in $\mathcal{T}$
  $c_\ell$ : channel assigned to link $\ell$
  $\omega^-(g)$: set of incoming link to the gateway $g$
  $\omega^+(g)$: set of outgoing link from the gateway $g$
  $counter^g_{in|out}(T)$: number of links in $T$ with a gateway as an endpoint
  $\forall v \in V$ and $g \in G$ MARK $[v] \leftarrow 0$ ; MARK$[g] \leftarrow 0$; $L^c \leftarrow \emptyset$
                              ▷ Step 1: Building new configurations, covering all links
  while $L^c \neq L$ do
    $counter^g_{in|out}(T) \leftarrow 0$ for all $g \in G$; $T \leftarrow \emptyset$
    for $\ell \in L \setminus L^c$ (in decreasing order of TRAFFIC$_\ell$) do
      if CanAdd$(\ell, T)$ then
        $T \leftarrow T \cup \{\ell\}$; $L^c \leftarrow L^c \cup \{\ell\}$
        MARK $[o(\ell)] \leftarrow$MARK$[o(\ell)] + 1$ ; MARK $[d(\ell)] \leftarrow$MARK$[d(\ell)] + 1$;
        if $\ell \in \omega^-(g)$ or $\ell \in \omega^+(g)$ then
          $counter^g_{in|out}(T) \leftarrow counter^g_{in|out}(T) + 1$
    end for
                              ▷ Step 2: Including at least one incoming link for each gateway
    for $g \in G$ do
      if $counter^g_{in}(T) = 0$ then                                  ▷ Phase 1
        for $\ell' \in \omega^-(g)$ do
          if canAdd$(\ell', T)$ then
            $T \leftarrow T \cup \{\ell'\}$; $counter^g_{in}(T) \leftarrow counter^g_{in}(T) + 1$
        end for
      Repeat Phase 1 for $\omega^+(g)$ and $counter^g_{out}$
      if $counter^g_{in}(T) = 0$ then                                  ▷ Phase 2
        Exchange$(T, g)$
    end for
                              ▷ Step 3: Attempt to enlarge the configurations
    $T \leftarrow$ CalcDataRate$(T)$
    $\mathcal{T} \leftarrow \mathcal{T} \cup \{T\}$
    $\forall \ell \in L$ MARK $[d(\ell)] \leftarrow 0$ ; MARK$[o(\ell)] \leftarrow 0$
  end while
  $\mathcal{T} \leftarrow$ ENLARGE$(\mathcal{T})$;
  return $\mathcal{T}$
```

If the number of incoming links to a gateway is still equal to zero, the algorithm tries to add an incoming-gateway link by exchanging an existing link. The mechanism of the exchanging links will be explained. In the next step, Procedure Enlarge tries to append new links to the current TC . Procedure Enlarge examines all available links for appending to a TC. Consequently, Procedure Enlarge can boost the capacity of transmission configurations and performance of networks. Finally, data rates of links in each TC are calculated by Procedure CalcRate.

Exchanging Links

Scheduling algorithms select a transmission configuration in each time slot for forwarding packets towards their destination. Every router sends packets to gateways in almost each time slot. If there is no incoming-gateway-link in a TC, the throughput of network can decline because a packet may not reach its destination. The purpose of Procedure Exchange is to exchange an incoming-gateway-link with another link if there is no incoming link for a specific gateway.

```
Procedure Exchange $(T, g)$
Input:
  $T$: set of links in the current transmission configuration
  $g$: a gateway
Output: $T$ modified

  for $\ell \in \omega^{-}(g)$ do
      for $\ell' \in T$ do
          $T' \leftarrow T \cup \{\ell\} \backslash \{\ell'\}$
          if $\textsc{sinr}_{\ell''}(T' \backslash \{\ell''\}) \geq \beta$, For All $\ell'' \in T'$ then
              $\Gamma \leftarrow \Gamma \cup \{\ell, \ell', \textsc{sinr}_{\ell}(T \backslash \ell')\}$
      end for
  end for
  $\gamma^{\max} = \operatorname{argmax}_{\gamma \in \Gamma} \gamma(\textsc{sinr})$ ; $T \leftarrow T \backslash \{\ell'(\gamma^{\max})\}$ ; $T \leftarrow T \cup \{\ell(\gamma^{\max})\}$ ; $L^c \leftarrow L^c \backslash \{\ell'(\gamma^{\max})\}$
```

Γ is a triple which keep a deleted link (ℓ'), appended link (ℓ) and the value of SINR. For each link in the current transmission configuration (ℓ') and each incoming-gateway link (ℓ) the following steps will be performed: *i)* A new transmission configuration which is denoted by T' is created by deleting ℓ' and adding ℓ; *ii)* SINR for each link (ℓ'') in T' is computed; *iii)* If all calculated SINRs are larger than β, the procedure adds ℓ, ℓ', and the value of SINR in Γ;

iv) Steps *i* to *iii* for all links in the current transmission configuration and all incoming-gateway links are repeated; *v*) The maximum SINR in Γ is calculated (γ^{max}); *vi*) γ^{max} indicates which links should be deleted ($\ell'(\gamma^{\max})$) and added ($\ell(\gamma^{\max})$) to the current transmission configuration (T); and *vii*) At the end of the procedure, the set of considered links (L^c) is updated by removing the deleted link.

Enlarge

Algorithm TCGBA inserts links that do not belong to any transmission configurations into each TC. Several considered links may append to a transmission configuration in order to improve the capacity of the transmission configuration. The responsibility of Procedure Enlarge is to extend the capacity of a transmission configuration by adding new links to it.

For every endpoint of a potential link in a TC, first, the number of occupied radios are calculated in order to prevent creating a connection between two nodes without at least one available radio. Then, if both endpoints of the link under study have a free communication interface, the link can be added to the TC with respect to the SINR and capacity of transmission configuration. If a link can increase capacity of a transmission configuration, it can be appended to the TC.

4.3.1.4 Pattern-Based Algorithm

Pattern-Based Algorithm is a new strategy for building all transmission configurations. Algorithm TCPBA reduces the number of steps and the complexity of Algorithm TCGBA. A transmission configuration pattern is an immature transmission configuration which consists only outgoing or incoming links from or to all available gateways in a topology.

Let r be the ratio of outgoing over incoming links from/to gateways in a pattern of transmission configuration. Algorithm TCPBA inserts outgoing or incoming links with respect to r into patterns. Let $\omega^+(g)$ be the set of outgoing links of gateways; and $\omega^-(g)$ be the set of incoming links of gateways. L^c is the set of links that have already been inserted in at least one pattern or TC.

Procedure Enlarge ($\mathcal{T}$, L)

```
Input:
  $T$: Current transmission configuration
  $L$: All available links

Output: Update $T$

  $L$ sorted in decreasing order with respect to traffic
  $d(\ell)$ and $o(\ell)$ are endpoint of $\ell$
  $\forall \ell \in T$: $\textsc{mark}[d(\ell)]$ and $\textsc{mark}[o(\ell)]$
      contain the number of occupied radio for each link in $T$

  for $T \in \mathcal{T}$ do
    for $\ell' \in L \setminus T$ do
      if $\textsc{mark}[d(\ell)] < n^{\text{RADIO}}_{d(\ell)}$ and $\textsc{mark}[o(\ell)] < n^{\text{RADIO}}_{o(\ell)}$ then
        for $\ell \in T$ do
          $T' \leftarrow (T \setminus \{\ell\}) \cup \{\ell'\}$
          if $\textsc{sinr}_{\ell}((T \setminus \{\ell\}) \cup \{\ell'\}) > \beta$
            and $\textsc{tcap}(T') \geq \textsc{tcap}(T)$ then
            $T \leftarrow T \cup \{\ell'\}$
            $\textsc{mark}[d(\ell)] \leftarrow \textsc{mark}[d(\ell)] + 1$
            $\textsc{mark}[o(\ell)] \leftarrow \textsc{mark}[o(\ell)] + 1$
        end for
    end for
    $T \leftarrow$ CalcDataRate(T)
    $T \leftarrow$ PowerControl(T)
  end for
  return $\mathcal{T}$
```

At the beginning, Algorithm TCPBA defines several patterns of transmission configuration by adding gateways' incoming and outgoing links. The algorithm creates new patterns until all gateways' links are covered. In addition, patterns are not final transmission configurations. We denote the set of patterns by $\mathcal{T}_p$. Afterward, the algorithm develops patterns by adding new links to them in step 2. In the next step, for those links that are not attached to any TC patterns, the algorithm creates several transmission configurations based on their SINR and TCAP. Finally, by calling Procedure Enlarge, Algorithm TCPBA tries to expand TCs as much as possible.

Algorithm TCPBA (L)

```
Input:
  $L$: Set of links with their assigned channel

Output:
  A set $\mathcal{T}$ of transmission configurations

  $L_g$: number of incoming or outgoing links of gateway $g$
  $r$: is a constant.
  $\text{DLnum} \leftarrow 0; \text{ULnum} \leftarrow 0; \mathcal{T}_p \leftarrow \emptyset$        ▷ Step 1: Patterns
  while $L^c \neq L_g$ do
      Create new configuration $T$
      for $g \in G$ do                                        ▷ Add gateways' links to a pattern
          $L^c \leftarrow \text{TryAddingLinks}(\omega^+(g), T, 1, L^c)$
          $\text{DLnum} \leftarrow \text{DLnum}$+number of links added
          $L^c \leftarrow \text{TryAddingLinks}(\omega^-(g), T, 1, L^c)$
          $\text{ULnum} \leftarrow \text{ULnum}$+number of links added
          if $\frac{\text{DLnum}}{\text{ULnum}} < \text{r}$ then
              $\text{newR} \leftarrow \text{r} - \frac{\text{DLnum}}{\text{ULnum}}$
              $L^c \leftarrow \text{TryAddingLinks}(\omega^-(g), T, \text{newR}, L^c)$
      end for
      $\mathcal{T}_p = \mathcal{T}_p \cup \{T\}$
  end while
  $\text{nLA} \leftarrow \text{.TRUE.}$                                   ▷ Step 2: Append links
  while nLA and $L^c \neq L$ do
      $\text{nLA} \leftarrow \text{.FALSE.}$
      for $T \in \mathcal{T}_p$ and $\ell \in L \setminus \{L^c\}$ do
          if  $\text{CanAdd}(\ell, T)$ then
              $\text{nLA} \leftarrow \text{.TRUE.}; L^c \leftarrow L^c \cup \{\ell\}$
      end for
  end while
  $\mathcal{T} \leftarrow \mathcal{T}_p$
  while $L^c \neq L$ do                                         ▷ Step 2: New TCs
      Create new configuration $T$
      for $\ell \in L \setminus \{L^c\}$ do
          if $\text{CheckAdd}(\ell, T)$ then
              $\text{nLA} \leftarrow \text{.TRUE.}; L^c \leftarrow L^c \cup \{\ell\}$
      end for
      $\mathcal{T} \leftarrow \mathcal{T} \cup \{T\}$
  end while
  $\mathcal{T} \leftarrow \text{Enlarge}(\mathcal{T})$                                   ▷ Step 4: Enlarge
  return  $\mathcal{T}$
```

Try Add Links

When one of endpoint of a link is a gateway, the link is a gateway link. Algorithm TCPBA controls the number of inserted gateways' links to patterns of transmission configuration by Procedure TryAdd. In other words, Procedure TryAdd adds a specified number of gateways links (*num*) in each execution of procedure. Procedure TryAdd appends *num* number of links through L' into a pattern of transmission configuration in each execution. Algorithm TCPBA calls Procedure TryAdd two times for adding one *uplink* and *downlink* to a pattern of transmission configuration. Afterward, it appends more gateways' links to the pattern of transmission configuration by comparing the number of added links with r. r is a constant parameter which equals to ratio of downlinks over uplinks.

```
Procedure TryAdd $((L', T, num, L^c))$
Input:
  $L'$: Gateway links
  $T$: Current transmission configuration
  $num$: Number of added links
  $L^c$ : Set of links which belong to at least one configuration
Output:
  $T$: updated the current transmission configuration

  $counter \leftarrow 0$
  while $counter < num$ do
      for $\ell \in L'$ do
          if $\ell \notin L^c$ and $\ell \notin T$ and CanAdd$(\ell, T)$ then
              $counter \leftarrow counter + 1$; $L^c \leftarrow L^c \cup \ell$
              if $counter == num$ then
                  exit
      end for
  end while
  return $T$
```

4.3.2 Packets Delivering

The final step in our scheduling approach is delivering packets from their origins to their destinations. It also determines the throughput of the network. Responsibilities of packet delivery algorithms are, first, choose an SB based on some criteria, and then, they select the best TC according to its links' weight. Finally, they deliver the packets to the destination or move the packets to the next node in their path towards destination.

4.3.2.1 Maximum-Buffer-First Algorithm

Algorithm DPMBF selects a buffer with the largest amount of traffic in each time slot. Dynamic Traffic Generator generates traffic for a random number of nodes in each time slot. Delivery packet algorithms retrieve the traffic in each time slot and distributes the traffic on the source buffers (UPDATETRAFFIC). Then, all buffers, which contain traffic, are sorted with respect to their amount of traffic. Afterwards, a source buffers with the largest amount of traffic is selected. A link can be in several transmission configurations with different data rates. In order to improve throughput of networks, it is necessary to choose the best possible transmission configuration. Hence, weights of links in TCs is defined for indicating which transmission configuration is the best possible TC for boosting throughput of network according to available traffic in buffers. After weights are determined by Procedure CalcW for each TC, an appropriate TC is selected. Finally, all links in the selected TC transfer data concurrently during a time slot. In each time slot, throughput is calculated based on the size of packets that reach their destinations. The same process is used for transmission buffers.

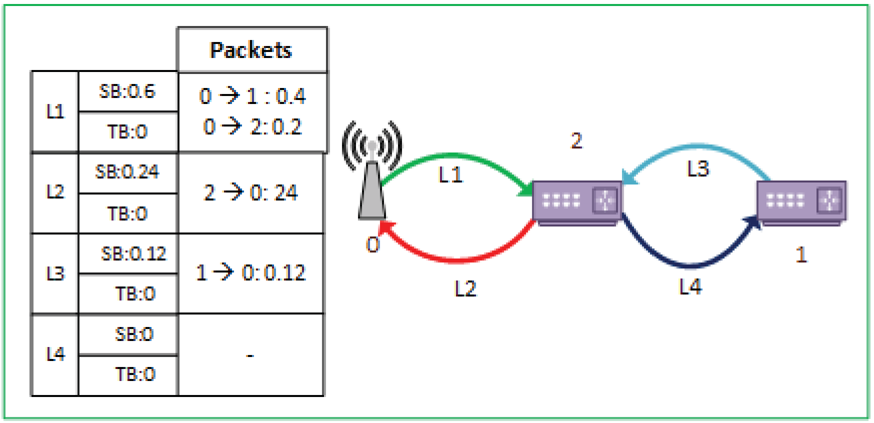
```
Procedure CalcW ($\mathcal{T}$,$B_{v\ell}$)
Input: $B_{v\ell}$: Buffers
Output: $\mathcal{T}$ with a weight associated to each link

  $T_\ell^{dr}$: Data rate of link $\ell$ in the current $T$
  $T_\ell^{weight}$: Weight of link $\ell$ in the current $T$

  for $T \in \mathcal{T}$ do
      for $\ell \in T$ do
          $\text{TRAFFIC}_{\mathbf{r}}^{\ell} \leftarrow$ retrieve the amount of traffic for link $\ell$ from $B_{v\ell}$.
          $T_\ell^{weight} \leftarrow T_\ell^{dr}/\text{TRAFFIC}_{\mathbf{r}}^{\ell}$
      end for
  end for
  return $\mathcal{T}$
```

```
Algorithm DPMBF ($\mathcal{T}$, $L$)
Input:
  $\mathcal{T}$: set of transmission configurations
  $L$: set of links

  INTERVAL is a constant parameter.
  $B^s_{v\ell}$: source buffer for node $v$.
  $B^t_{v\ell}$: transmit buffer for node $v$.
  TIMESLOT ← 0;

  while ∃ at least one non-empty buffer $B^s_{u\ell}$ or $B^t_{u\ell}$ Or DURATION $\neq 0$ do
                    ▷ Appends the traffic which generate at TIMESLOT to the source buffer $B^s_{v\ell}$
      $B^s_{u\ell}$ ← UPDATETRAFFIC(TIMESLOT);
      if TIMESLOT%INTERVAL == 0 then            ▷ Recreating transmission configuration
          PATTERNBASED Or GREEDYBASED

                                   ▷ Step 1: delivery the packets from the source buffers
      $\mathcal{B}^s_{\text{MAX}}$ ← Select the maximum source buffer according
      WEIGHT$_{\mathcal{T}}$ ← CALCWEIGHT($\mathcal{T}, B^s_{v\ell}$)
      Select proper number of transmission configurations based on the weights of their
          links in each $T$ which cover $\mathcal{B}^s_{\text{MAX}}$.
      Move the amount of packets according the data rates of links in the
       selected configuration. The data is removed if it reaches
       its destination OR it moves to a transmission buffer.
      DURATION ← DURATION − 1; TIMESLOT ← TIMESLOT + 1;

                                              ▷ Step 2: scheduling in-transit packets
      $B^s_{u\ell}$ ←UPDATETRAFFIC(TIMESLOT);
      Same as Step 1 but instead of $B^s_{v\ell}$ it works with $B^t_{v\ell}$
      DURATION ← DURATION − 1; TIMESLOT ← TIMESLOT + 1;
  end while
```

Procedure CalcW shows how weights of links in a TC are calculated. The inputs of the procedure is the traffic that remain in buffers and all TCs. For each link in a TC, the procedure retrieves the available traffic ($\text{TRAFFIC}^{\ell}_{\mathbf{r}}$). Then, the weight of ℓ will be equal to the data rate of link divided by traffic. In each iteration of the main loop in Algorithm DPMBF, weights of links are calculated for choosing the best possible TC in a time slot. It is possible that several TCs contain a link; hence, the weights reveal the best possible TC.

For example, Figure 4.11 shows a network and the amount traffic in each buffer. The buffers are sorted increasingly with respect to traffic. Data rate of links are shown in (4.5).

$$\mathcal{T} : \{T_1 = \{\ell_1 : .36, \ell_4 : .12\}, T_2 = \{\ell_2 : .72, \ell_1 : .72\}, T_3 = \{\ell_3 : 1.08\}\} \tag{4.5}$$



		Packets
L1	SB:0.6	0 → 1 : 0.4 0 → 2:0.2
	TB:0	
L2	SB:0.24	2 → 0: 24
	TB:0	
L3	SB:0.12	1 → 0:0.12
	TB:0	
L4	SB:0	-
	TB:0	

Figure 4.11: Illustration of Algorithm DPMBF

In the first iteration, the SB of link ℓ_1 is selected because its traffic is the highest in the network. Then, weights of links for each TC are calculated as shown in (4.6). T_1 and T_2 are two possible options for ℓ_1 but T_2 is the best option since its weight is greater than T_1.

$$\textsc{Weights} : \{T_1 = \{\ell_1 : 0.6, \ell_4 : 0\}, T_2 = \{\ell_2 : 3, \ell_1 : 1.21.0\}, T_3 = \{\ell_3 : 9\}\}. \tag{4.6}$$

Algorithm DPMBF sends packets to the transmit buffer of ℓ_4 because its destination is not node #2. The same process will be performed for the packets, which exist in TBs of links.

4.3.2.2 Back-Pressure Algorithm

Back-Pressure Algorithm (BPA) is a centralized algorithm, which can maximize throughput of networks [30]. In each time slot, Algorithm DPBP searches entire of a network for an appropriate buffer. As a result, Back-Pressure Algorithm (BPA) not only can boost performance of networks but also its complexity is noticeable.

The data with destination node $\mathcal{N} \in \{n_1, n_2, ..., N\}$ is referred to as commodity $\mathcal{N}$ data. $D_{n_1}^{\mathcal{N}}(t)$ is the size of a packet in n_1's buffer with destination $\mathcal{N} \in \{n_2, n_3, ..., N\}$. In each time slot, $D_{n_1}^{n_1}(t)$ is equal to zero because a node cannot send packets to itself. $[\ \mu_{n_1 n_2}\ ]$ is a matrix that refers to data transmission rates based on the capacity of each TC. Data transmission rates were calculated by Procedure CalcW.

Algorithm DPBP selects the optimal packet size based on Equation (4.7) for each node and its neighbors. In other words, $\mathcal{N}_\ell^{\text{OPTI}}(t)$ should be calculated for each outgoing ($\ell(n_1, n_2)$) link in a network in each time slot.

$$\mathcal{N}_\ell^{\text{OPTI}}(t) = \textsc{Maximize}\{D_{n_1}^{\mathcal{N}}(t) - D_{n_2}^{\mathcal{N}}(t)\}. \tag{4.7}$$

For example, Figure 4.12 illustrates the amount of three different packets (Yellow-Top, Green-Middle, Red-Bottom).

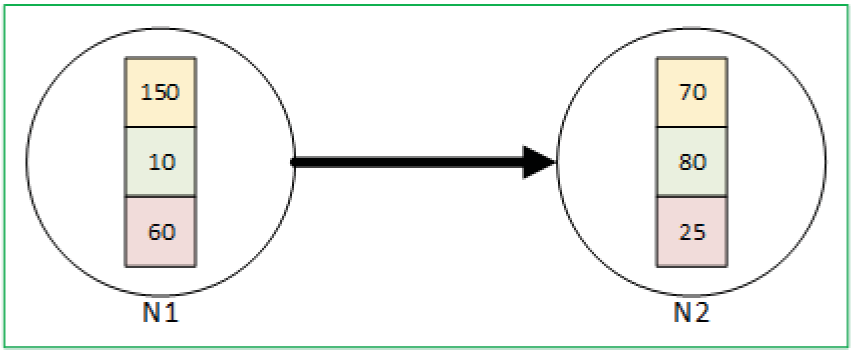


Figure 4.12: The optimal commodity

The optimal value of commodity between node n_1 and n_2 is calculated based on the following equation.

$$\begin{aligned}\mathcal{N}_\ell^{\text{OPTI}}(t) = \textsc{Maximize}\{D_{n_1}^{yellow} - D_{n_2}^{yellow} &= 80,\\ D_{n_1}^{green} - D_{n_2}^{green} &= -70,\\ D_{n_1}^{red} - D_{n_2}^{red} &= 35\} = D_\ell^{yellow}\end{aligned}$$

After the optimal value is calculated , Algorithm DPBP computes the weights ($W_\ell(t)$) based on Equation (4.8).

$$W_\ell(t) = \max\{D_{n_1}^{\mathcal{N}_\ell^{\text{OPTI}}(t)} - D_{n_2}^{\mathcal{N}_\ell^{\text{OPTI}}(t)}, 0\}. \tag{4.8}$$

Finally, it selects the best TC for sending data based on Equation (4.9).

$$\textsc{Maximize} : \sum_{\ell}^{\ell_m} \mu_\ell W_\ell(t). \tag{4.9}$$

As we will see in Section **??**, the complexity of Algorithm DPBP is exponential; however, Algorithm DPMBF has a liner complexity. Algorithm DPBP checks whole of a network to calculate the $\mathcal{N}_\ell^{\text{OPTI}}(t)$ in each time slot. In addition, the difference between Algorithm DPBP and DPMBF is that Back-Pressure selects the best possible buffer and TC, which can maximize throughput of networks. In contrast, the maximum buffer is chosen by Algorithm DPMBF in each time slot.

Algorithm DPBP *BackPressure($\mathcal{T}$, $\mathcal{N}$,* TRAFFIC *)*

```
Input: Set of transmission configuration $\mathcal{T}$,
  $\mathcal{N}$ : all nodes in networks,
  TRAFFIC : $B^S + B^T$

  INTERVAL is a constant parameter.
  TIMESLOT ← 0;
  while TRAFFIC $\neq 0$ Or DURATION $\neq 0$ do
      if TIMESLOT%INTERVAL == 0 then                ▷ Recreating transmission configuration
          PATTERNBASED Or GREEDYBASED
      TRAFFIC ←UPDATETRAFFIC(TIMESLOT)
      $[\mu_\ell]$ ← CALCULATEWEIGHT($\mathcal{T}$, TRAFFIC)
      for $n \in \mathcal{N}$ do
          NEIGHBOR$^n$ ← retrieve all neighbor of node $n$
          for $n' \in$ NEIGHBOR$^n$ do
              calculate $\mathcal{N}_\ell^{\text{OPTI}}(t)$             ▷ Based on Equation (4.7)
          end for
      end for
      calculate $W_\ell(t)$                             ▷ Based on Equation (4.8)
      $T$ ← MAXIMIZE : $\sum_\ell^{\ell_m} \mu_\ell W_\ell(t)$
      for $\ell \in T$ do
          send the packets on $\ell$ according to its path
      end for
      TIMESLOT ← TIMESLOT + 1;DURATION ← DURATION − 1
  end while
```

Algorithm DPBP illustrates how Back-Pressure algorithm works. TRAFFIC refers to available packets in both SBs and TBs. There is no difference between source and transmit buffers in Algorithm DPBP. In each iteration of main *While* loop, traffic for a specific time slot is distributed on corresponding source buffers. Then, Algorithm DPBP creates a weight matrix using Procedure CalcW. Afterwards, neighbors of each node in a network are obtained; in addition, $\mathcal{N}_\ell$ is computed for every neighbor of a node based on (4.7). Then, the algorithm selects the best possible TC based on (4.8) and (4.9). Finally, it sends the packets, which are in the selected buffer, to the next node by using TC's links.

4.4 Power Control Algorithm (PCA)

The power control problem refers to specifying the optimized power levels (P_i) of each node in a network in order to keep the SINR in the minimum required level. Using power control not only improves the battery life of networks' nodes but also it helps to reuse channels more effectively. In order to obtain the minimum level of required SINR for establishing a stable connection between two nodes with the maximum possible data rate, Perron-Frobenius Theorem (PFT) is mainly used to assign an optimized amount of power to a link in a transmission configuration.

PFT provides a simple characterization of the eigenvectors and eigenvalues for certain types of matrices with non-negative entries [34]. The input of PFT should be positive matrices so that all entries of matrices have to be non-negative numbers. Matrix A is primitive if for some integer s_0, A^{s_0} is a positive matrix. $Ax = \lambda x$ where x is an eigenvector and λ is an eigenvalue. Hence, the spectral radius of matrix A is calculated by the following equation.

$$\rho\left(A\right) = \max_i \left|\lambda_i\left(A\right)\right|. \tag{4.10}$$

Let γ_i be the required SINR threshold (Table 4.3 last column) for link ℓ_i to transmit successfully in a particular data rate. G_{ij} measures the path gain from the transmitter of link ℓ_j to the receiver of link ℓ_i as illustrated in Equation (4.11).

$$G_{ij} = I_f(c_{\ell_i}, c_{\ell_j})\frac{d_{u'v}^{-\alpha}}{d_{uv}^{-\alpha}}. \tag{4.11}$$

where (u, v) and (u', v') are endpoints of links ℓ_i and ℓ_j, respectively. A is the result of multiplying D and G as illustrated in Equation (4.12).

$$D = \begin{pmatrix} \gamma_1 & 0 & \cdots & 0 \\ 0 & \gamma_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \gamma_m \end{pmatrix}, G = \begin{pmatrix} 0 & G_{1j} & \cdots & G_{1m} \\ G_{21} & 0 & \cdots & G_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ G_{m1} & G_{mj} & \cdots & 0 \end{pmatrix} \Rightarrow A = DG \tag{4.12}$$

The Equation (4.13) shows how power of link ℓ_i is related to G_{ij} and γ_i.

$$\gamma_i \left(\sum_{i \neq j} G_{ij} P_j + q_i \right) \leq P_i, q_i = \frac{\sigma}{d_{uv}^{-\alpha}}. \tag{4.13}$$

where σ is the ambient noise.

The following equation can be obtained by replacing the matrices in (4.12) by (4.13):

$$(I - A)P \geq \underbrace{Dq}_{b}. \tag{4.14}$$

There is a positive solution for (4.14) if and only if the maximum of absolute values of eigenvalue is less than 1 according to Equation (4.15).

$$(I - A)^{-1} \geq 0 \quad ifandonlyif \quad \rho(A) = |\lambda_{\max}(A)| < 1. \tag{4.15}$$

Finally, the amount of power(vector P) is calculated as follow if the condition (4.15) is satisfied:

$$P = \underbrace{(I - A)^{-1}}_{H} b. \tag{4.16}$$

Power Control Algorithm (PCA)(Algorithm POWERC)'s responsibility is to assign a minimum required amount of power to each link in the current TC. $P_{\max}$ is a constant, which refers to the maximum possible value of the power. In other words, $P_{\max}$ is a threshold for the power of each link in a TC. In Algorithm POWERC, first, the matrices D and G are created based on SINR threshold and Equation (4.11). In addition, *I-Factor* is used with the notation G in order to illustrate the usage of POC. Then, the existence of a feasible solution for allocating power to a transmission configuration's links is examined by calculating the value of Perron eigenvalue. Hence, if eigenvalue ($\rho(A)$) is less than one, there is a solution for the value of power for each link in the current TC. Next step is to calculate the vector of power (P) by using the Equation (4.16). Afterward, each value of power in vector P should be less than $P_{\max}$, if all values of P are less than $P_{\max}$, vector P is acceptable. However, the feasibility of a TC was already checked by Procedure CanAdd. Procedure CanAdd verify that the SINR of all links in a transmission configuration is higher than β. In addition, the amount of SINR is calculated by using the value of maximum power. According to these two points, all TCs are feasible for assigning the actual value of power to their links. However, Algorithm POWERC checks the value of Perron eigenvalue and compares all powers with the value of $P_{\max}$ for making sure all procedures and algorithms work correctly.

```
Algorithm POWERC ($T$)
Input: A Transmission configuration $T$
Output: An updated $T$ which contains the powers values for links.
  set of power $T_{\mathcal{P}}$ which is associated to each link in the current $T$ Indexed by $T_{\mathcal{P}_\ell}$
  $T_{\mathcal{P}} \leftarrow \emptyset$
  for $\ell \in T$ do
      Create Matrix $A$                                  ▷ Based on equation (4.12)
  end for
  if $\rho(A) < 1$ then                                  ▷ Based on equation (4.15)
      Calculate $P$                                      ▷ Based on equation (4.16)
      if $\forall p \in P | p < P_{\max}$ then
          $T_{\mathcal{P}} \leftarrow P$
          return $T_{\mathcal{P}}$
  $T \leftarrow$ Calculate data rate based on powers
  return INCREASER($T_{\mathcal{P}}$, $T$)
```

Procedure INCREA illustrates how power control can improve the capacity of a TC. In order to calculate data rate of a link, Equation (2.2) uses the amount of maximum power instead of the actual value of power. In addition, the precise value of links' power is calculated by Algorithm POWERC which is less than or equal to the value of $P_{\max}$. Hence, we can reduce the amount of interference by Algorithm POWERC; in addition, Algorithm POWERC and Procedure INCREA can boost capacity of transmission configurations.

Procedure INCREA $(T_{\mathcal{P}}, T)$

```
Input:
  A Transmission configuration $T$
  $T_{\mathcal{P}}$: Vector of powers for each link in $T$

Output: A transmission configuration with more capacity.

  $\textsc{rate}_\ell$: data rate of link $\ell$.
  All links are sorted based on their data rate.

  $T_{\textsc{feasible}} \leftarrow \emptyset$
  $T' \leftarrow T$
  for $\ell \in T'$ do
      if $T_{\textsc{feasible}}$ is $\emptyset$ then
          $T' \leftarrow T$
      else
          $T' \leftarrow T_{\textsc{feasible}}$
      for $dr$: all rates that are grater than $\ell$'s rate do
          $\ell_{\textsc{rate}} \leftarrow dr$
          Create Matrix $A$                                  ▷ According to $dr$
          if $\rho(A) < 1$ then
              Calculate $P$
              if $\forall p \in P | p < P_{\max}$ then
                  $T' \leftarrow P$; $T_{\textsc{feasible}} \leftarrow T'$
      end for
  end for
  return $T_{\textsc{feasible}}$
```

At the beginning of Procedure INCREA, all links are sorted in decreasing order according to their data rates. Afterwards, it performs the following steps for each link in the current transmission configuration: *i*) The next data rate, which is denoted by dr, is assigned to the current link; *ii*) Matrix A is created with respect to the new data rate of link ℓ; *iii*) If $\rho(A) > 1$, the algorithm goes back to step *i*; *iv*) Actual value of powers are computed. If one of them is higher than $P_{\max}$, it jumps back to step *i*; *v*) The new data rate (dr) is assigned to link ℓ in T'; and *vi*) $T_{\textsc{feasible}}$ gets the value of T'. If Procedure INCREA increases data rate of a link in an iteration, $T_{\textsc{feasible}}$ holds the updated transmission configuration. In next iterations, Procedure INCREA uses the updated values of data rates, which are available in $T_{\textsc{feasible}}$.

4.5 Complexity of Algorithms

Let $\bar{\ell}$ be the number of links in a transmission configuration. The complexity of creating matrix A is $\bar{\ell}^3$ in Algorithm POWERC. In addition, the complexity of obtaining eigenvalue is $\bar{\ell}^3$. Hence, the complexity of Power Control Algorithm is gained as the following:

$$\mathcal{O}(POWERC) = \mathcal{O}(\bar{\ell}^3 + \bar{\ell}^3) = \mathcal{O}(\bar{\ell}^3).$$

Let $\bar{\mathcal{T}}$ be the number of available transmission configurations. First, Algorithm Enlarge appends new links to each transmission configuration. Then, it optimized the power of each link by using Algorithm POWERC.

$$\mathcal{O}(Enlarge) = \mathcal{O}(\bar{\mathcal{T}}(\bar{\ell} + \underbrace{\mathcal{O}(\bar{\ell}^3)}_{PowerControl})) = \mathcal{O}(\bar{\mathcal{T}}\bar{\ell}^3).$$

Let L be the number of available links in a topology. The main loop of Algorithm TCGBA repeats L times. Moreover, the first *For* loop iterates L time in the worst-case scenario. The number of iteration for second *For* loop is equal to the number of all gateways ($\bar{g}$) in a topology. Let L' be the number of all gateways links. There is another *For* loop in the second *For* loop which iterates L' times. Let ℓ_g be the number of gateways links. Hence, The complexity of Procedure Exchange is $\mathcal{O}(\ell_g\bar{\ell})$. As a result, the complexity of Algorithm TCGBA is shown in the following:

$$\mathcal{O}(TCGBA) = \underbrace{\mathcal{O}(L(L + \bar{g} * (\ell_g + \ell_g\bar{\ell}))}_{Alg.TCGBA} + \underbrace{\mathcal{O}(\bar{\mathcal{T}}\bar{\ell}^3)}_{Enlarge}.$$

We can assume that the amount of $\ell_g, \bar{\ell}, \bar{\mathcal{T}}$ and $\bar{g}$ are much less than L. Hence, the complexity of Algorithm TCGBA is $\mathcal{O}(TCGBA) = \mathcal{O}(L^2)$.

Algorithm TCPBA has three *while* loops. The first *while* loop iterates ℓ_g times. It also contains a *For* which iterates $\bar{g}$ times. The algorithm calls TryAddingLinks method at least three times. TryAddingLinks's complexity is L. The next two other *while* loop repeats L times. Finally, Algorithm TCPBA calls Procedure Enlarge. Thus, the complexity in a worst-case scenario can be calculated as the following:

$$\mathcal{O}(TCPBA) = \underbrace{\mathcal{O}(\ell_g(\bar{g}(L+L+L)+L+L)}_{Alg.TCPBA} + \underbrace{\mathcal{O}(\bar{\mathcal{T}}\bar{\ell}^3)}_{Enlarge} = \mathcal{O}(L).$$

Let t be the amount of all generated traffic. The main *while* loop of Algorithm DPMBF repeats $Max(t, \text{DURATION})$ times. The amount of traffic is much more then the value of DURATION. Let b be the number of buffers which is equal to $2L$ because each link contains two buffers. Complexity of Procedure CalcW is $\mathcal{O}(\bar{\mathcal{T}}\bar{\ell})$. In each iteration of the main loop, Algorithm DPMBF calculates the maximum buffer which can be done in at most L iteration. In nut shell, the complexity is calculated by the following equation:

$$\mathcal{O}(DPMBF) = \mathcal{O}(\max\{t, \text{DURATION}\}(L + \bar{\mathcal{T}}\bar{\ell} + \bar{\mathcal{T}}) = \mathcal{O}(tL).$$

Algorithm DPBP has a main loop which iterates $Max(t, \text{DURATION})$ times. However, the algorithm has to be repeated for each node and calculates $\mathcal{N}_\ell^{\text{OPTI}}$ for the node's neighbors. We can assume topology of a network is a complete graph with n nodes for a worst-case scenario. Complexity of solving Equation (4.9) is $\mathcal{O}(L^3)$. Consequently, the complexity of back-pressure algorithm can be obtained by the following:

$$\mathcal{O}(DPBP) = \mathcal{O}(\max\{t, \text{DURATION}\}(n^2 + L^3)) = \mathcal{O}(tn^2 + tL^3).$$

Table 4.4 presents the execution time of different combinations of algorithms. When Algorithm DPBP is used as a packets delivery strategy, the execution time increases dramatically based on its complexity. However, when Algorithm TCGBA takes responsibility of creating TCs, the execution time declines. The reason is that packets delivery algorithms depend on the CAPACITY; in addition, Algorithm TCGBA increases the amount of CAPACITY. Consequently, it can decrease the complexity of packets delivery algorithms.

Node	Back-Pressure		Round-Robin	
	Pattern-Based	Greedy-Based	Pattern-Based	Greedy-Based
70	$28,510$	$23,039$	$5,261$	$4,069$
89	$24,041$	$18,286$	$4,490$	$3,804$

Table 4.4: CPU time for different algorithms (ms)

Chapter 5

Experiments and Results

5.1 Introduction

The purpose of this chapter is to explain the efficiency of proposed algorithms. In Section 5.2, all parameters and constants are expressed. Results of our experiment are analyzed in Section 5.3. We will conclude this chapter with an evaluation of our numerical experiments.

5.2 Parameters and Constants

Table 5.1 provides the value of constants and parameters. β is the minimum SINR i.e, associated with the minimum rate, which is required for establishing a stable connection between two nodes within reach of each other. $P_{\max}$ is the maximum power, which a link needs to transfer data in all possible data rate without power control mechanism. Moreover, P_{max} is used for calculating the value of SINR in Equation (2.2). $d_{\max}$ refers to the maximum distance for identifying neighboring nodes, i.e., nodes within reach of each other in a topology. A distance less than $d_{\min}$ between two nodes in a random topology is not allowed. The number of interfaces of routers and gateways is specified by $Radio_r$ and $Radio_g$ respectively. DURATION refers to a period of time in which traffic is generated for all nodes in a time slot.

Symbol	Name	Value
β	Threshold for SINR	8.51
α	Path loss exponent	2
η, σ	Power of ambient noise	$10^{-9}mW$
$P_{\max}$, P	Maximum of power	$25mW$
d_{max}	Maximum distance between two nodes within reach of each other	$200m$
d_{min}	Minimum distance between two nodes in a random generated topology	$50m$
$Radio_g$	Number of radios for gateway	4
$Radio_r$	Number of radios for router	2
DURATION	Duration of the time period of the experiments	$25,000ms$

Table 5.1: The value of the constant parameters

5.3 Results

5.3.1 Topology

Topologies were randomly generated with a fixed number of gateways. The positions of gateways are predefined in all topologies. Topology generator satisfies the constraints described in Chapter 4, in Section 4.2.1, with respect to minimum and maximum distance $d_{\min}$ and $d_{\max}$. It also creates a random topology using the normal distribution random function with respect to the position of the routers. Verifying the existence of at least one path from a router to a gateway is the next responsibility of the topology generator. If all nodes are accessible from at least a gateway, the network topology satisfies the requirements.

In this study, we use two random topologies in two different sizes. Figure 5.1 illustrates a random topology with 65 routers and five gateways in a 2-dimensional square with $1km$ side length. The positions of gateways are fixed and their coordinates are $(200, 200)$, $(200, 800)$, $(800, 200)$, $(800, 800)$, and $(500, 500)$.

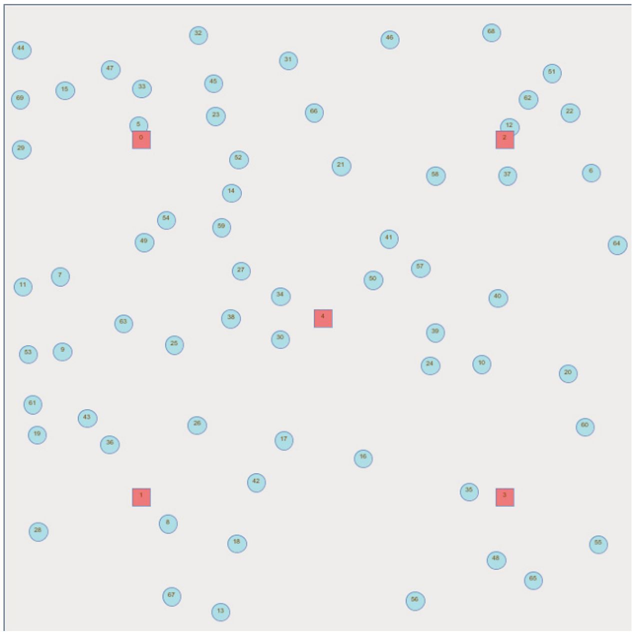


Figure 5.1: Network topology with 70 nodes

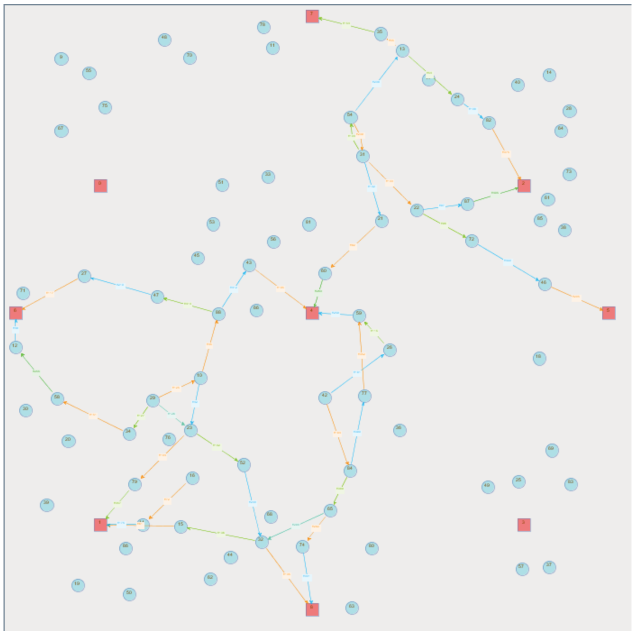


Figure 5.2: Network topology with 89 nodes

The second random topology contains 80 routers and nine gateways. Nodes are scattered in a square with $1.4km$ side length as shown in Figure 5.2. Gateways' coordinates are $(200, 400)$, $(200, 1200)$, $(1200, 1200)$, $(700, 700)$, $(1400, 700)$, $(0, 700)$, $(700, 0)$ and $(700, 1400)$

5.3.2 Traffic Instances

We use Poisson distribution for producing dynamic traffic for all nodes in a topology. We also analyze the behaviors of networks with respect to different amounts of generated traffic in each time slot. Algorithm DyTr controls the amount of offered load traffic by the arrival rate (λ) for each node, i.e., λ_n. The total amount of traffic is raised by increasing the value of λ. A stable network can handle the generated traffic properly. For instance, the network in Figure 5.3 is a stable network because the trend of traffic in source and transit buffers (red-button and green-middle diagram) is not increasing continuously. The trend of graph in Figure 5.3 indicates that the rate of delivery packets to their destination is almost same as the rate of generated traffic. In other words, the traffic never accumulates in the buffers. However, the network in Figure 5.4 is an unstable network because traffic is accumulated in the buffers. In an unstable network, the rate of generated traffic is much more than the rate of delivered packets.

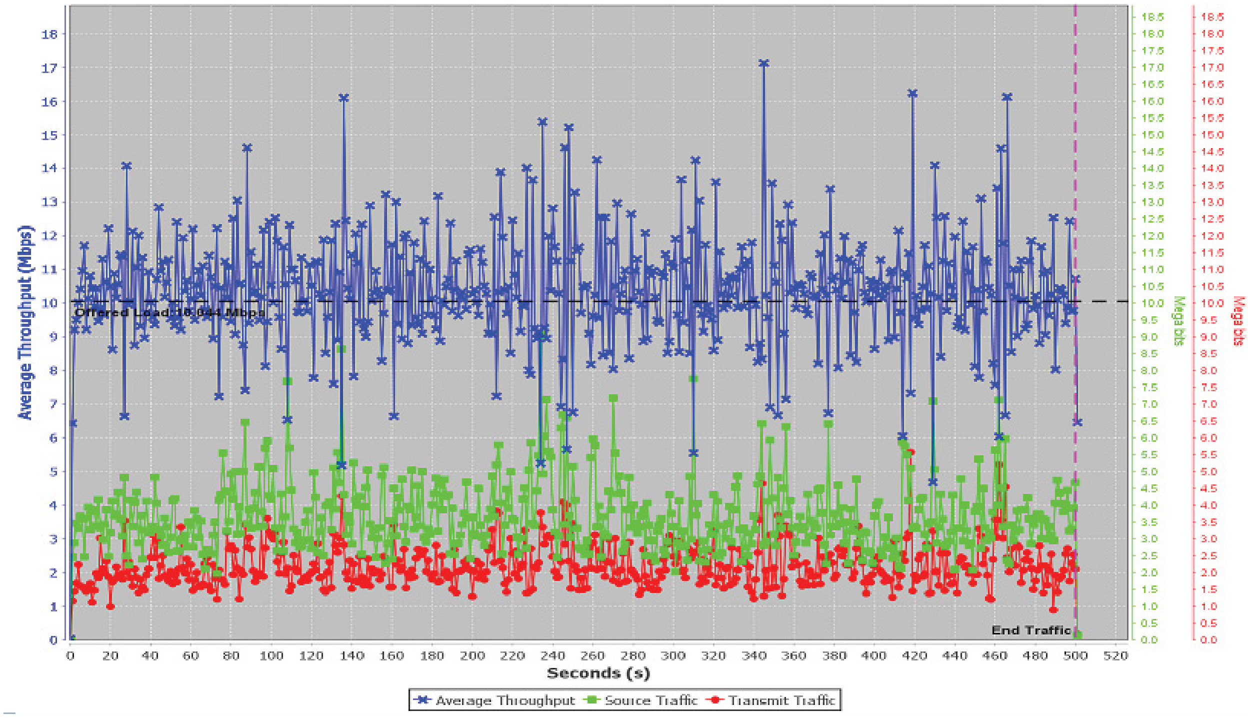


Figure 5.3: A stable network

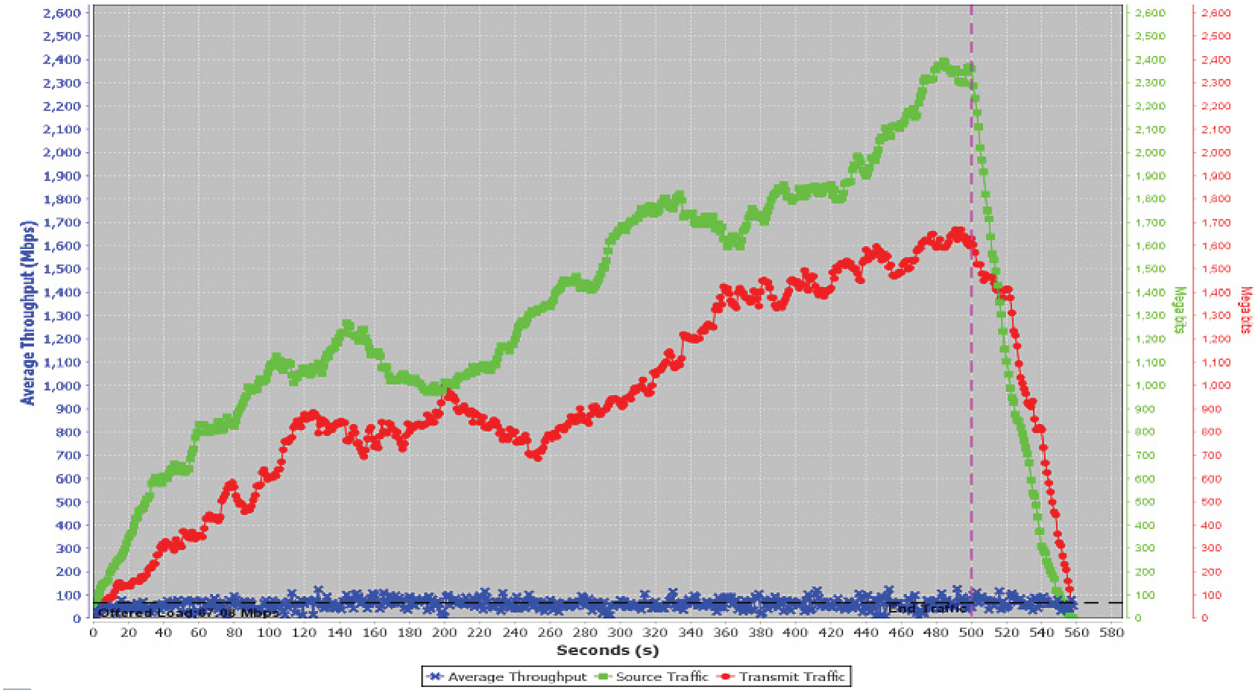


Figure 5.4: An unstable network

Generally, there are three factors which reveal an unstable network. If a network meets one of them, it is an unstable network. The first factor is network delay. Network delay refers to a period of time after generating traffic is stopped (the period of time after dashed vertical line in Figure 5.4). In this study, if the network delay is more than 30 seconds for a specific offered load, the network is an unstable network in the corresponding offered load. The second factor is the ratio of average throughput to offered load in a network. In this research, if average throughput of a network is 5% less than the offered load, the network becomes unstable. The last factor is the trend of amount of traffic in source and transit buffers. As we mentioned before in this section, if traffic is accumulated in buffers in a network, the network cannot handle the generated traffic.

We calculate average throughput and delay when a network is in a stable condition. In addition, our goal is to maximize throughput of a topology by employing all 11 channels. We increase offered load of traffic by increasing the value of λ. The amount of λ is boosted in each step for a given network until the network becomes unstable. When the network becomes unstable, the last throughput in the stable condition is the maximum average throughput for the network.

We assume that rate of sending data for a node is 10Mbps. Hence, the node can send $10,000,000$ bits in a second. In addition, duration of a time slot is 20ms. As a result, there are 50 time slots in a second. Thus, a node can sent $200,000$ bits per time slot based on previous points. As we mentioned in Chapter 4 Section 4.1 the size of a packet in wireless networks is 12000 bits. Finally, the number of sent packets in a time slot with respect to the rate of a node is as follows.

$$\lambda = \frac{200,000}{12,000} = 16.66 \text{ pockets in a ms(\#ms).}$$

Networks' behaviors are analyzed for reaching the best possible value of λ in order to maximize the throughput of networks.

Length of Packets (bits)	Duration of Time slots (ms)	Rate of Node (Mbps)	Lambda #ms
12000	20	0.1	0.16
12000	20	0.5	0.83
12000	20	1	1.6
12000	20	2	3.33
12000	20	5	8.33
12000	20	10	16.66

Table 5.2: Values of λ for different data rate of nodes

5.3.3 Transmission Configuration

In this section, we study the impact of transmission configuration algorithms on the following aspects of our work:

- The average number of links in TCs.
- The average capacity of TCs.
- The effect of transmission configuration algorithms on network throughput.

Figure 5.5 presents the average number of links in transmission configurations. Figure 5.5 reveals that there has been a slight growth in the number of links in transmission configurations when Greedy-Based Algorithm (GBA)(Algorithm TCGBA) is used for creating transmission configurations.

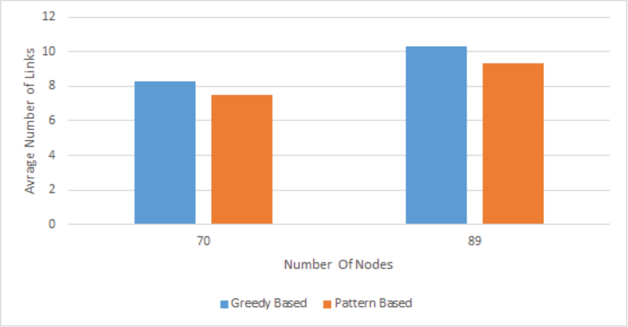


Figure 5.5: Average number of links in transmission configurations

Figures 5.6 and 5.7 demonstrate the average capacity of TCs. Horizontal axis illustrates the number of available channels when transmission configuration algorithms try to build TCs. For example, 1..11 means the numerical results is obtained when all 11 channels are available. In addition, the vertical axis demonstrates the average of TC capacities. The diagram shows that there has been a marked rise in the average of capacity when Greedy-Based Algorithm (Algorithm TCGBA) is employed for building transmission configurations.

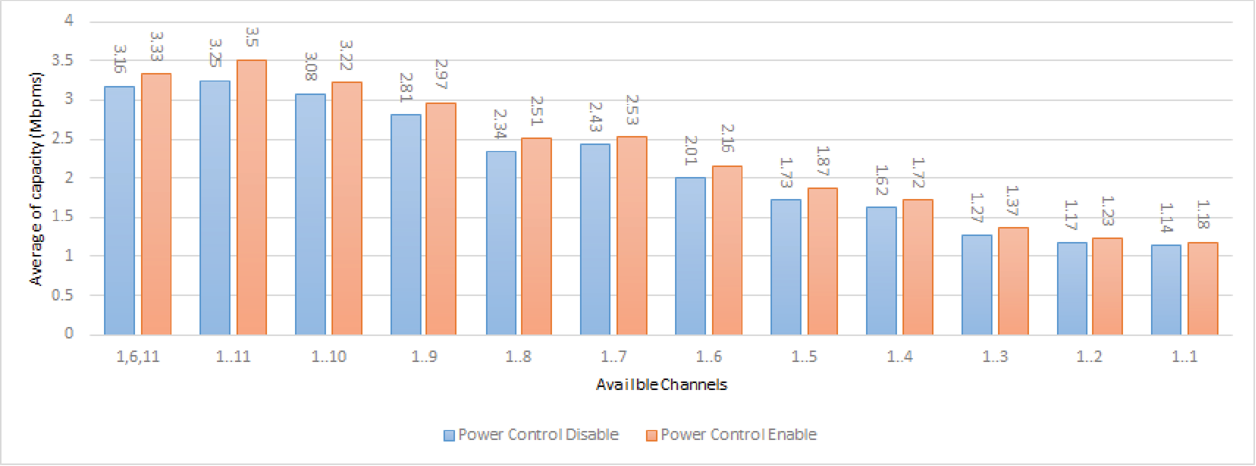


Figure 5.6: TC capacities based on Greedy-Based Algorithm

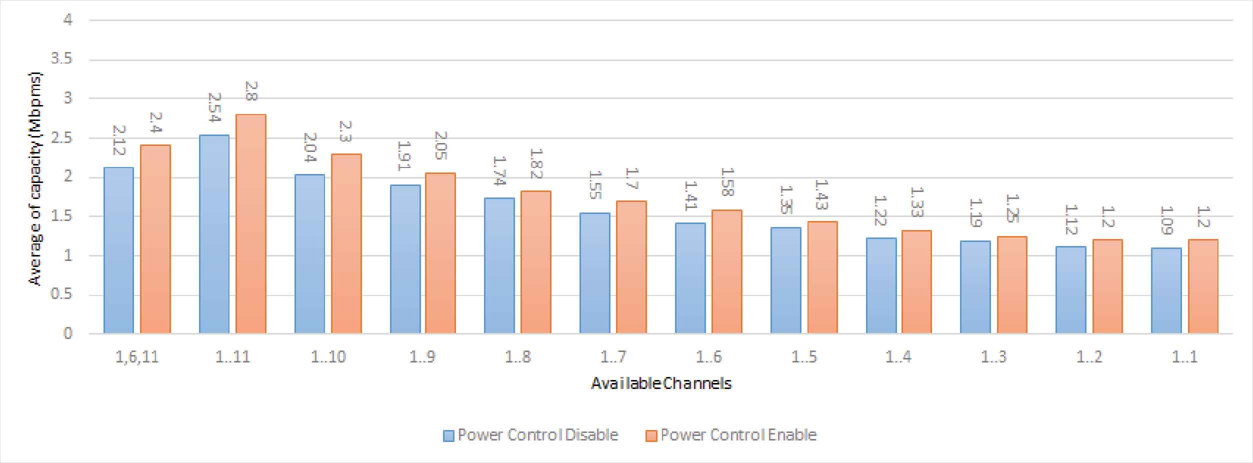


Figure 5.7: TC capacities based on Pattern-Based Algorithm

It is difficult to get away from impact of power control on the capacity of transmission configurations. The capacity of TCs can be increased by 7% when the Power Control Algorithm adjusts the amount of power in each transmission configuration.

Table 5.3 presents the impact of transmission configuration algorithms on throughput. As can be seen from Table 5.3, Greedy-Based Algorithm can positively affect the average of throughput in comparison with Pattern-Based Algorithm. For example, when Greedy-Based Algorithm creates the transmission configurations, the throughput of networks is 23.5% (bold value) higher than Pattern-Based Algorithm with respect to power control.

#Nodes	PC Enable	PC Disable
70	$26\%, TCGBA \uparrow$	$21\%, TCGBA \uparrow$
89	$21\%, TCGBA \uparrow$	$22\%, TCGBA \uparrow$
Average	$\mathbf{23.5\%, TCGBA} \uparrow$	$21.5\%, TCGBA \uparrow$

Table 5.3: Comparing Throughput: Algorithm TCGBA vs. Algorithm TCPBA

5.3.4 Throughput

Throughput is the amount of packets that have been delivered to their destinations in a time slot. Apparently, the performance of WMNs relies on several factors such as topology, traffic pattern, and channel assignment strategy. However, we can observe in a consistent manner that using POCs always leads to noticeable throughput increase and delay decrease with respect to the three traditional orthogonal channels (1,6,11).

We also use all possible combinations of proposed algorithms for reaching better conclusions.

5.3.4.1 Throughput Behavior

Figure 5.8 is a sample of diagram, which is generated by implemented system. The diagram depicts a throughput of a network. The horizontal axis shows time slots; in addition, the vertical axis refers to the throughput in each time slot. Green line (light line) demonstrates the total amount of available traffic in SBs in each time slot. Moreover, red line (dark line with arrow) illustrates the accumulated amount of traffic in the TBs. Finally, blue line (dark line with × symbol) refers to the quantity of throughput in each time slot.

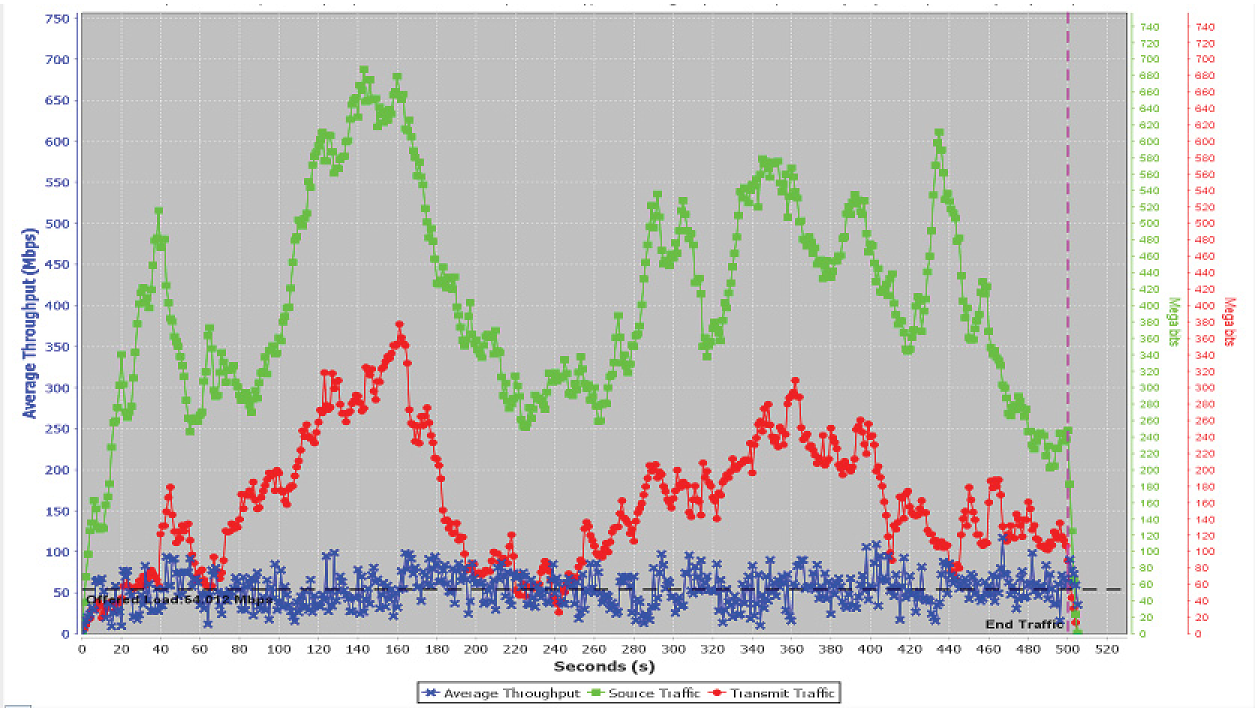


Figure 5.8: A generated Diagram

Our system generates traffic in the first 25, 000 time slots (violet or dashed vertical line). Hence, the amount of traffic in the SBs and TBs is increased rapidly in this range of time slots. Consequently, traffic in both buffers is dropped dramatically after generating traffic is stopped.

One interesting finding is the existence of throughput at time slot zero which is shown in Figure 5.9. It is a zoom version of Figure 5.8 for indicating the existence of throughput in time slot zero. The reason of existing throughput at the beginning point is that there are several paths with only one link from a gateway to a router and vice versa. For example, in Figure 5.10 there are five paths made of one link between a gateway to the different routers $(2 \blacktriangleright 6, 2 \blacktriangleright 9, 2 \blacktriangleright 52, 2 \blacktriangleright 8, 2 \blacktriangleright 69)$. There may exist *downlink* or *uplink* traffic for this type of path.

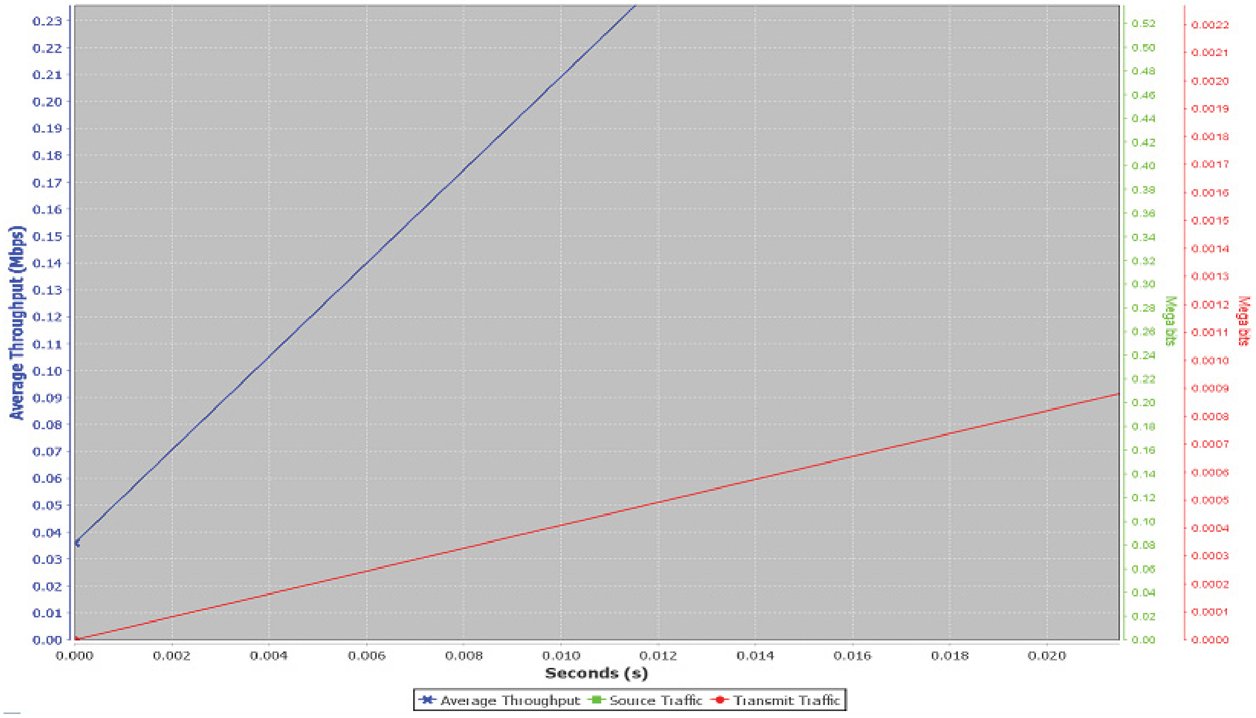


Figure 5.9: Throughput in time slot zero

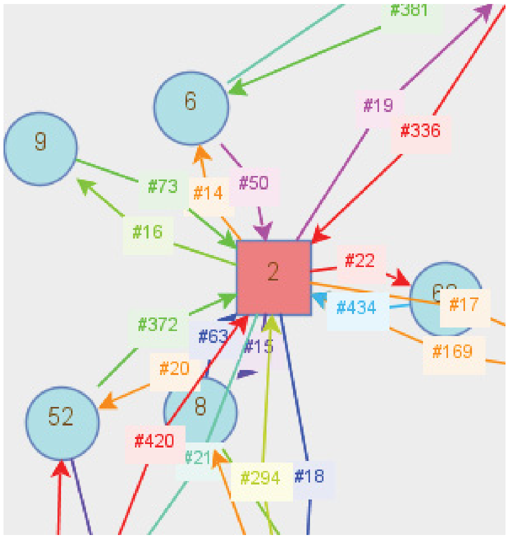


Figure 5.10: One-Link Paths

5.3.4.2 Average Throughput

Throughput is the amount of packets that have reached to their destinations in one second. In this section, we study the impacts of following algorithms/parameter on the throughput:

- Packets Delivery Algorithms.
- Transmission Configuration Algorithms.
- Power Control Algorithm.

The average throughput obtained from Back-Pressure Algorithm are presented in Figure 5.11. Figure 5.12 demonstrates the average of throughput when Maximum-Buffer-First Algorithm delivers packets. They also present the impact of transmission configuration and power control in networks performance. The vertical axes refers to network throughput, and the horizontal axes points to the available channels(1..11 means all 11 channels available). Blue(lighter) bars show throughput when the power control algorithm optimized the power of each link in transmission configurations. In addition, orange(darker) bars indicate the throughput of networks when the power control algorithm does not involve. These diagrams contain two parts which are separated by a red(dark-bold) line. The left part of the line presents the average throughput when Greedy-Based Algorithm defines transmission configurations. In contrast, the right part points to the average throughput of networks when Pattern-Based Algorithm is chosen for building transmission configurations. From the data in Figures 5.11 and 5.12, it is apparent that existence of 11 channels helps to improve the throughput of networks despite of which proposed algorithms are used. However, the combination of Back-Pressure Algorithm and Greedy-Based Algorithm with power control lead the throughput of networks to summit.

Node	PC Enable		PC Disable	
	Pattern-Based	Greedy-Based	Pattern-Based	Greedy-Based
70	$\mathbf{47}\%, \mathbf{BPA} \uparrow$	$41\%, BPA \uparrow$	$46\%, BPA \uparrow$	$46\%, BPA \uparrow$
89	$34\%, BPA \uparrow$	$42\%, BPA \uparrow$	$38\%, BPA \uparrow$	$45\%, BPA \uparrow$
Average	$40\%, BPA \uparrow$	$42\%, BPA \uparrow$	$42\%, BPA \uparrow$	$45\%, BPA \uparrow$

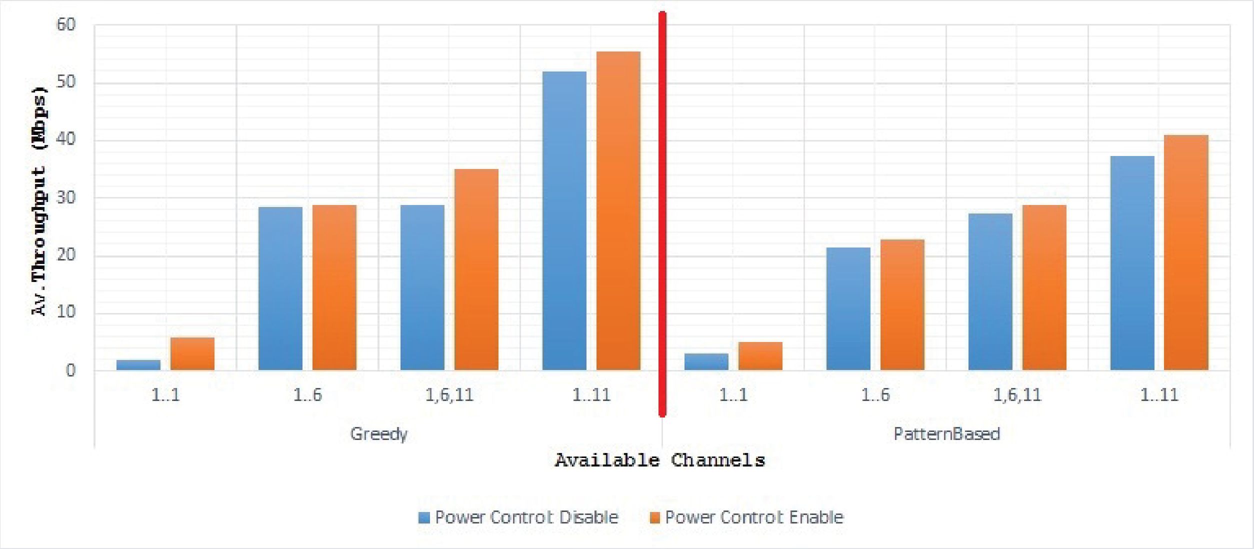
Table 5.4: Average Throughput: BPA vs. Maximum-Buffer-First Algorithm (MBF)

Node	PC Enable		PC Disable	
	Pattern-Based	Greedy	Pattern-Based	Greedy
Max-Buffer-First Algorithm				
70	$\mathbf{23}\% \uparrow$	$16\% \uparrow$	$14\% \uparrow$	$23\% \uparrow$
89	$15\% \uparrow$	$19\% \uparrow$	$14\% \uparrow$	$21\% \uparrow$
Back-Pressure Algorithm				
70	$65\% \uparrow$	$47\% \uparrow$	$60\% \uparrow$	$46\% \uparrow$
89	$30\% \uparrow$	$37\% \uparrow$	$26\% \uparrow$	$44\% \uparrow$

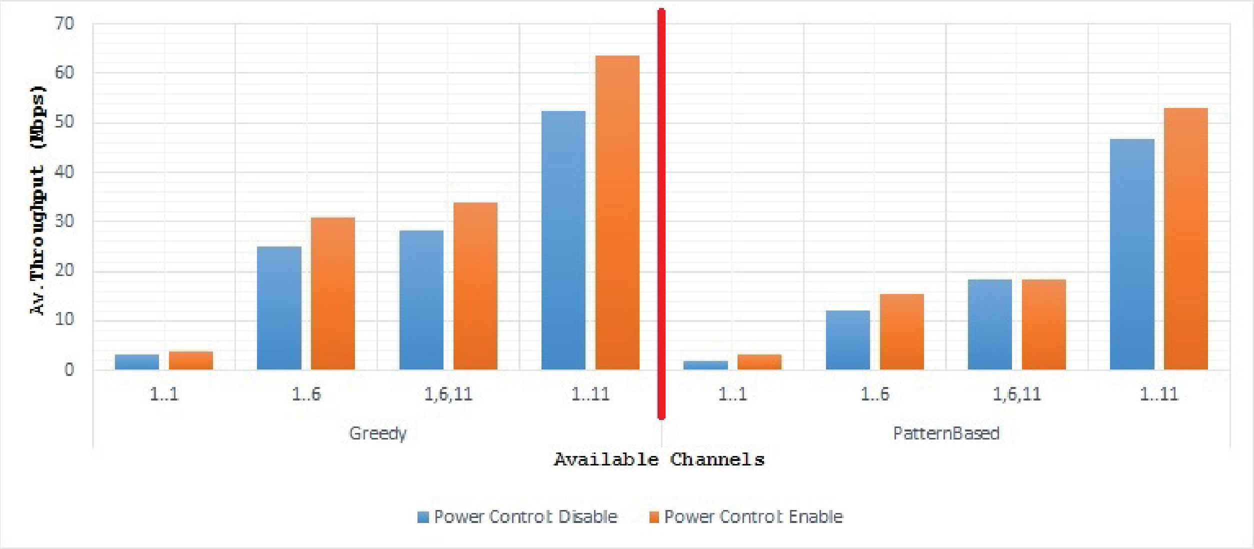
Table 5.5: POCs vs. OCs

We also summarize displayed data in Table 5.4 and 5.5. Table 5.4 compares two proposed scheduling algorithms with each other when all 11 channel are available. For example, BPA can boost the throughput more than 47% (bold value) in comparison with the MBF under following conditions: *i*) The power control is enabled; *ii*) PBA creates TCs; *iii*) There are 70 nodes in the topology; and *iv*) 11 channels are available.

Table 5.5 presents the impact of proposed algorithms on average throughput with respect to use of POCs as channel assignment strategy. For example, average throughput can improve 23% (bold value) in comparison with OC under following conditions: *i*) network contains 89 nodes; *ii*) POCs is employed for assigning channels; *iii*) Scheduling algorithm is MBF; *iv*) PBA takes responsibility for building TCs; and *v*) Power control is activated.

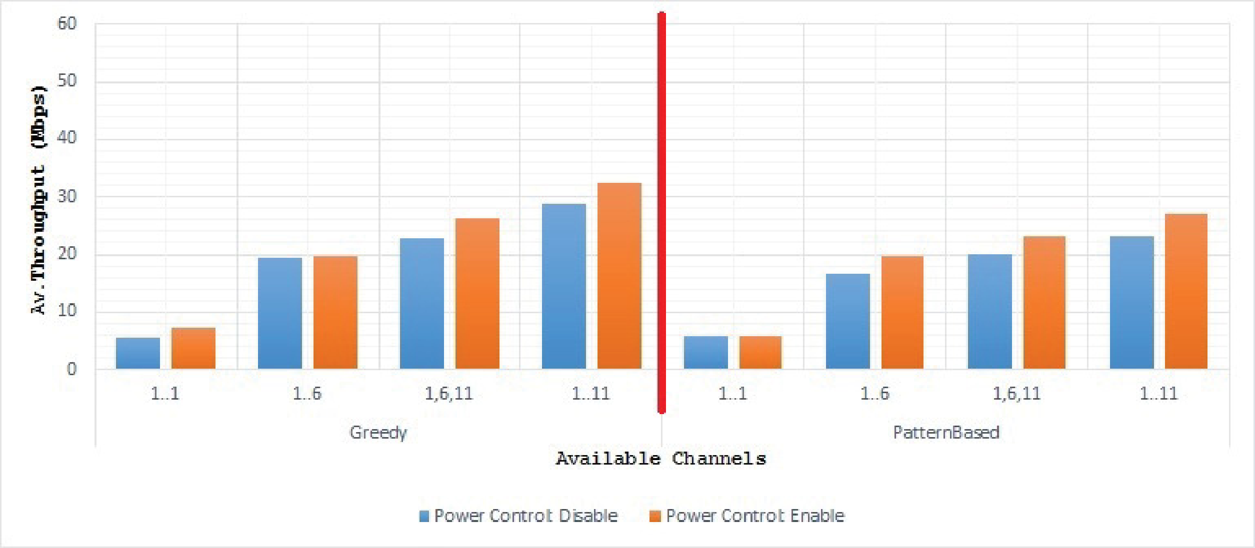


(a) 89 Nodes

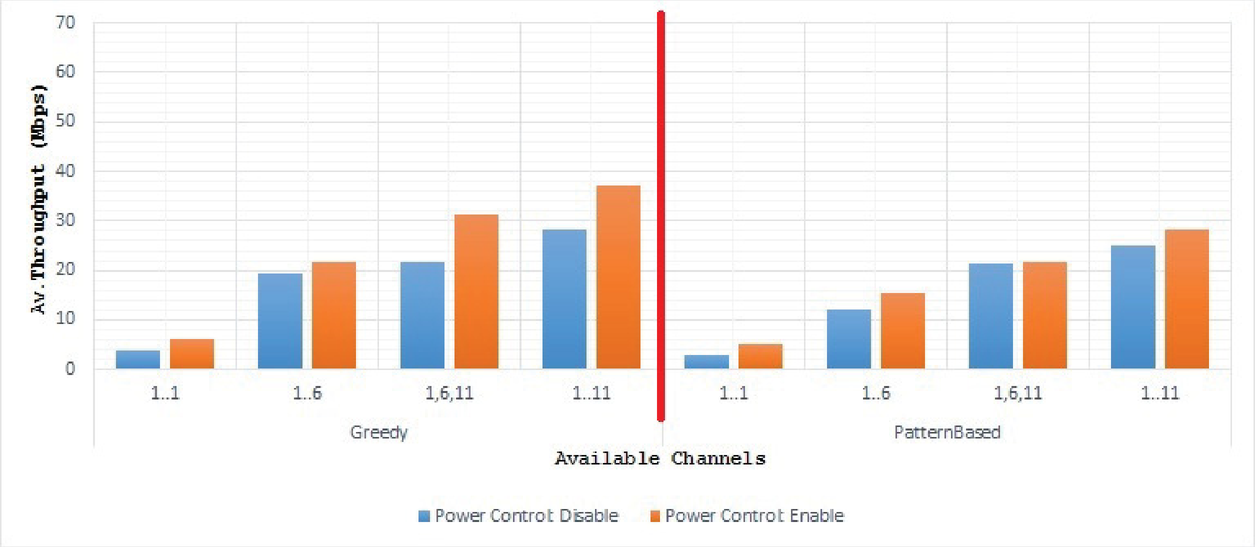


(b) 70 Nodes

Figure 5.11: Throughput - Back Pressure Algorithm (Algorithm DPBP)



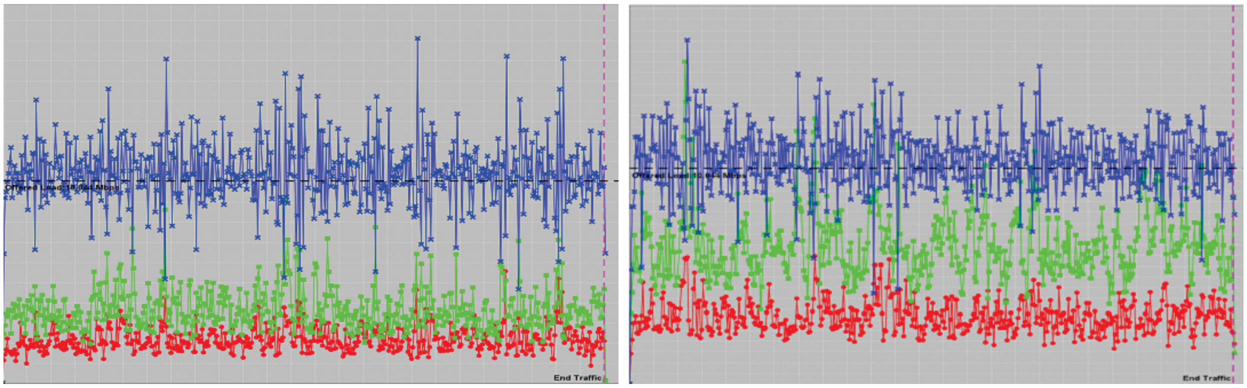
(a) 89 Nodes



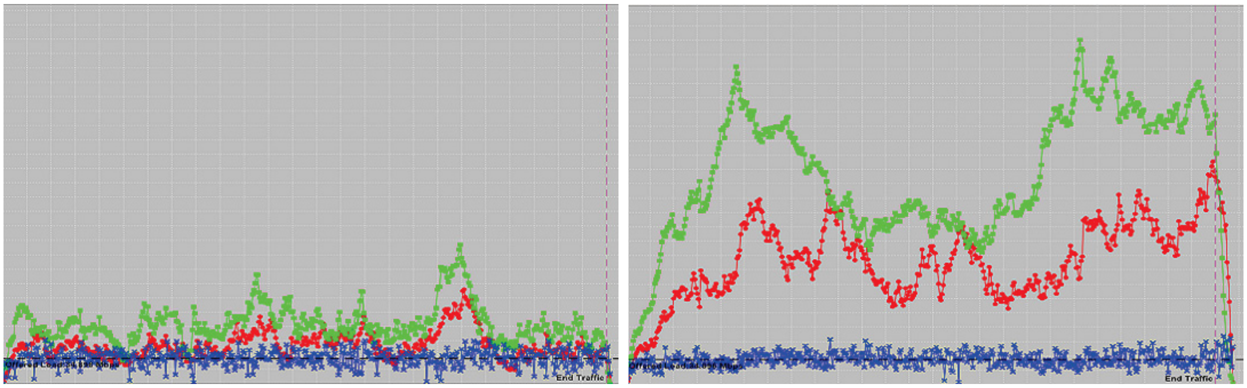
(b) 70 Nodes

Figure 5.12: Throughput - Maximum-Buffer-First Algorithm (Algorithm DPMBF)

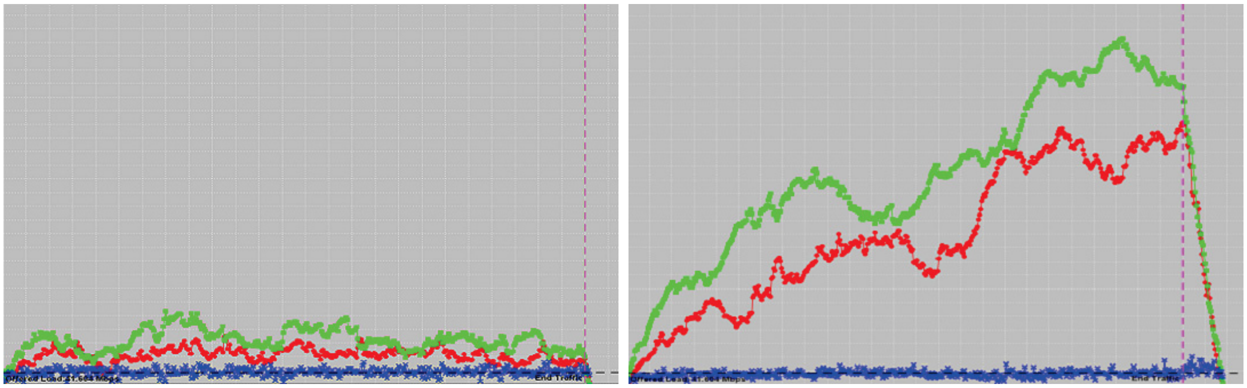
Figure 5.13 illustrates that how all 11 channels can help a network remains stable when λ is more than 0.6; in contrast, when λ is reached to 0.6, the same network cannot endure generated offered load under traditional orthogonal channels assignment. In other words, a network can handle more traffic when the partial overlapping channels assignment is employed. The horizontal axis shows a period of time in which the network has unscheduled traffic; in addition, the vertical axis refers to the amount of throughput. Green(light) line demonstrates the total amount of available traffic in SBs in each time slot. Moreover, red(dark with a arrow) line illustrates the accumulated amount of traffic in TBs. Finally, blue line (dark line with × symbol) refers to the quantity of throughput in each second. Figure 5.13 indicates a network with 89 nodes with different channels assignment strategy and amount of generated traffic (λ) in each time slot. In Figure 5.13a, 5.13c, and 5.13e, all 11 channels are available. Moreover, channel assignment algorithm uses only orthogonal channels in Figure 5.13b, 5.13d, and 5.13f. According to Figure 5.13a and 5.13b, the network can handle generated traffic in both channel assignment strategies. In addition, the network stays in a reliable condition according to Figure 5.13d when only orthogonal channels are used because traffic in both buffer is not completely accumulated. In other words, the trend of traffic in source and transit buffers fluctuates. However, as can be seen from Figure 5.13f the network becomes unstable by using OCs when amount of generated traffic is increased ($\lambda = 0.6$).



(a) 1..11, $\lambda = 0.1$ (b) 1,6,11, $\lambda = 0.1$



(c) 1..11, $\lambda = 0.5$ (d) 1,6,11, $\lambda = 0.5$



(e) 1..11, $\lambda = 0.6$ (f) 1,6,11, $\lambda = 0.6$

Figure 5.13: Improvement in Capacity of Network with 89 Nodes by Using POCs

5.3.5 Delay

Packet delay is a performance metric to measure the fairness of proposed algorithms. When a packet is created by traffic generator in time slot x, it is supposed to reach its destination after y time slots based on the number hops. The amount of time slots more than y is the packet's delay. For example, if there is a path with three different links, 'Y' is equal to 3. Hence, if a packet is generated at 50ms(it is generated in second one), it is supposed to reach its destination at 53ms. However, it reaches to its destination after 4 seconds(200ms). Hence, the amount of delays is 3 seconds or 150ms. It is necessary here to clarify exactly what is meant by network delay. Network Delay is a period of time between generating traffic is stopped (Horizontal-Dashed line) and the network contains no unscheduled traffic.

we investigate the impacts of following algorithms/parameter on the throughput:

- Packets Delivery Algorithms.
- Power Control Algorithm.

The state of networks has to be stable for measuring the delay of packets because if the state of a network is unstable, packets are accumulated in the buffers and the amount of average delay is increased dramatically. Therefore, the amount of delay in unstable networks is not a realistic value. As a result, the delay of packets is calculated based on different offered load traffic(λ) in which networks remain in a stable condition.

Figure 5.14 presents the amount of average delay in each second for Figure 5.8. The horizontal axis shows a period of time in which the network has unscheduled traffic; in addition, the vertical axis refers to the amount of packets delay in millisecond. Black line demonstrates the average of packet delay in each second. As can be seen from these two diagrams, the pattern of delay is almost same as pattern of source and transit buffers. The reason of this phenomenon is that the delay is increased when traffic is accumulated in the buffers.

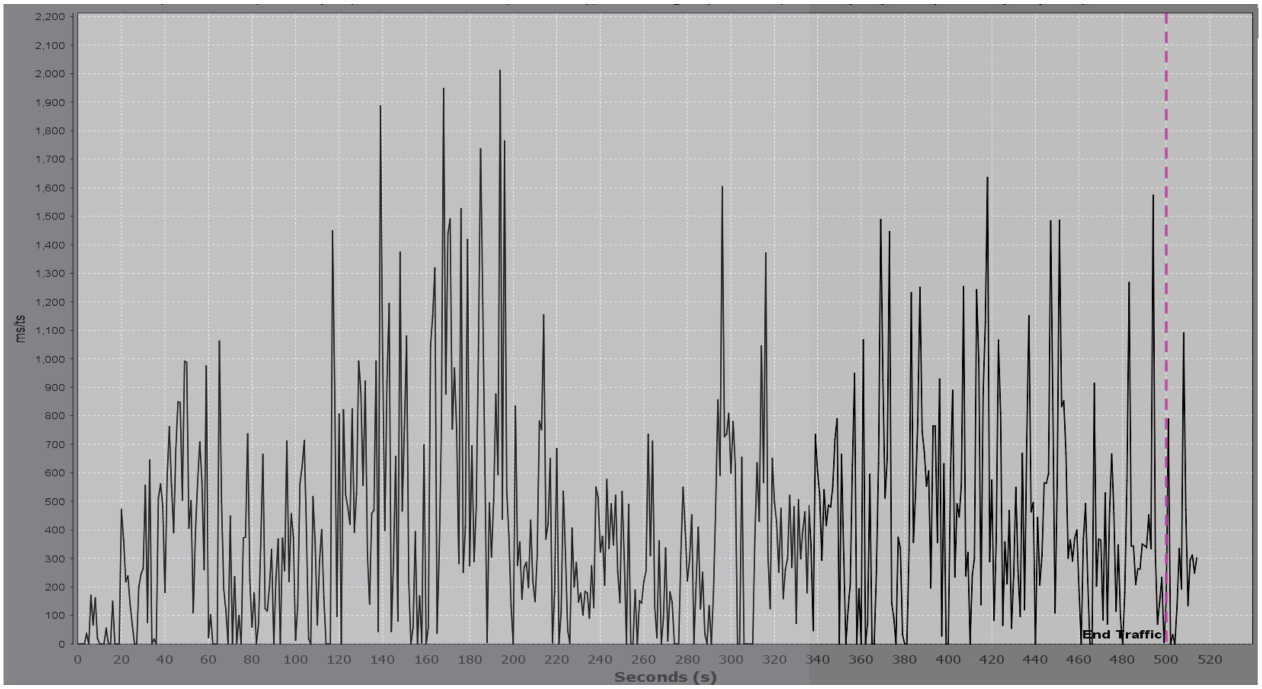
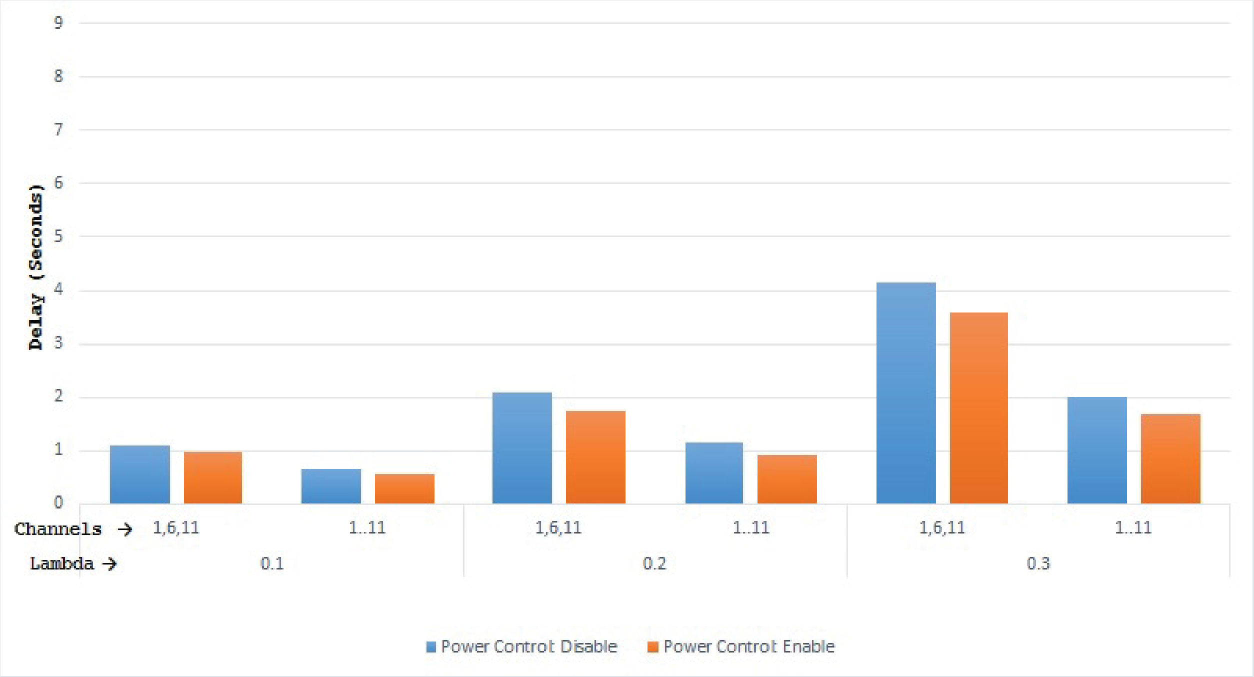
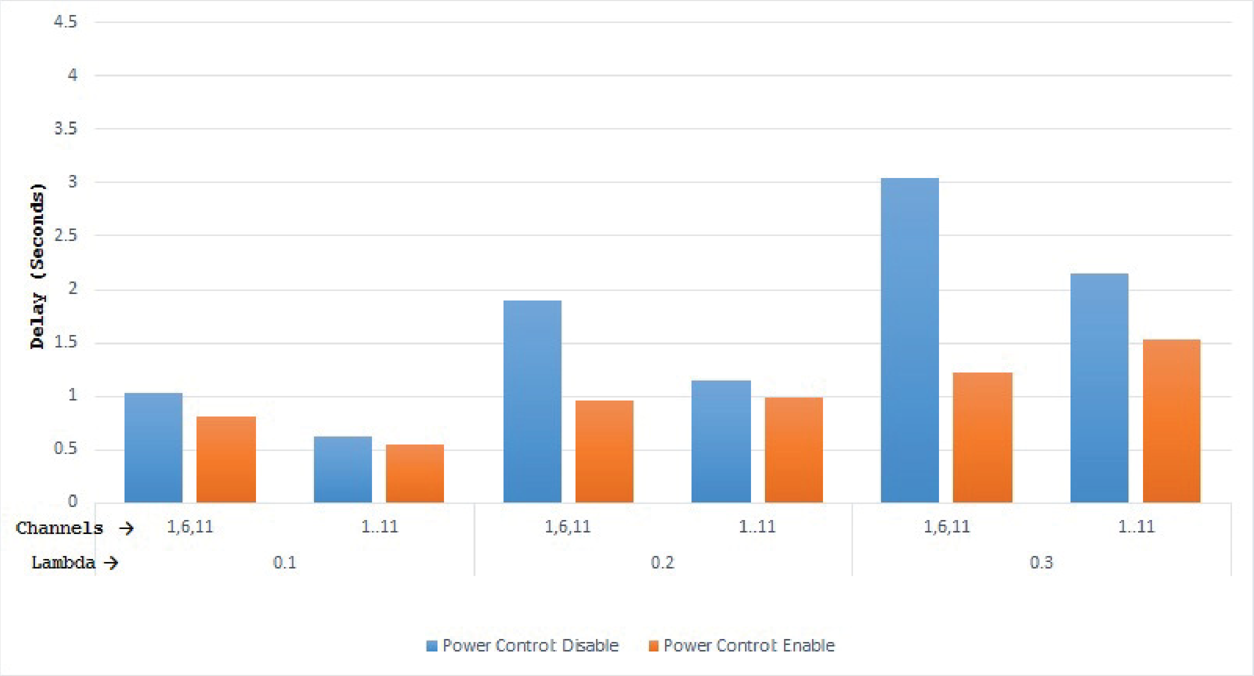


Figure 5.14: Average Delay in each time slot

Figure 5.15 shows the amount of average delay when BPA takes the responsibility of delivering packets to their destinations. In addition, MBF shows different results that are presented in Figure 5.16. The vertical axes refers to average of packets delay, and the horizontal axes points to the available channels(1..11 means all 11 channels available). Blue(lighter) bars show average delay when the power control algorithm is not activated. Moreover, orange(darker) bars indicate delay of packets when the power control algorithm is enabled. All transmission configurations are created by GBA. As we shown in Figure 5.15 and 5.16, average delay is increased when the amount of generated traffic is increased. However, using BPA and all 11 channels decrease the average of delay significantly. It is clear that they delay is inversely related to the throughput. In other words, when the average throughput of a network is increased, the average delay of packets and network delay are decreased and vise versa.

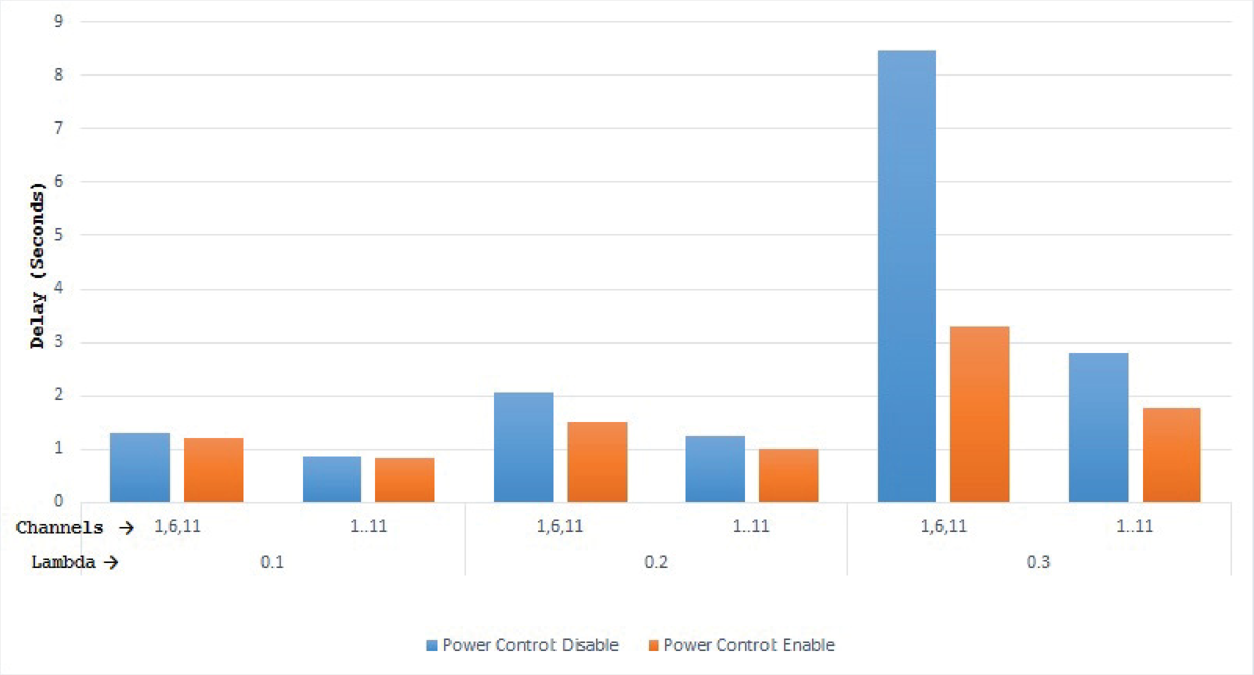


(a) 89 Nodes

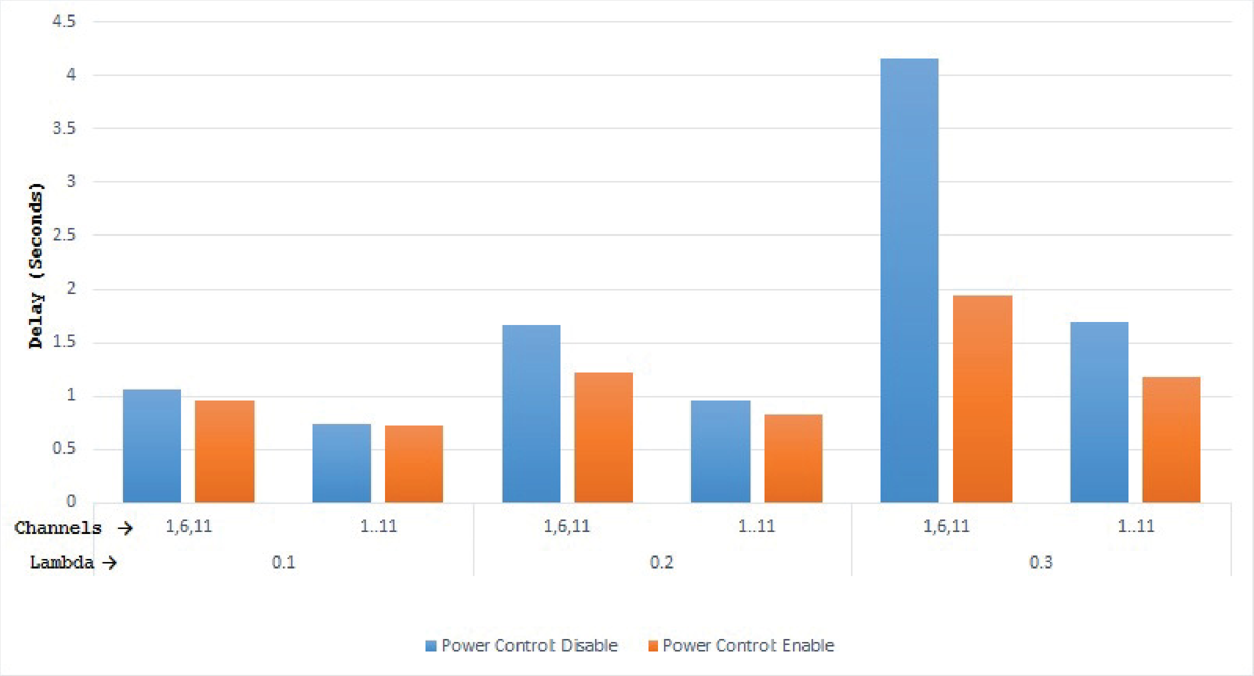


(b) 70 Nodes

Figure 5.15: Delay - Back Pressure Algorithm (Algorithm DPBP)



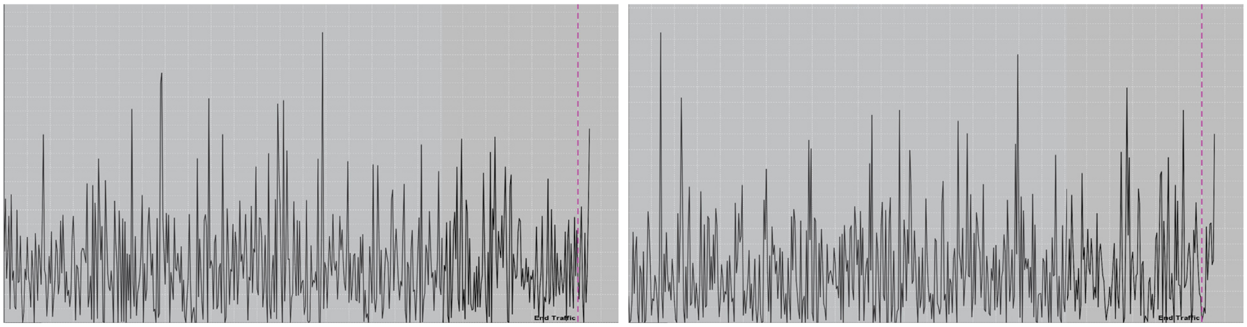
(a) 89 Nodes



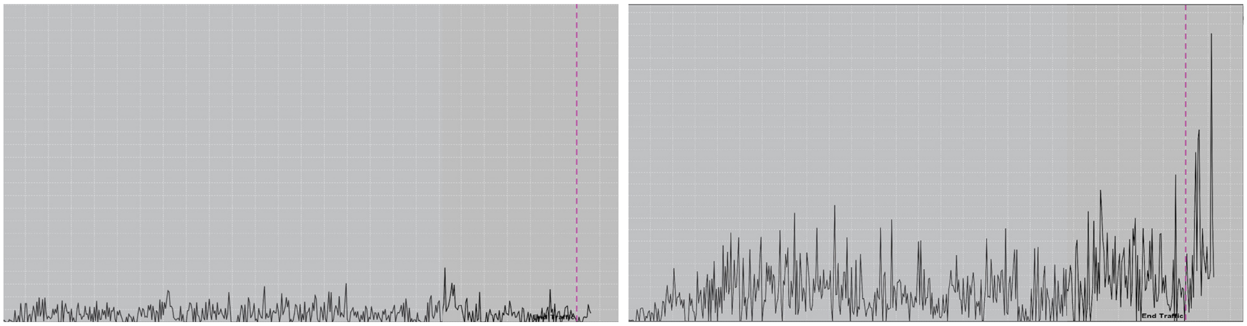
(b) 70 Nodes

Figure 5.16: Delay - Maximum-Buffer-First Algorithm (Algorithm DPMBF)

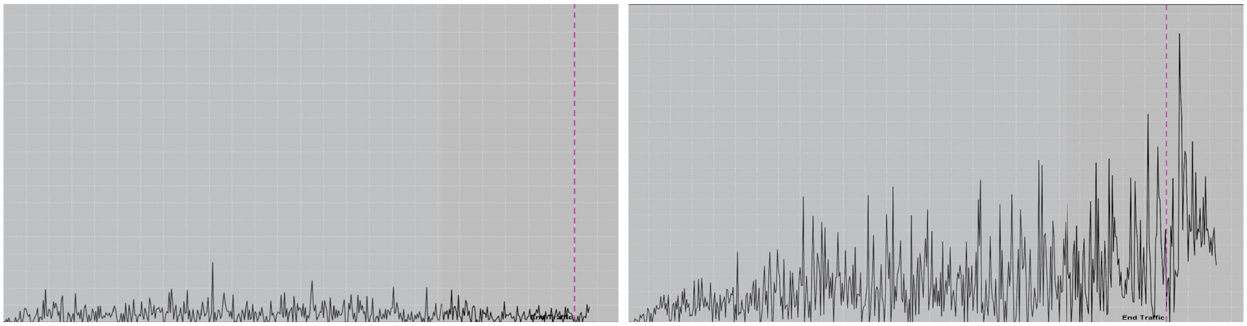
Figure 5.17 illustrates several diagrams for the delay of packets. Their throughput diagrams was presented previously in Figure 5.13.



(a) 1..11, $\lambda = 0.1$ (b) 1,6,11, $\lambda = 0.1$



(c) 1..11, $\lambda = 0.5$ (d) 1,6,11, $\lambda = 0.5$



(e) 1..11, $\lambda = 0.6$ (f) 1,6,11, $\lambda = 0.6$

Figure 5.17: Average Delay per Time Slots

Using all 11 channels for assigning channels to networks' links not only reduces the average of delay but also decreases the delay of networks. From the diagrams in Figure 5.17, it is apparent that the amount of average delay is increased when the amount of generated traffic is boosted. However, the delay is remained in an acceptable level when all channels are available.

5.3.6 Power Control

As mentioned in Section 4.4, Power Control Algorithm (PCA) can positively affect the average capacity of TCs because Power Control Algorithm (PCA) assigns an appropriate power, which is less then the maximum power. Initially, the maximum power was used in Equation (2.2) and Procedure CanAdd in order to calculate the amount of interference between links. PCA (Algorithm POWERC) calculates the precise amount of power which is less than or equal to the maximum value. As a result, by adjusting the amount of power for a number of links in a TC we can reduce the amount of interference and boost the data rate of links. Hence, power control can improve the average capacity of TCs.

Node	Throughput		Delay	
	Pattern-Based	Greedy-Based	Pattern-Based	Greedy-Based
Back-Pressure Algorithm				
70	13% ↑	22% ↑	17% ↓	44% ↓
89	10% ↑	7% ↑	14% ↓	22% ↓
Maximum-Buffer-First Algorithm				
70	13% ↑	**32**% ↑	17% ↓	22% ↓
89	17% ↑	12% ↑	15% ↓	59% ↓

Table 5.6: Impact of Power Control on Throughput and Delay

Table 5.6 illustrates the impact of PCA on the throughput. For instance, PCA can boost the throughput 32%(bold value) in comparison with non-power control mechanism under following conditions: *i*) Network contains 70 nodes; *ii*) All 11 channels are available; *iii*) MBF is used for delivering packets; and *iv*) TCs are created by GBA.

5.4 Summary

The overriding purpose of this study was to improve the throughput and decrease the delay of wireless mesh networks under partial overlapping channel assignment. To accomplish that goal, it became necessary to propose several algorithms in various aspects of wireless mesh network. We also implemented a dynamic traffic generator for bringing our experiments close to a real WMN.

For modeling a TDMA based system, transmission configuration algorithms divide time to several frames for concurrent transmission of data in a frame. We proposed different algorithms for creating transmission configurations. Greedy-Based Algorithm (GBA) (Algorithm TCGBA) boosts throughput 23% in comparison with Pattern-Based Algorithm (PBA) (Algorithm TCPBA).

Power Control Algorithm(Algorithm POWERC) calculates the optimized amount of power. The maximum power was used for calculating the amount of SINR in Equation (2.2). Moreover, the amount of SINR can decline for a link by power control algorithm at a particular data rate. Hence, data rate can be improved, and the performance of networks is boosted. In consequence, throughput can increase by 18% and delay can decline 35% when power control is enabled.

We proposed two algorithms for delivering packets to their destination. Back-Pressure Algorithm raises throughput 40% and decrease delay 15% compared to Maximum-Buffer-First Algorithm. However, the back-pressure algorithm is a more time-consuming algorithm because of its complexity compared to its counterpart. Alternatively, Maximum-Buffer-First Algorithm provides less improvement in throughput of network but its complexity is much less than Back-Pressure Algorithm (BPA). In a nutshell, there is a substantial trade-off to consider between performances in terms of QoS and complexity of algorithms.

Chapter 6

Conclusions and Future Work

In this thesis, we studied the effect of Partially Overlapping Channels (POCs) on Quality of Service (QoS) of Wireless Mesh Networks (WMNs). Using Orthogonal Channels (OCs) was the well-known strategy for assigning channels over last decade. Perhaps the most serious disadvantage of OCs is that the limited number of them in Multi-Radio Multi-Channel (MRMC) networks. Recently, researchers have found that POCs can not only raise the throughput of wireless mesh networks but also it can decrease the delay of packets delivery. Most of researches in this area use a simple scenario for evaluating behaviors of WMNs under partial overlapping channel assignment.

We provide a step-by-step approach based on a dynamic traffic generator to handle channel assignment, establishing transmission configurations, adjusting power of links, and delivery packets to their destinations. In this study, many efforts have been made aiming to evaluate wireless mesh networks' performance in a real world scenario.

We introduced several heuristic algorithms with polynomial time in different aspects of wireless mesh networks. In the first step, Algorithm DyTr generates traffic in a dynamic way. Afterwards, topology generator manages creating a random topology. Then, channels are assigned to links by Algorithm ChanA. Afterwards, for creating a Time-Division Multiple-Access (TDMA) based network, two algorithms build transmission configurations. Power Control Algorithm (PCA) adjusts the power of link in each transmission configuration. Finally, packets deliver to their destination by Algorithm DPMBF and DPBP.

Finally, numerical results shows that POCs can improve the throughput of WMNs and decrease the delay of packets delivery.

6.1 Future Work

Although the results presented here have demonstrated the effectiveness of our approach, it could be further developed in a number of ways such as dynamic routing, topology control, and creating an optimal model for channel assignment and transmission configurations.

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