

**IMPACTS OF CHANNEL SWITCHING OVERHEAD ON THE
PERFORMANCE OF MULTICAST IN WIRELESS MESH NETWORKS**

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Abstract

Wireless mesh networks (WMNs) have emerged as a promising technology for next-generation wireless networking. A WMN extends network coverage using wireless mesh routers that communicate with each other via multi-hop wireless communications. One technique to increase the network capacity of WMNs is to use routers equipped with multiple radios capable of transmitting and receiving on multiple channels. In a Multi-Channel Multi-Radio wireless mesh network (MCMR WMN), nodes are capable of transmitting and receiving data simultaneously through different radios and at least theoretically doubling the average throughput. On the other hand, the use of multi-radio and multi-channel technology in many cases requires routers to switch channels for each transmission and/or reception. Channel switching incurs additional costs and delay. In this thesis, we present a simulation-based study of the impacts of channel switching overheads on the performance of multicast in MCMR WMNs. We study how channel switching overheads affect the performance metrics such as packet delivery ratio, throughput, end-to-end delay, and delay jitter of a multicast session. In particular, we examine:

1. the performance of multicast in MCMR WMNs with three orthogonal channels versus eleven overlapping channels defined in IEEE 802.11b.
2. the performance of the Minimum-interference Multi-channel Multi-radio Multicast (M4) algorithm with and without channel switching.
3. the performance of the Multi-Channel Minimum Number of Transmissions (MCMNT) algorithm (which does not do channel switching) in comparison with the M4 algorithm (which performs channel switching).

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Chapter 1

Introduction

Wireless mesh networks (WMNs) have emerged as a promising technology for next-generation wireless networking. As opposed to traditional networks that rely on a small number of wired access points or wireless hotspots to connect users, a WMN extends network coverage using wireless mesh routers that communicate with each other via multi-hop wireless communications [1,2]. Potential applications of WMNs include broadband home, community, neighbourhood and enterprise networking, building automation, health and medical systems, public safety and security systems, intelligent transportation systems, emergency/disaster networking and broadband Internet access in metropolitan areas.

A wireless mesh network is a communication network composed of clients, wireless routers, and gateways as illustrated in Figure 1.1. Clients are wireless devices such as cellphones or laptops that send or receive data from wireless routers. Wireless routers have minimal or no mobility and are connected in a mesh topology to provide a network

backbone for mesh clients. Wireless routers relay data from one client to another and between clients and the Internet. Gateways are routers that provide connectivity to the Internet or to other networks.

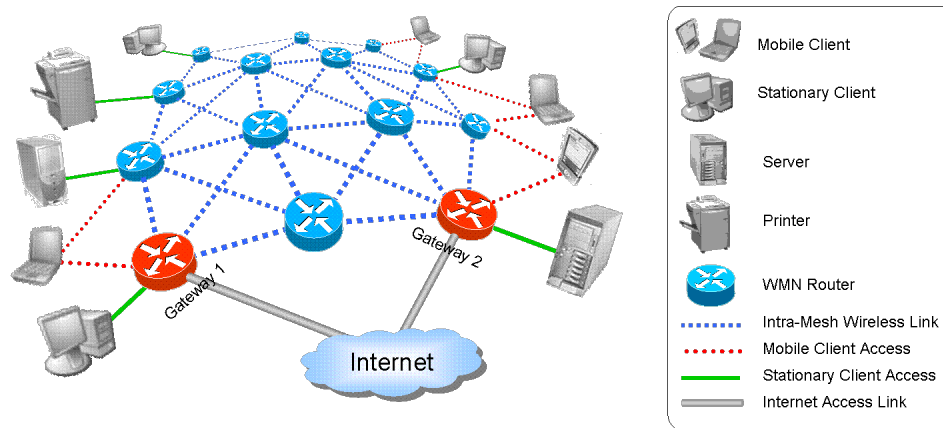
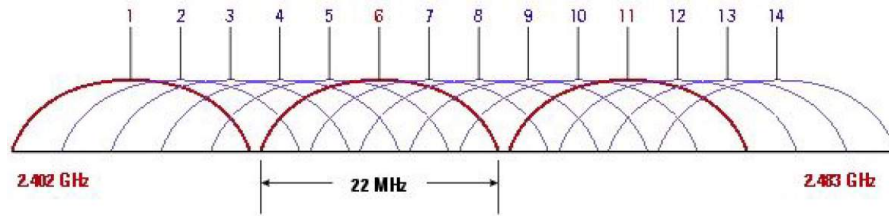


Figure 1.1: Components of a wireless mesh network

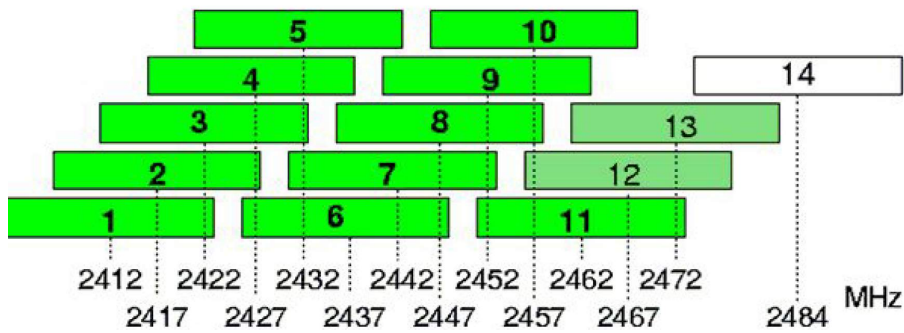
Overview of Wireless Communications

A radio, also known as a wireless interface, is a wireless network interface card (NIC) that is attached to the antenna of a wireless device. A channel represents a band of frequencies over which signals are transmitted. Figure 1.2 illustrates the set of channels defined in IEEE 802.11b standard. In Figure 1.2a, each channel is identified by a half circle that covers the band of frequencies allocated to that channel. The number on top of each channel represents the alias for that channel. Figure 1.2b illustrates the frequency corresponding to each channel which is defined as the middle frequency of the band. Channels with the middle frequencies more than 25 MHz apart are considered

non-overlapping (orthogonal) and therefore they do not interfere with each other. In Figure 1.2a, orthogonal channels are represented by red half circles. Channels that are less than 25 MHz apart are overlapping and hence interfere with each other.



(a) Channels defined in IEEE 802.11b along with their aliases (indicated on top of each channel) and the band of frequencies used for each channel



(b) Frequency corresponding to each channel

Figure 1.2: Channels and their frequencies defined in IEEE 802.11b

Single-channel Single-radio WMNs

A single-channel single-radio WMN consists of nodes that possess only one radio and use only one shared channel for communication. In a single-channel single-radio network, the

throughput capacity degrades significantly as the network size increases. In a random ad hoc network with ideal global scheduling and routing, the theoretical achievable throughput is estimated as $\theta(1/\sqrt{n \log n})$, where n is the number of nodes in that network [3]. For multicast flows, the situation is even worse and the theoretical aggregate throughput is estimated as $O(1/\sqrt{n^\epsilon \log n})$, where $0 \leq \epsilon \leq 1$ [4]. The above two upper bounds imply that as n grows beyond a certain limit, the capacity of a single-channel WMN becomes unacceptably low.

Critical factors that contribute to this rapid degradation are: (1) a single channel shared by all nodes in the network and (2) the use of a single, half-duplex radio per node. The former refers to performance degradation due to medium contention, interference and packet collisions that occur among nodes that share the same channel. The latter means that a single half-duplex radio is only able to either send or receive at any point in time, but not simultaneously. One of the most effective solutions to these problems and increase network throughput is to use nodes that possess multiple radios in networks using multiple channels.

Multi-channel Multi-radio WMN

A multi-radio node is able to send on one channel and receive on another simultaneously by using two different radios, and thereby at least doubles the throughput. Figure 1.3 illustrates a node with multiple radios interacting with a multi-channel network.

A WMN consisting of nodes that have multiple radios and use different channels is

called a Multi-Channel Multi-Radio wireless mesh network (MCMR WMN). To provide connectivity in a MCMR WMN, each pair of neighbour nodes have to be tuned to a common channel and establish a wireless link to communicate. An example MCMR WMN is shown in Figure 1.4. In this figure, nodes are represented by alphabetical letters in circles and a wireless link between two nodes is represented by a line that connects them. The channel used by a link is indicated as a number associated with that link. In a WMN, each node may establish one or more link(s) with neighbour nodes. For instance, node I has two radios and uses three links for communication: one radio communicates with nodes N and J, and the other communicates with node H. Assigning appropriate channels to wireless links in a MCMR is the task of a channel assignment algorithm (CA).

The objective of a CA algorithm can be to maximize the overall network throughput [5], to minimize interference [6], or to balance the traffic load in a network [7]. For the purpose of the study in this thesis, a CA algorithm can be categorized into one of the following two groups depending on the relation between the number of radios a node possesses and the number of channels assigned to it.

1. The number of assigned channels c is less than or equal to the number of radios r the node is equipped with, i.e., $c \leq r$. In this case, each radio is tuned to an assigned channel to communicate with the corresponding neighbours. For instance, as illustrated in Figure 1.4, assuming that node O is using two radios: one radio uses channel 1 to communicate with nodes F, S, N and the other radio uses channel 2 to communicate with node H.

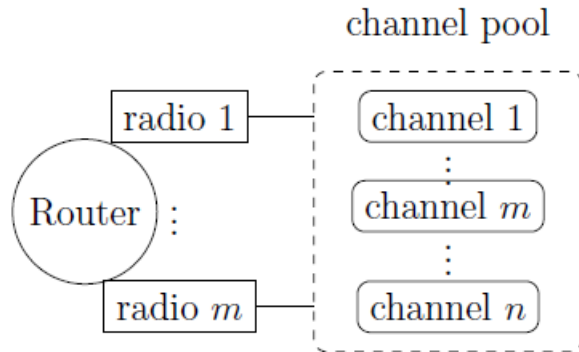


Figure 1.3: A Multi-Channel Multi-Radio (MCMR) node

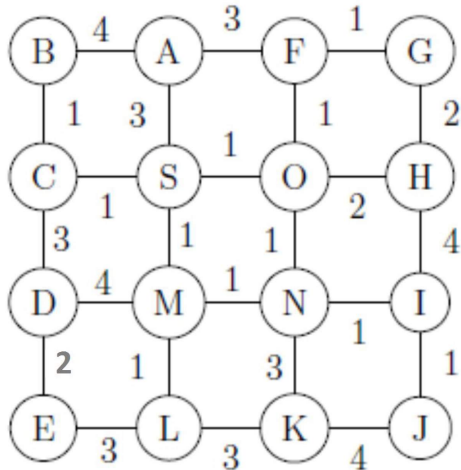


Figure 1.4: A MCMR WMN

2. The number of assigned channels is greater than the number of radios the node has, i.e., $c > r$. In this case, at least one radio has to switch among two or more assigned channels to communicate with neighbour nodes. Assume that node D in Figure 1.4 has two radios and has been assigned channel 3 to communicate with C, channel 4 to communicate with M and channel 2 to communicate with E. Given

two radios and three channels, one radio has to switch, say, between channels 2 and 4 for D to communicate with E and M. Channel switching incurs hardware and software latencies [8, 9], and requires synchronization and scheduling. There exist many channel switching algorithms [10–13].

For the purpose of the research in this thesis, we categorize existing channel assignment schemes [14–23] into two groups: $c \leq r$ [14–20] and $c > r$ [21–23].

Multicast

Multicast is a form of communication that delivers a data message from a source to a group of destinations simultaneously in an efficient manner. As opposed to unicast communication where the sender targets only one receiver for each data packet in a multicast session, the sender targets multiple receivers simultaneously when transmitting each data packet. Following are important applications of multicast:

- Scheduled audio/video distribution: Any type of scheduled event whose multimedia coverage could benefit audiences, for instance, audio/video conference, presentations, meetings, IP television and distance education.
- Push media: Such as news headlines, weather updates, sports scores, or other types of non-essential dynamic information [24].

Motivations

In this thesis, we study the following problems:

- the performance of multicast in MCMR WMNs with 3 orthogonal channels versus 11 overlapping channels defined in IEEE 802.11b.
- the performance of the Minimum-interference Multi-channel Multi-radio Multicast (M4) algorithm with and without channel switching.
- the performance of the Multi-Channel Minimum Number of Transmissions (MCMNT) algorithm (which does not do channel switching) in comparison with the M4 algorithm (which requires channel switching).

Following are the factors that motivated us to solve the above problems.

Performance Evaluation of Multicast Using Overlapping and Non-overlapping Channels

In an IEEE 802.11b network, there are eleven overlapping and three non-overlapping channels available to use. While non-overlapping (orthogonal) channels do not interfere, overlapping channels do interfere with each other. Since interference is an important factor that degrades the performance of any wireless network, using three orthogonal channels may be perceived as offering higher performance than using eleven overlapping channels. On the other hand, using three orthogonal channels may result in more medium contention and thus lower throughput, because the same number of nodes are sharing three channels instead of eleven.

Therefore, using orthogonal channels benefits from no interference but suffers from higher medium contention within a channel. On the other hand, using eleven overlap-

ping channels benefits from lower medium contention but suffers from adjacent-channel interference. To the best of our knowledge, there have been no studies addressing this issue. Therefore, we compare the performance of multicast using three non-overlapping channels and eleven overlapping channels defined in the IEEE 802.11b standard. Our simulation results show that using eleven overlapping channels offers higher performance in terms of packet delivery ratio, end-to-end delay, throughput and jitter. As a result, we use the eleven-channel configuration in the next studies.

Channel Switching Overheads on Multicast in MCMR WMNs

When evaluating the performance of a MCMR WMN, the overhead of channel switching may or may not be negligible [19, 20]. Such overheads are incurred at multiple levels. For example, hardware latency is incurred at the physical layer and software delay, at the MAC layer for synchronization and scheduling. Channel switching has been the topic of many studies [8, 10–13, 25–29]. In these studies, channel switching algorithms are proposed for unicast communications. Moreover, the impacts of channel switching latency were not considered in the simulation results reported in these papers. Furthermore, there has not been any work on the impact of channel switching on the performance of multicast in MCMR WMNs. Therefore, we conduct a simulation-based study to evaluate the overheads of channel switching on the performance of multicast in a MCMR WMN. In particular, we study the performance of the M4 algorithm in two cases: with channel switching and without channel switching.

Comparison between the $c > r$ and $c \leq r$ Approaches

Using the $c \leq r$ approach in a network does not require channel switching and, therefore, benefits from a simple implementation. However, using a low number of channels in a network increases medium contention, channel sharing and interference, which in turn reduces the number of simultaneous transmissions, hence lowers the network throughput. On the other hand, the $c > r$ approach requires efficient channel switching schemes and carries additional channel switching costs, which are not negligible as shown in [30, 31] and demonstrated in Chapter 4. To the best of our knowledge, there has not been any research that compares the performance of a network using the $c \leq r$ approach versus the $c > r$ approach. As part of our work, we compare the performance of multicast in a MCMR WMN for the following two cases:

- The number of channels assigned to a node may be greater than the number of radios the node has ($c > r$) and thus channel switching is required. The M4 algorithm is used for channel assignment and breadth first search, for routing in this case.
- The number of channels assigned to a node is less than or equal to the number of radios the node possesses ($c \leq r$) and thus no channel switching is required. The MCMNT algorithm is used for routing together with random CA in this case.

The results obtained from simulations indicate that in all cases the ($c \leq r$) approach offers better results in terms of average packet delivery ratio, end to end delay and throughput, thanks to no channel switching overhead. As for the average delay jitter, the

M4 algorithm provides better results.

Contributions

Following are the contributions of the thesis.

- First, we present a performance evaluation of multicast in MCMR WMNs for the two cases where three orthogonal and eleven overlapping channels defined in the IEEE 802.11b standard are used.
- Second, we provide experimental results that show how channel switching overheads affect the performance of the M4 algorithm in a MCMR WMN.
- Third, we compare the performance of multicast in MCMR WMNs for the two cases $c > r$ (using the M4 algorithm) and $c \leq r$ (using the MCMNT algorithm).

We believe that our results and analysis will be valuable to researchers undertaking research on channel switching and channel assignments in MCMR WMNs.

Outline of the Thesis

The remainder of the thesis is organized as follows. Chapter 2 presents an overview of single-channel and multi-channel networks, and literature reviews of multicast routing, channel assignment and channel switching schemes. In Chapter 3, we provide a simulation-based study of the performance of multicast in MCMR WMNs using three

orthogonal and eleven overlapping channels defined in the IEEE 802.11b standard. In Chapter 4, we present a simulation-based study to evaluate the effects of channel switching latency on the performance of the M4 algorithm in MCMR WMNs. In Chapter 5, we compare the performance of multicast via simulations for the two cases: $c \leq r$ (using the MCMNT algorithm) and $c > r$ (using the M4 algorithm). We conclude the thesis and outline future research directions in Chapter 6. A brief description about the simulator that we used is provided in Appendix A and sample network topologies used in our simulations are given in Appendix B.

Chapter 2

Literature Review

This chapter presents an overview of wireless communications and wireless mesh networks followed by surveys multicast routing in MCMR WMNs, channel assignment and channel switching.

2.1 Overview of Wireless Communications

In its traditional sense, *radio* is the radiation of electromagnetic signals through the atmosphere or free space. In the wireless networking literature, radio is often used to describe the wireless network interface card (NIC) that is attached to the antenna of a wireless device. In this thesis, the terms “radio” and “interface” are used interchangeably.

A channel represents a band of frequencies over which signals are carried from sources to destinations. At any instant of time, a radio is capable of sending or receiving signals on a specific channel. The *transmission range* of a radio is defined to be the range in which nodes can receive the radio’s data transmissions correctly (assuming no interfer-

ence). The transmission range of a node is usually represented by a circle which is drawn around the node (see Figure 2.1). As illustrated in this figure, if node B located within the transmission range of node A, then node B can receive data successfully from A, assuming that both nodes are in an interference-free environment. When a sender node

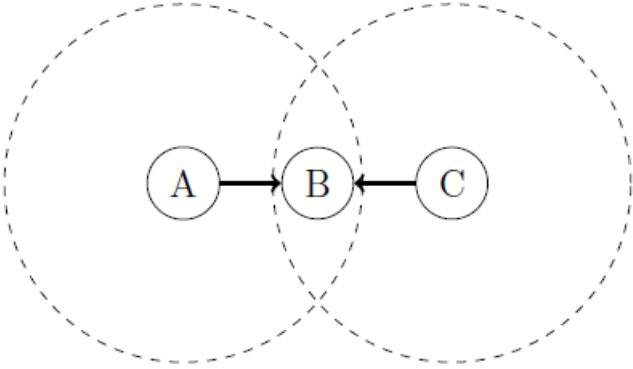


Figure 2.1: Transmission range of nodes A and C is represented by the dotted circles

is transmitting data to a receiver, all nodes in the transmission range of the sender may overhear its transmissions even if they are not the intended recipients of these transmissions. An example of the overhearing effect is illustrated in Figure 2.2. In this example, node A is the multicast source and nodes B, C, D and E are forwarders. There is a wireless link between node B and C, but it is not part of the routing tree; therefore, B and C are not connected directly, however, they are in the transmission range of each other. Since B is receiving multicast flow on channel 3 and C is transmitting on the same channel, node B is able to overhear the data that node C is transmitting to node E. In this case, if node B does not receive a packet from its parent, node A, (due to e.g., a

collision or interference), there is another chance for B to receive (overhear) the packet from node C. As a result, the broadcast nature of wireless communication provides the *overhearing* effect which has the potential to improve packet delivery ratios of nodes.

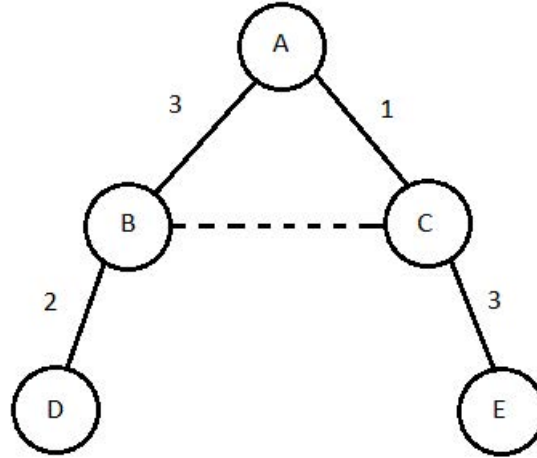


Figure 2.2: Overhearing effect

In wireless communications, concurrent data transmissions on the same channel from nodes A and C to node B (as illustrated in Figure 2.1) cause a packet collision at B and leads to data loss. In order to minimize such a collision, the Career Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm [32] is used. CSMA/CA is a Medium Access Control (MAC) protocol and was approved for use in IEEE 802.11 standards in June 1997.

As illustrated in Figure 2.6, the IEEE 802.11 MAC layer consists of two sublayers: PCF (Point Coordination Function) and DCF (Distributed Coordination Function), both of which provide stations in a network with methods to access the shared medium. While the DCF sublayer provides access to the medium for transmitters using a contention-

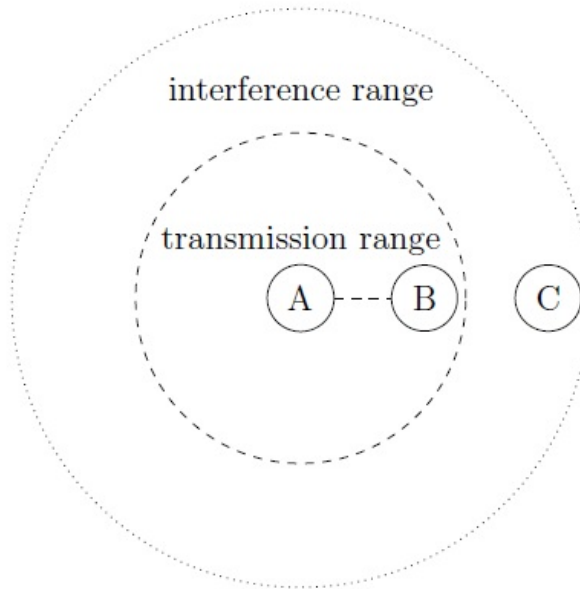


Figure 2.3: Illustration of interference range and transmission range

based algorithm, the PCF uses a centralized and contention-free algorithm to provide medium access. Below, we explain the DCF and PCF in detail.

2.1.1 Distributed Coordination Function

The DCF sublayer uses the CSMA/CA algorithm which is illustrated in Figure 2.4 and works as follows. A transmitter wishing to transmit a MAC frame has to wait until the channel remains idle, in which case, the station may transmit; otherwise the station must wait until the ongoing transmission is complete and a time interval called backoff time has elapsed before transmitting. To ensure the smooth and fair functioning of the CSMA/CA algorithm, DCF applies a set of delays, called interframe space (IFS). The logic behind using interframe space is to define different priority levels for different types of frames

(e.g., control frames, data frames, acknowledgements) when accessing the medium. IFS is a general term referring to the four different types of time intervals: SIFS, PIFS, DIFS and EIFS. To see how IFS is used in practise, following is the CSMA/CA algorithm with the use of IFS:

1. A station with a frame to transmit, has to wait until the channel remains idle for a time equal to IFS. If so, the station may transmit immediately.
2. If the medium is busy (due to an ongoing transmission or the channel becoming busy during the IFS), then the transmitter defers the transmission and keeps monitoring the medium until it gets idle.
3. After the ongoing transmission is over, the transmitter does not transmit the frame immediately, instead, it delays the transmission for the duration of another IFS. If the medium remains idle for this period, then the transmitter backs off as long as a time interval whose value is randomly generated. During the backoff period, if the channel is found busy, the backoff timer is frozen until the channel is again idle for the duration of another IFS. The process continues until the backoff time reaches zero, in which case the node immediately transmits the data. In order to handle heavy traffic loads, IEEE 802.11 uses binary exponential backoff which works as follows. When a station attempts to transmit repeatedly in the face of repeated collisions, for the first 10 retransmission attempts, the mean value of the random delay is doubled. This mean value then remains the same for six additional

attempts. After 16 unsuccessful attempts, the station gives up and reports an error. Thus, as congestion increases, stations back off by larger and larger amounts to reduce the probability of collision. Without such a backoff, the following situation could occur: Two or more stations attempt to transmit at the same time, causing a collision. These stations then immediately attempt to retransmit, causing a new collision. Repeated failed attempts to transmit result in longer and longer backoff times, which helps to smooth out the load.

4. After receiving the data frame successfully, the receiver transmits an acknowledgment message to the sender.

In order to provide priority-based access to the medium, the CSMA/CA algorithm uses three values for IFS:

- SIFS (short IFS): The shortest IFS, used for all immediate response actions, e.g., ACK, RTS, CTS.
- PIFS (point coordination function IFS): Midlength IFS used by the centralized controller in the PCF scheme when issuing polls. We will explain the PCF in Section 2.1.2.
- DIFS (distributed coordination function IFS): The longest IFS, used as a minimum delay for asynchronous frames contending for access.

Figure 2.5 illustrates the use of these values. Data frames with highest priority use the shortest IFS (SIFS) to gain access in preference to a station waiting an amount of

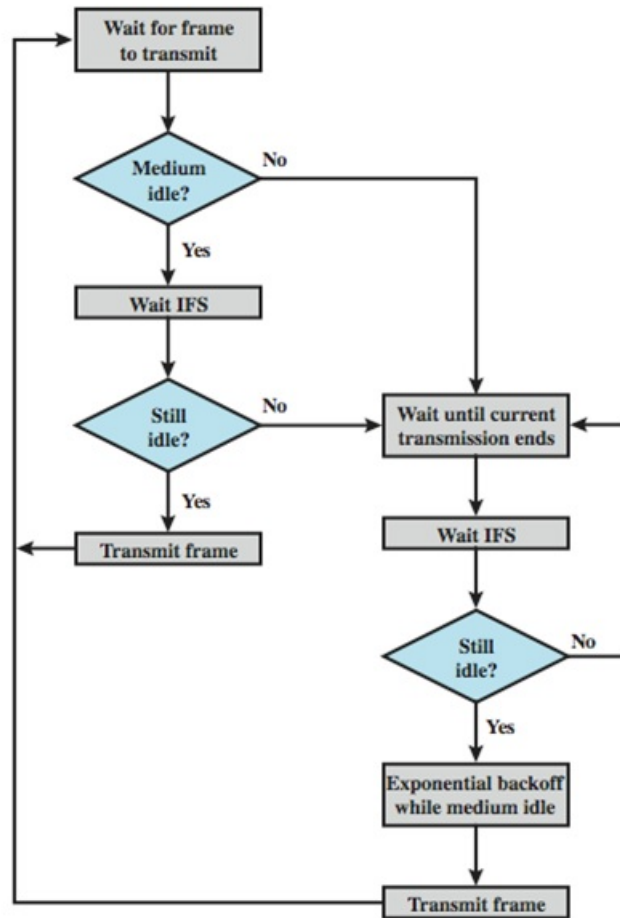


Figure 2.4: IEEE 802.11 medium access control logic

time equal to PIFS or DIFS. The frames that use SIFS consist of Acknowledgement (ACK), Clear To Send (CTS) and Poll response and will be explained in Section 2.1.1. The midlength IFS interval is the PIFS which is used by the PCF function that will be explained in Section 2.1.2. The PIFS takes precedence over normal contention traffic. The DIFS is the longest IFS and is used for all ordinary asynchronous traffic.

The occurrence of collision can not be detected by the transmitter due to two reasons:

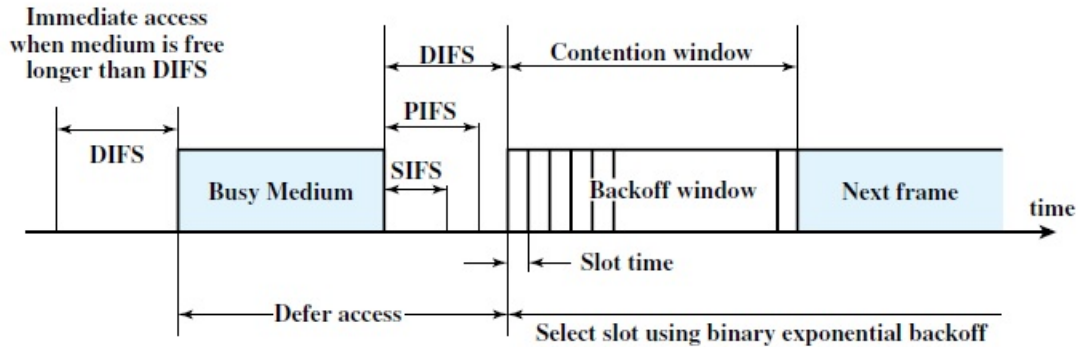


Figure 2.5: IEEE 802.11 basic access method

First, the transmitting signal power is much higher than the incoming signal. Second, a radio has only one antenna for both sending and receiving which can not be used for both transmitting and detecting collisions simultaneously. In case of using multiple radios per node, still the collision is hard to be detected since the signal power of the transmitting radio saturates other radios' reception. Therefore, the transmitter assumes that a collision has occurred based on the absence of an acknowledgement message from the receiver. If the transmitter does not receive an ACK (due to collision or transmission errors), it generates the random backoff time after the channel remains idle for an EIFS (Extended Interframe Space) which is the longest IFS interval.

Although using CSMA/CA reduces the probability of collision among nodes, it can not prevent the *hidden terminal problem* as explained below. A hidden terminal refers to a terminal C, that resides outside of the interference range of node A as illustrated in Figure 2.1. In this case, terminal C is not able to sense the ongoing transmission from A to B, and hence may try to transmit a packet to B. This results in two concurrent

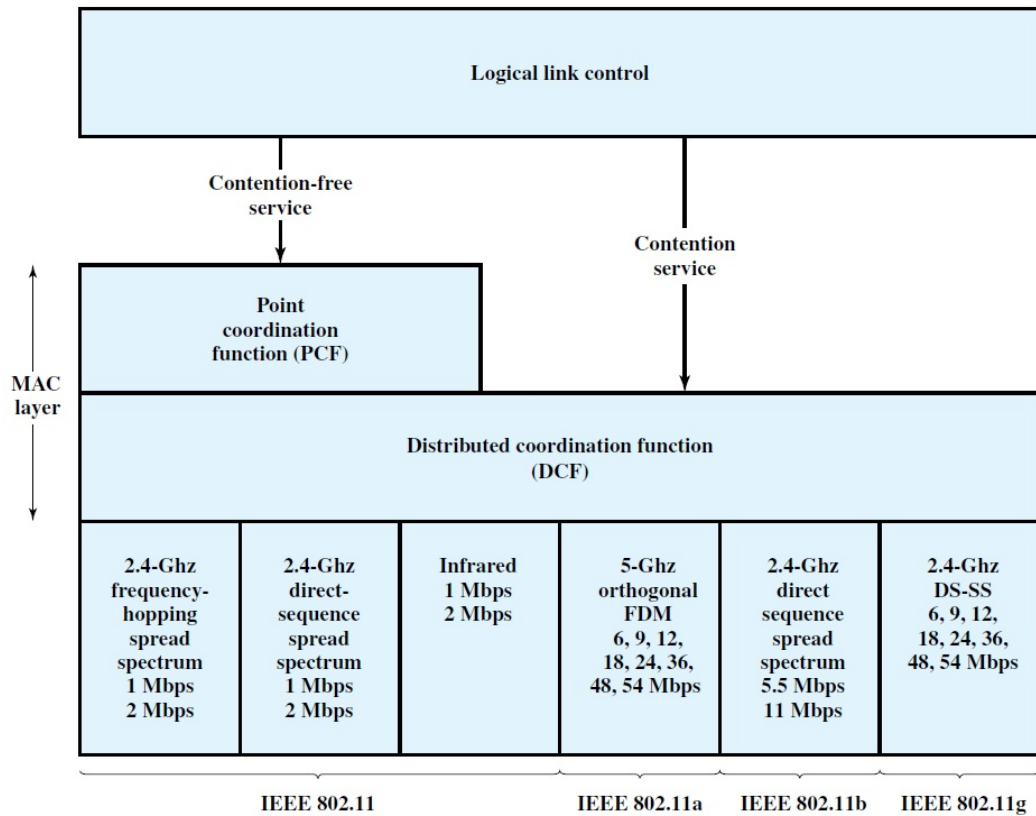


Figure 2.6: IEEE 802.11 protocol architecture

transmissions from A and C which interfere with each other and cause packet loss at the receiving node B. To solve the hidden terminal problem, RTS/CTS (Request To Send/-Clear To Send) handshake mechanism is used between the transmitter and its intended receiver before the actual transmission takes place (see Figure 2.7). Before transmitting the actual data, the transmitter A first sends a request-to-send (RTS) message to request permission for transmission. Then, receiver B replies with a clear-to-send (CTS) message if there is no ongoing transmission between B and another node. Upon overhearing the CTS from B, node C will then defer any transmission. For better reliability, an ACK

is added at the end of the data transmission. Figure 2.7 illustrates the timing diagram corresponding to a complete transmission between nodes A and B.

Although the RTS/CTS handshake mechanism is used in unicast communication, it is not used in multicast communication. Therefore, multicast communication still suffers from the hidden terminal problem. Currently, there does not exist an effective algorithm for implementing RTS/CTS exchanges at the branch points of a multicast tree. The reason is that CTS messages sent by the multicast receivers of a transmitter have a very high probability of colliding at the transmitter. More importantly, it may not be possible for all the multicast receivers to agree on a common time slot for the transmission of a packet, or the delay would be very long to reach such an agreement, e.g., polling each receiver one by one [33,34], or require extensive modifications to the IEEE 802.11 standards [34–38].

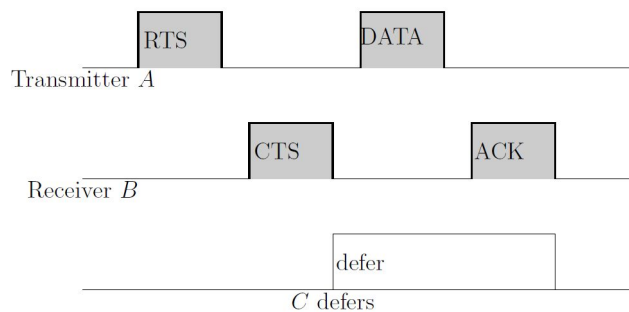


Figure 2.7: Time diagram of transmission with RTS/CTS/DATA/ACK

Another problem that may occur during wireless transmission is the *exposed terminal problem* and is caused by the carrier sense operation. As illustrated in Figure 2.8, nodes

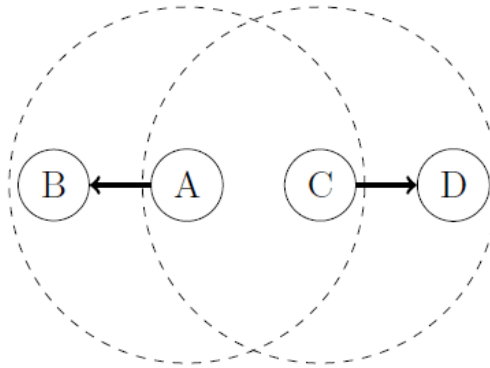


Figure 2.8: Illustration of exposed terminal problem

A and C are in transmission range of each other (exposed to each other) and therefore if either one initiates a transmission, the other has to defer in order to avoid collision. Now, assuming that A is transmitting data to B, node C defers its transmission to D to avoid a collision. But, such deference is not necessary, since transmission from A to B does not interfere with the transmission from C to D. As a consequence, C's deferral lowers its own throughput and degrades the overall throughput of the whole network. Note that the exposed terminal problem only reduces the network throughput and is not an operational problem.

2.1.2 Point Coordination Function

The PCF is an alternative access method in the IEEE 802.11 MAC Architecture which can be implemented directly on top of the Distributed Coordination Function (DCF). The PCF resides in a point coordinator also known as Access Point (AP) and coordinates the communication within a network by providing a centralized coordination and using a

polling system. The point coordinator sends CF-Poll frame to a PCF capable station to permit it to transmit a frame. In case the polled station does not have any frames to send, then it must transmit null frame. When issuing a polling frame, the AP waits for a duration of PIFS rather than DIFS to allocate the channel. Because PIFS is smaller than DIFS, the point coordinator always has the priority to access the channel and can seize the medium and lock out all asynchronous traffic while it issues polls and receives responses. To prevent this, a repetition interval has been designed to cover both (Contention free)PCF and (Contention Based)DCF traffic. The repetition interval which is repeated continuously, starts with a special control frame called Beacon Frame. When stations hear the beacon frame, they start their network allocation vector for the duration of the contention free period of the repetition period.

2.2 Communication Channels and Channel Interference

A communication channel represents a band of frequencies over which signals are transmitted. In wireless communications, a channel is identified by its centre frequency, bandwidth and alias. The alias is an integer assigned to the channel, for instance channel 1. Figure 2.9 illustrates all channels in IEEE 802.11b standard along with their corresponding channel numbers, centre frequencies and bandwidths. For instance, channel number 6 has a centre frequency of 2.437 GHz and its frequency bandwidth is 22 MHz. IEEE 802.11b operates on a 2.4 GHz spectrum and has 11 out of 14 channels available for use. Two channels are called *overlapping channels* if their frequency bands intersect with each

other and are called *non-overlapping* or *orthogonal* otherwise. For instance, in Figure 2.9, channels 1 and 3 are overlapping channels while channels 1 and 6 are orthogonal channels.

In wireless communications, *interference* refers to anything that alters or disrupts a signal as it travels along a channel between a transmitter and a receiver. Outside the transmission range, a receiver is not able to receive data correctly from a transmitter because the signal from is not strong enough. However, the signal from the transmitter is still strong enough to interfere with the receiver's reception from another transmitter. As illustrated in Figure 2.3, C is not in the transmission range of A, but in the transmission range of B. However, the signal from A can interfere with C's reception from B. Therefore, the *interference range* of a node is the range inside which a new transmission may interfere with the packet reception. Notice that the interference range is always larger than and covers the transmission range (see Figure 2.3).

There are two types of interference that may occur in wireless communication: co-channel interference and adjacent-channel interference. Co-channel interference occurs when two radios in the interference range of each other send data simultaneously on the same channel to the same receiver. Adjacent-channel interference happens when two radios located in the interference range of each other transmit signals simultaneously on two overlapping channels. Channels with more overlap generate more adjacent-channel noise. For example, channels 1 and 2 introduce more adjacent-channel interference than channels 1 and 4.

In any case, both co-channel and adjacent-channel interference degrade the network

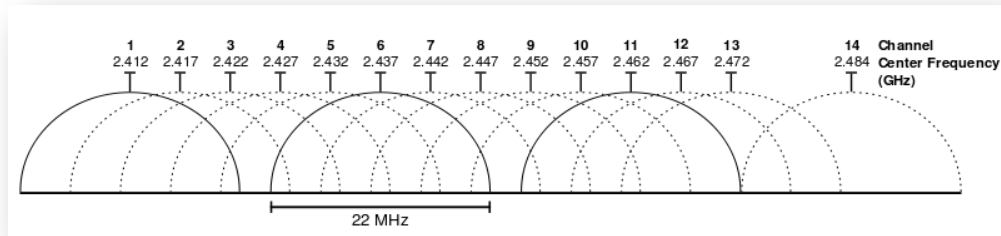


Figure 2.9: IEEE 802.11b standard

performance.

2.3 Wireless Mesh Networks (WMNs)

A WMN consists of mesh routers, mesh clients and mesh gateways. Mesh routers provide connectivity among themselves. for the whole network and mesh clients communicate with mesh routers. Mesh gateways are regular mesh routers, except that they are connected to external resources such as another WMN or an Internet service provider and therefore are able to provide external connectivity for the WMN. Mesh clients communicate with mesh routers in order to connect to other clients or the Internet.

The rest of this section is organized as follows. In Section 2.3.1, we explain several applications of WMNs. Section 2.3.2 and 2.3.3 explains the Single-channel Single-radio and Multi-channel Single-radio WMNs, respectively. Finally, in Section 2.3.4, we describe the Multi-channel Multi-radio WMNs.

2.3.1 Applications of WMNs

One of the most substantial applications of WMN is to provide multi-hop wireless connectivity to areas where wiring or installing cables is difficult or expensive. Moreover, because of their low-cost deployment, WMNs have become very popular and been used in several applications.

- **Cities and Municipalities:** WMNs provide connectivity among citizens and public services over widespread wireless connections. Public services provide the following advantages:
 - Citizens can read news or check their emails when they are on a train or on the road.
 - By installing wireless nodes on the resources that are not easily accessible, such as under-ground pipes and electricity switches, responsible authorities are able to monitor the status of such resources without performing any construction work and with minimum cost.
 - When cellular networks are down, WMNs can be used as an alternative backbone to maintain connectivity among smart devices such as smart phones.
- **Education:** Colleges and universities plan to eliminate the old cabling systems that provide on-campus network access to students. As an alternative, WMNs can be used to provide network access to an entire campus. Everybody on campus is able to connect to the network easily by mounting dozens of indoor and outdoor

routers.

- **Developing Countries:** Wireless mesh networks can be applied to provide internet access in countries without a widespread wired infrastructure, e.g., phone service. In this case, mesh routers can be connected to a satellite internet connection and keep the whole city online.

2.3.2 Single-channel Single-radio Wireless Mesh Networks

In a single-channel single-radio network, each node has only a single radio and operates on a single channel to communicate with other nodes (see Figure 2.11 (a)). In such networks, the throughput capacity has a significant limitation. The theoretical upper bound of per node throughput capacity is asymptotically limited by $O(1/\sqrt{n})$, where n is the number of nodes in the network [3]. Hence, as the number of nodes in a network increases, the throughput capacity degrades very rapidly.

In practise, the situation is even worse due to many factors that have not been considered when deriving the theoretical network capacity. For instance, overheads of routing and transport protocols or the use of a realistic Medium Access Control (MAC) are two examples of factors typically neglected in theoretical analysis of network capacity. Experimental results show that in a string topology network with the use of CSMA/CA-based MAC, the throughput degrades to $1/n$ of the raw channel bandwidth [39]. One of the main factors that contributes to such degradation is the exposed terminal problem (Section 2.1) due to the use of a single channel in the network. One of the most effective

approaches to enhance the throughput capacity of such networks is to use systems with multiple channels and multiple radios per node (MCMR). In a MCMR network, nodes may possess many radios and use different channels for communications.

2.3.3 Multi-channel Single-radio Wireless Mesh Networks

Any end-to-end path in a multi-hop network should utilize all available channels in a way that maximizes the number of simultaneous transmissions in the network area. The study conducted in [40] shows that in a large network with n nodes, if every node has a single interface, then up to $\log(n)$ channels can be fully utilized. Unfortunately, a key limitation of single-radio wireless devices is that they can only use one channel at a time to transmit and receive data, even if multiple channels are available. One solution to address this limitation is to use nodes that are equipped with multiple radios as explained in the next section.

2.3.4 Multi-channel Multi-radio Wireless Mesh Networks (MCMR WMN)

The multi-channel multi-radio (MCMR) technology allows each wireless router to have two or more interfaces that operate independently on different channels (see Figure 2.10). As a result, each router is capable of transmitting and receiving data simultaneously through different radios, and at least theoretically doubling the average throughput [41]. However, MCMR WMNs require efficient channel assignment (CA) and routing protocols to benefit from the MCMR technology.

One important challenge in WMNs is to provide sufficient network capacity to accommodate the demands of high-bandwidth applications and to support high throughput. In a WMN, a heavy traffic is expected to be directed between the mesh gateway and mesh hosts. Such a heavy traffic can be accommodated by properly assigning channels to the interfaces of routers. Therefore, channel assignment is an important topic when studying MCMR WMNs.

Furthermore, applying different strategies to distribute the traffic load across all channels appropriately is an important factor that affects the performance. This requires a proper channel assignment and routing algorithm which are other challenges in MCMR WMNs.

In contrast to a single channel network in which a transmitter may initiate a communication to neighbouring nodes whenever the channel is free, in a MCMR WMN, the transmitter and receiver have to agree on a common channel prior to any transmission. Therefore, channel co-ordination among nodes is another topic of interest when studying MCMR WMNs.

2.4 Channel Assignment (CA)

In this section, we describe the problem of channel assignment and represent it as a mathematical problem. Then, we review and categorize the existing channel assignments for MCMR WMNs. Then, we describe the M4 algorithm since it is used in chapters 4 and 5 in this thesis. Finally, we explain the relation between channel assignment and

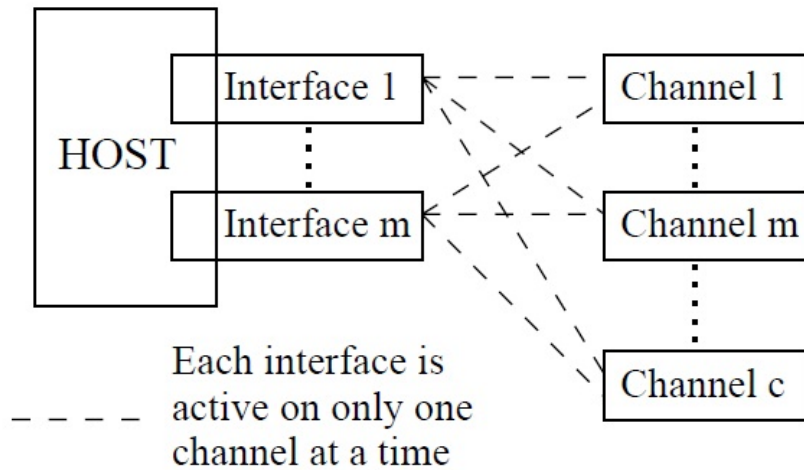


Figure 2.10: Channel and interface model

routing in MCMR WMNs.

2.4.1 Overview

The task of a CA scheme is to decide which channel two neighbour nodes should share for communication. A channel assignment algorithm is an important factor in improving the network performance. When deciding about channel assignment, different CA algorithms consider different goals. Some examples of the goals are: to minimize the interference [19, 20], to maximize the overall network throughput [5], or to balance the traffic load within the MCMR WMN [7]. Channel assignment problem can be formally represented by using the concept of graph. To do this, we assume that:

1. $G = (V, E)$ is a graph in which vertices represent mesh nodes and edges represent the direct communication links.

2. There exist a communication link between a pair of nodes (u, v) if the Euclidean distance between the nodes $D(u, v)$ is less than or equal to some threshold D_{max} (the transmission range of radios given that all radios use the same power to transmit data).
3. Two nodes are neighbours if there is a link between them.

The CA problem is represented as assigning channels to either all $e \in E$ or $v \in V$. The former refers to assigning channels to the links individually and the latter refers to assigning channels to every node $v \in V$ such that every two neighbouring nodes have at least one common communication link.

CA in MCMR WMNs has been the topic of extensive research. Subramanian et al. [19] propose a CA algorithm with the objective of minimizing the overall network interference. They design centralized and distributed algorithms to solve the channel assignment problem. Finally, to evaluate the quality of the obtained solutions, they develop a semi-definite and a linear program formulation of the CA problem to obtain lower bounds on overall network interference. Finally, they check the obtained results against the lower bounds achieved from the semi-definite and linear program formulation.

Ramachandran et al. [6] propose a CA scheme that minimizes the interference within the mesh network and between the mesh network and co-located wireless networks. In this work, they formulate the Joint Optimal Channel Assignment and Congestion Control (JOCAC) as a decentralized utility maximization problem with constraints that arise from the interference of the neighbouring transmissions. Their CA algorithm is able to assign

both orthogonal and overlapping channels as specified in IEEE 802.11b.

Raniwala et al. [31] propose a centralized load-aware CA algorithm. They focus on wireless mesh networks that serve as the backbone for relaying end-user traffic from wireless access points to the wired network. As a result, the source-destination pairs with associated traffic demands and routing paths are required to be known prior to channel assignment. Such a load-aware CA scheme binds each network interface to a channel in such a way that the available bandwidth on each link is proportional to its load capacity. Therefore, a load-aware CA scheme requires pre-determined knowledge of traffic load on each link before assigning channels.

In [42], Doraghinejad et al. propose an improved version of the gravitational search algorithm (GSA) [43] to solve CA problems. The main goal is to minimize the overall interference and to increase the network throughput while ensuring network connectivity.

Tsao et al. [44] propose an end-to-end channel assignment scheme (EECAS) that extends the radio-frequency-slot method to minimize co-channel interference. The EECAS first separates the transmission and reception of packets into two channels. Next, the state of each radio is classified as transmitting, receiving, interfered, free, or parity. A node that initiates a communication session with a quality of service requirement can propagate a channel allocation request along the communication path to the destination. The simulation results in the paper show that the proposed approach performs well in intra-mesh and inter-mesh communications, and it outperforms previous channel allocation schemes [14, 45, 46] in terms of end-to-end throughput.

Athota et al. [47] propose a distributed CA scheme called cluster-based channel assignment (CBCA) that aims at minimizing co-channel interference yet preserving the network topology through non-default CA. Topology preservation is important since it avoids network partitions and is compatible with single-interface routers in the network.

In [48], Cheng et al. propose a channel assignment scheme aiming at minimizing the overall network interference. They formulate an approach for CA based on the particle swarm optimization (PSO) algorithm [49]. Such approach can be used to find the approximate optimized solution in small-size networks. Furthermore, it can be used as a baseline that other algorithms can be compared with. Finally, they propose a centralized and a distributed heuristic algorithm for the CA problem. They compare the performance of their proposed algorithms with a centralized Tabu-based CA algorithm. The simulation results presented in the paper show that the proposed schemes provide high performance in terms of network throughput and fractional interference (the ratio of overall interference number over the overall potential interference number in the network [19]) in both dense and sparse networks.

In [50], Chen et al. address the problem of CA with the constraint that the number of different channels assigned to the links incident on a node must not exceed the number of interfaces the node is equipped with (i.e. the $c \leq r$ approach). They use simulated annealing [51] which is a probabilistic technique for approximating the global optimum of a given function. The first step of their CA algorithm generates random solutions that need not conform to the interface constraint. In the second step, by applying a penalty

function technique, the solutions gradually converge to feasible solutions. This step allows only feasible solutions to be generated during the simulated annealing process.

Over the last decade, many channel assignment algorithms have been developed [6,14–20,31,42,44,47,48,50,52–61]. This has resulted in a wide range of approaches with respect to the network technology, application scenario and network architecture. Because of the variety, existing CA algorithms can be classified according to different key properties. H. Skalli et al. [53] present a comprehensive taxonomy of CA schemes for WMNs. In [62], Wang et al. provide a survey on channel assignment algorithms designed for multicast in MCMR WMNs. Below, we present a major categorization of CA algorithms published so far:

- **Static CA:** These schemes assign channels to interfaces either permanently or for long period of time with respect to the interface switching time [53]. Further, H. Skalli et al. [53] subdivide fixed CA schemes into *common channel assignment* and *varying channel assignment*. Common CA schemes assign the same set of channels to the radio interfaces of each node [30]. For instance, if three interfaces are used at each node, then the three interfaces are assigned to the same three channels at every node. A single channel single radio network is a special case of the static, common channel assignment strategy. In varying CA schemes, interfaces of different nodes may be assigned different sets of channels [18,31,41,42,44,56,59,63].
- **Dynamic CA:** These algorithms allow any interface to be assigned to any channel, and interfaces can frequently switch from one channel to another [28,64]. Therefore,

when nodes need to communicate with each other, a coordination mechanism has to ensure they are on a common channel. The benefit of dynamic assignment is the ability to switch an interface to any channel, thereby offering the potential to use many channels with few interfaces. However, the key challenges involve channel switching delays (typically on the order of milliseconds in commodity IEEE 802.11 wireless cards), and the need for coordination mechanisms for channel switching between nodes [6, 14, 19, 55, 65–67].

- **Centralized CA:** Rely on a central control entity that calculates channel assignment for the whole network; the central control entity is often referred to as channel assignment server (CAS) [6, 31, 57, 68–73]. The CAS gathers network topology information, calculates the channel assignment based on the global network view and notifies the network nodes about the result to adjust their channel assignment accordingly.
- **Distributed CA:** Such an algorithm runs on every network node and executes channel assignment decisions based on local information about neighbour nodes [47, 58, 74–78]. In distributed approaches, the communication overhead for a CAS is not required. However, communication among nodes is still necessary to exchange local information and to notify neighbours about any changes in channel assignment. Distributed algorithms are considered to be less prone to node failures because they do not rely on a CAS which may constitute a single point of failure. Also distributed algorithms are usually more adaptive to a dynamic network topology in

regard to node mobility and node failures, the corresponding topology changes can be handled locally. Still, distributed algorithms lack the advantage of using a global network view for the channel assignment calculations. This may lead to suboptimal results for network-wide channel assignment. F. Juraschek et al. [79] present a detailed study on state-of-the-art distributed channel assignment algorithms.

For the purpose of the research in this thesis, we categorize CA schemes based on the following criteria:

- **Unicast and Multicast** The problem of CA has been studied extensively in the context of unicast communications [6, 14, 15, 31, 52, 80–82] and multicast communications [41, 52, 71–73, 76–78, 83]. In [52], Zeng et al. proposed a CA scheme for multicast in MCMR WMN called Multi-Channel Multicast (MCM). However, it suffers from *hidden channel problem* (HCP) as explained in Section 2.4.4. In [41], the authors propose an algorithm called Minimum-interference Multi-radio Multi-channel Multicast (M4) that resolves the HCP that MCM suffers from.
- **Number of radios per node** Early channel-assignment algorithms enforce the constraint that for each node, the number of channels assigned to that node have to be less than or equal to the number of radios the node possesses [6, 14–20, 50], i.e., $c \leq r$. An example of such CA scheme is illustrated in Figure 2.11(a). In this figure, nodes are equipped with two radios and a total number of four channels are available to be assigned. As shown in this figure, the number of channels assigned to the links in each node is not more than the number of radios: two.

On the other hand, there are also other type of CA schemes that do not impose the above constraint [21–23]. Such CA algorithms assign channels to the links regardless of the number of radios that a node has. In this case, it may happen that the number of assigned channels to the links of a node is more than the number of its radios, i.e. $c > r$.

As indicated in Figure 2.11(b), some nodes are assigned more than two channels, such as node S that is assigned 4 channels. In this case, at least one radio has to switch among assigned channels to compensate for the shortage of radios. There are several ways to divide the radios among assigned channels. For instance, for node S, one possible solution is to let one radio to switch between channels 1 and 2 communicating with M and N, respectively and the other radio to switch between channels 3 and 4 communicating with A and C, respectively. However, no matter how assigned channels are divided among radios, at least one radio has to switch given that the node has two radios and four channels are assigned to the node. However, as explained in 2.6, channel switching has complications and requires enormous amount of coordination among the transmitter and the receivers and, therefore suffers from different type of latencies.

In conclusion, the first approach benefits from simplicity since no channel switching is involved when $c \leq r$.

2.4.2 Channel Assignment and Routing

In a MCMR WMN, channel assignment and routing are two inter-related problems [70]. We clarify this by using an example. In a MCMR WMN, all links do not carry equal traffic loads. In fact, in a typical mesh topology, the traffic to and from the mesh gateways is usually higher than traffic elsewhere in the network. As a general rule, the amount of traffic loads on different links in MCMR depends on the choice of routing protocol and associated routing metric. In this case, choosing an optimal CA that maximizes the network throughput requires a pre-knowledge about a given set of traffic demands and a given routing protocol.

Conversely, finding an optimal routing algorithm based on a given MCMR depends on how nodes are connected together which in turn depends on the CA scheme applied to the network. The reason is that in a MCMR WMN, when a flow is routed over a particular link, the available capacity of that link is reduced as well as the capacity of all other co-channel links within carrier sense range. This is due to bandwidth sharing among all co-channel links within the same carrier sense. As a result, when choosing the optimal routing algorithm that maximizes network throughput, it is important to have a pre-knowledge about the channels that links use for communication. By what mentioned above, it is easy to see that CA and routing problems are inter-dependant

The routing and CA problem can be classified into the following two approaches:

- Separate CA and routing: This approach considers the CA and routing as two separate problems that have to be solved individually and sequentially.

- **Joint CA and routing:** In this approach, both CA and routing are considered as a single problem to be solved. Once solved, the solution to the problem contains the answer for CA and routing at once.

In the following two sub-sections, we describe the above mentioned approaches.

2.4.2.1 Separate Channel Assignment and Routing

Since the CA and routing are considered as two separate problems, depending on which problem is solved first, we have two approaches both of which are applicable to unicast [14, 16, 17] and to multicast [22, 72, 73, 76, 77, 84, 85]. The first approach is called “routing-first, CA-second” wherein routing tables are built first and then a CA scheme is applied on top of the constructed routing tables.

Existing algorithms/protocols based on this approach often assume that routing tables are available in advance and then focus on the CA problem. Further, a node may be assigned more channels than the number of radios it possesses and thus requires channel switching as explained in Section 2.6.

The second approach to addressing the “routing and CA” problem in MCMR WMNs is called “CA-first, routing-second”. In an MCMR network, when a CA scheme has been applied to the network prior to routing, the design and operation of a new routing algorithm should take into account the underlying CA scheme. Given an MCMR network with pre-assigned channels, the goal of CA-first, routing-second based algorithms is to construct routing tables that optimize some objective function.

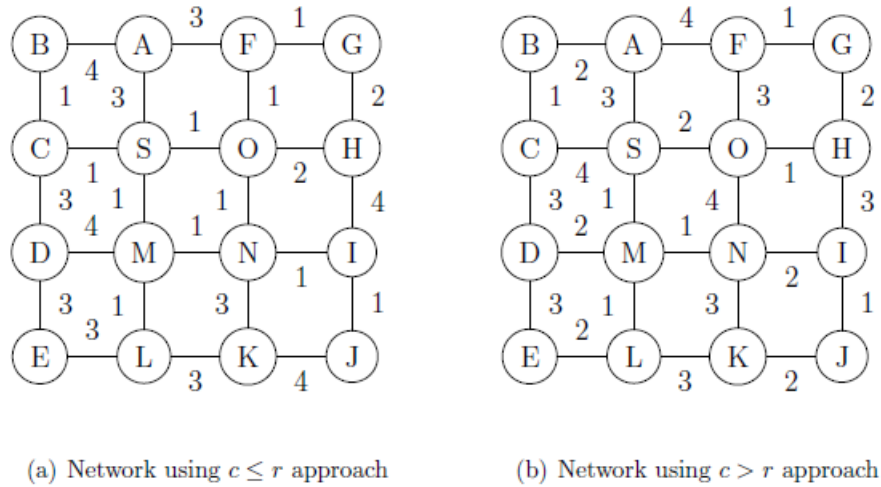


Figure 2.11: Example of two networks using the different CA approaches

2.4.2.2 Joint Channel Assignment and Routing

Since CA and routing problems are inter-dependant, to maximize the network throughput, it is more appropriate to consider the two problems as a joint problem [15, 86–95]. This approach adapts to network conditions and optimizes the CA and routing based on the most recent network information. In [15], Alicherry et al. mathematically formulate the joint channel assignment and routing problem, considering interference constraints, the number of channels in the network, and the number of radios available at each mesh router. They use this formulation to develop a solution for the joint CA and routing problem that optimizes the overall network throughput. To the best of our knowledge, there currently exist no work that quantitatively compares the performance of the three approaches.

2.4.3 Multi-Channel Multicast (MCM)

In this section, we describe in detail MCM [63], the Multicast channel assignment algorithm that use the $c > r$ approach.

MCM considers the interference factor and one-hop neighbours of a node when assigning channel to the node. The interference factor of a node is defined as the ratio of the interference range over the transmission range. The interference range depends on various factors such as the transmission rate, transmission power, antenna gain, antenna height, physical layout of network surroundings, signal reflection and fading. Therefore, measuring the interference factor accurately is usually a complicated task. Zeng et al. [96] describe a simple method for measuring the interference range as follows. Using four wireless routers, the authors established two wireless links (one link between each pair of routers) transmitting simultaneously at a specified transmission rate and then moved the two wireless links far away from each other gradually until they no longer interfered. The distance between the two links at this point is considered as the interference range between them and can be used to compute the interference factor defined above. Using this method, the values of the interference factor with respect to different channel separations, when the transmission rate at the physical layer is 2, 5.5 and 11 Mbits/s in 802.11b system, are listed in Table 2.1.

Before assigning channels, MCM partitions the mesh routers into different levels based on the Breadth First Search (BFS). Then, MCM assigns channels to interfaces of mesh routers in a level-based method starting from the smallest level: the source node. Next,

all of the children of the source node listen on this channel to receive multicast data from source. Following the same algorithm, the whole multicast tree is traversed in BFS order [97]. MCM assigns a channel to a node such that the assignment minimizes interference between the node and its one-hop neighbours who have been previously assigned a channel. Assume that $N(x)$ is the set of one-hop neighbours of node x that have already been assigned a channel. Also, consider that c_x represents the channel assigned to node x and $\delta_{(c_x, c_u)}$ to be the interference factor between two channels c_x and c_u . When assigning a channel to node x , MCM selects a c_x that minimizes the following optimization function:

$$\sum_{\forall u \in N(x)} \delta_{(c_x, c_u)}^2 \quad (2.1)$$

When assigning channel to a node, MCM utilizes all eleven overlapping channels defined in IEEE 802.11b and if more than one channel satisfies the equation 2.1, then MCM chooses one of the solutions randomly. However, MCM has the following limitations:

1. It suffers from hidden channel problem (HCP) which is as follows. Given a multicast tree in Figure 2.12(a) where node S is the multicast source and nodes H, J, K, L are multicast destinations, the corresponding CA outcome generated by the MCM algorithm is shown in Figure 2.12(b). With regard to node E, the set of neighbours is C, F and K. In this case, since node C receives data from node S on channel 1 and is within the transmission range of node E, which also transmits on channel 1,

concurrent transmissions from nodes S and E will collide at C. This channel conflict is called “hidden channel problem” and results from the CA computation at node E in which the channel transmitted by node S, a two-hop neighbour of E, is not taken into account.

2. It relies on the interference factor which makes it inflexible and inefficient.
3. It chooses a random channel whenever there are many choices of channels available, which result in a sub-optimal solution.

Table 2.1: Interference factors

Channel separation	2 Mbits/s	5.5 Mbits/s	11 Mbits/s
0	2.5	2.2	2.0
1	1.6	1.5	1.2
2	1.2	1.0	0.7
3	0.9	0.8	0.5
4	0.5	0.3	0.2
≥ 5	0.0	0.0	0.0

2.4.4 Minimum-interference Multi-radio Multi-channel Multicast (M4)

In this section, we describe in detail M4 [41], a channel assignment algorithm for multicast that uses the $c > r$ approach.

In order to resolve the limitations that MCM suffers from, in [41], the authors proposed the M4 algorithm that offers the optimized CA solutions without using the interference factor. M4 exploits IEEE 802.11b overlapping and non-overlapping channels. The goal of the M4 is to minimize the interference among nodes in a given MCMR WMN. It is applied on a pre-built multicast tree; that is, a routing tree for the multicast group has to be built before M4 is applied. The order that M4 visits the nodes stays the same as MCM (breadth-first-search). However, when assigning channel to nodes, M4 eliminates the use of the interference factor (as opposed to MCM) by defining the following optimization function:

$$F(c_x) = \frac{\prod_{\forall w \in N^*(x)} |c_x - c_w|}{\max_{\forall w \in N^*(x)} |c_x - c_w| \div \min_{\forall w \in N^*(x)} |c_x - c_w|} \quad (2.2)$$

Assuming K to be the set of all channels, the M4 assigns channel $c_x \in K$ to node x such that the value of $F(c_x)$ is maximal. M4 considers one-hop and two-hop neighbours of a node when assigning channels to the node. For instance, as illustrated in Figure 2.12(c), when M4 is assigning channel(s) to node E, all previously assigned channels of one-hop and two-hop neighbours of E are considered; nodes C, F, K, L, S. (Dotted lines are not part of the multicast tree but shown to represent direct connectivity between nodes) The reason for considering two-hop neighbours is to avoid the hidden channel problem.

In cases where there are multiple channels that satisfy Equation (2.2), as opposed to MCM that randomly chooses a channel which in turn can result in a sub-optimal solution, M4 chooses the channel that yields the best result.

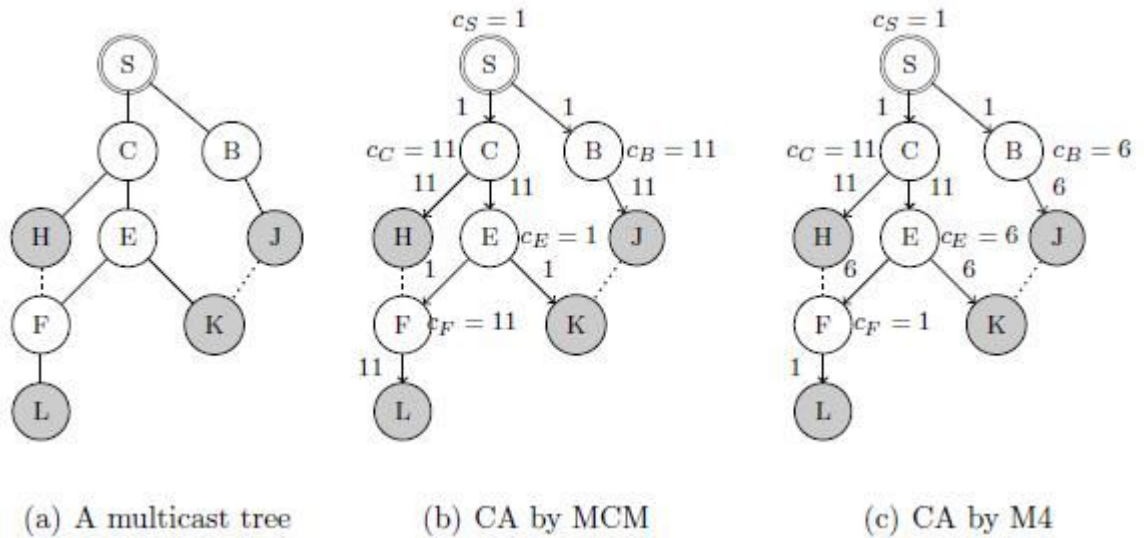


Figure 2.12: Channel assignment by M4 and MCM

2.5 Multicast Routing in MCMR WMN

In this section, we describe the problem of routing in WMNs and review the existing routing algorithms for single-channel and multi-channel WMNs.

2.5.1 Overview

One of the most essential issues of multicast in WMNs is routing. Before sending multicast data, we need a path between a source and each multicast destination through which data packets can be transmitted. The set of such paths rooted from the multicast source is called a multicast tree as illustrated in Fig. 2.13. Therefore, a multicast tree consists of (i) multicast source that generates data packets (ii) forwarders that route the data along the tree toward receivers, and (iii) multicast receivers that belong to the multicast group

and receive the multicast data.

Given a multicast routing algorithm, a routing protocol specifies the actions to be taken and messages to be exchanged in order to build a tree based on the algorithm.

There are three major issues to be addressed by a multicast protocol as follows:

- Route construction, which specifies how a multicast tree is built, i.e., how routes are established.
- Maintenance of the routing tree, which indicates how the tree is updated upon changes such as members joining/leaving and network topology updates due to node mobility or node/link failures
- Data forwarding by multicast relay nodes, which dictates the strategy that relay nodes use in order to forward the data packets.

There are two main route construction approaches: table-driven (proactive) and on demand (reactive). In a table-driven routing protocol, every node maintains consistent, up-to-date routing information to every other node in the network in the form of routing tables. The tables respond to changes in network topology by propagating updates throughout the network in order to maintain a consistent network view. On-demand protocols, in contrast, do not maintain the information of the entire network topology, but only information of active routes. When a node requires a route to a destination, it initiates a route discovery process within the network. This process is completed once a route is found, or all possible routes have been examined.

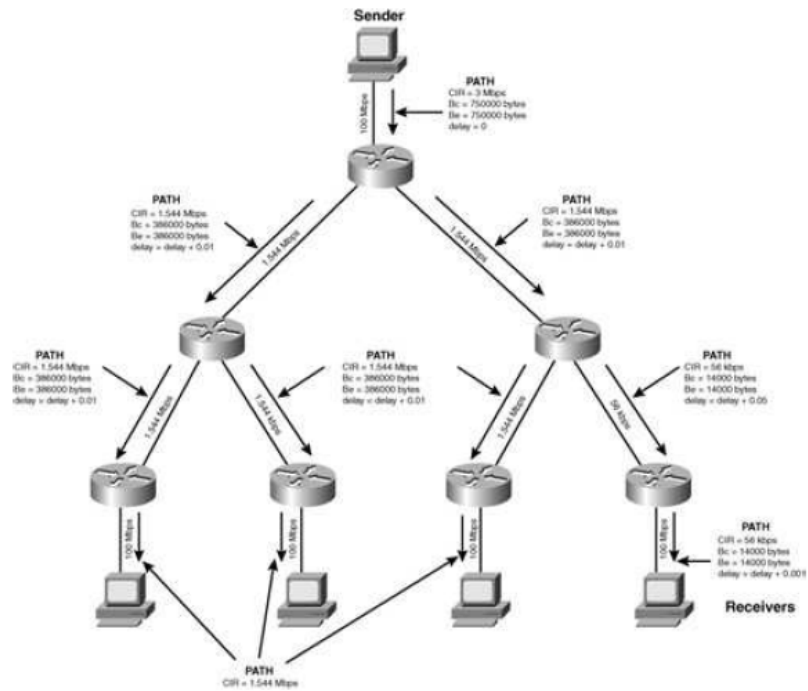


Figure 2.13: Illustration of multicast tree

Table-driven routing is suitable for networks with relatively stable topology and stable network conditions that do not change the routing metric(s) often such as WMN. The majority of Internet routing protocols belong to this category due to static topology (e.g., MOSPF [98], DVMRP [99], GMLL [100]). On-demand routing better responds to dynamic network conditions or frequent topology changes because a path is computed only when it is needed using the current network information. On-demand multicast routing protocols are commonly seen in MANETs (Mobile Ad-hoc Networks) because of their highly dynamic topologies (e.g., ODMRP [101], CAMP [102], MAODV [103], LAMR [92], MDMF [104]).

2.5.2 Multicast Routing in Single-channel WMNs

Multicast routing and performance study of routing approaches in single-channel networks have been the topics of many studies [105–108]. Before reviewing these research, we explain the multicast routing trees that have been applied in these studies. Such routing algorithms are originally applied in Single-Radio Single-Channel WMNs. In our explanations, we consider the following assumptions:

Two nodes are directly connected and form a communication link if they are within the transmission range of each other and share a common channel. We model the network as a connected graph $G = (V, E)$, where V is the set of wireless mesh routers (nodes), and E is the set of communication links (edges). We assume that the connectivity and the channel assignment between any two adjacent nodes are symmetric. That is, if a node u is within the transmission range of a node v , then v is also within the transmission range of u . Finally, in order to support multicast, there is one node $s \in V$ that generates multicast data and there exists a subset of nodes $R \subset V$ that are multicast receivers.

- **Shortest path tree (SPT):** The goal of SPT is to establish a tree that is rooted at s (multicast source) and spanning all the multicast receivers $r \in R$ such that the number of hops between the s and every $r \in R$ along the tree is minimum. One advantage of SPT algorithms is minimum end-to-end delay, a desirable quality of service parameter for most real-life multicast applications. Easy implementation and minimum delay from sender to each receiver, make SPT a better multicast routing approach to be used in the Internet.

- **Minimum cost tree (MCT):** The goal of MCT algorithms is to minimize the overall cost of the multicast tree. An example of an MCT algorithm is the Steiner tree problem. Formally, a Steiner tree is a tree rooted from s and connects s to every receiver $r \in R$ such that the sum of weights of all edges in the tree is the minimum. Computing a Steiner tree is an NP-complete problem and therefore, several heuristics have been proposed to compute the approximate Steiner tree such as the 2-approximation [109] and 11/6-approximation [110] heuristics. Applying Steiner trees for multicast routing in the Internet requires very complex computations due to unknown topology and the large scale of Internet.
- **Minimum number of transmissions tree (MNT):** MNT is a multicast tree rooted from a source s and connects s to every receiver $r \in R$ such that the total number of nodes in the tree is minimum [105]. This definition is based on the wireless broadcast advantage: in a broadcast medium, the transmission of a multicast data packet from a given node to any number of its neighbours can be done by a single data transmission. Thus, in a wireless multi-hop network, the minimum cost tree is the one that connects sources and receivers by issuing a minimum number of transmissions rather than having a minimal edge cost as defined for traditional minimum Steiner trees (MSTs). Also, the authors demonstrated that the problem of computing a MNT is NP-complete and proposed heuristics to approximate such trees [105]. They presented experimental results to show that their MNT heuristics offers the least number of transmissions compared with the MST and the SPT

algorithms in most cases.

In [106], Nguyen presented a simulation based performance comparison of Minimum Cost Tree (MCT) and Shortest Path Tree (SPT) methods of multicasting in WMN. The simulation results showed that SPT algorithms offer better performance to multicast flows than MCT algorithms. In this study, average multicast Packet Delivery Ratio (PDR), average end-to-end delay, average throughput and average delay jitter metrics used to measure the performance of multicast protocols.

In [105], Ruiz et al. study the efficiency of Steiner trees in terms of bandwidth consumption in multi-hop wireless mesh networks. They show that in multi-hop wireless mesh networks, a Steiner tree is no longer offering the lowest bandwidth consumption. They reformulate the problem in terms of minimizing the number of transmissions and show that the new problem is also NP-complete and propose heuristics to approximate such trees. Finally, by using simulations, they show that the proposed heuristics offer a lower cost than Steiner trees over a variety of scenarios.

In [106], Nguyen conducts a simulation based study to compare the performance of SPTs, MSTs and MNT trees in WMNs using most concerned performance metrics such as packet delivery ratio, throughput, end-to-end delay, delay jitter and multicast traffic overheads. Based on the results obtained from simulations, this work provides insights into the performance of multicast routing algorithms in WMNs and recommendations for suitable routing approaches.

In [108], Roy et al. study the routing metrics for multicast in high-throughput net-

works. In this work, they adapt certain unicast routing metrics for high-throughput multicast routing and propose new ones not previously used for high-throughput. Finally, they study the performance improvement achieved by using different link-quality-based routing metrics via extensive simulation and experiments on a mesh network testbed, using ODMRP [101] as a representative multicast protocol.

In [100], Yuan et al. propose a multicast routing tree based on bandwidth capacity of the links. Based on this architecture, they provide a model to pre-estimate the bandwidth capacity of links in WMN. Based on this algorithm, links with better bandwidth conditions are contributed when building the multicast tree. The proposed routing algorithm, called Gateway Assisted Multicast Algorithm towards Low Latency for Wireless Mesh Networks (GAMLL), benefits from shorten latency; therefore, it can be applied to real-time applications such as streaming media services and VoIP. The authors' simulation results show that the GAMLL performs better for VoIP and video transmission services than the On-Demand Multicast Routing Protocol (ODMRP) [111] in terms of average latency and maximum latency. ODMRP has lower latency for VoIP and media streaming when compared to other proven routing protocols [100]. Compared to ODMRP, GAMLL reduces the average latency and maximum latency by up to 28% and 52%, respectively.

In [104], Kumar et al. propose a new multicast routing algorithm which has maximum traffic flow and minimum delay under capacity constraints. They formulate the problem of multicast as a linear programming problem with associated constraints and define a cost function to choose the least loaded route among the available ones. Finally,

they propose a Minimum Delay Maximum Flow (MDMF) multicast routing algorithm to solve this problem using the proposed cost function and associated constraints. As part of their work, they compare the performance of their proposed algorithm with other well-known algorithms [101, 112] with respect to packet delivery ratio latency, and network throughput. Their simulation results show that their proposed algorithm has lower numbers of transmissions, higher throughput, higher packet delivery ratio and shorter latency compared to other well-known algorithms.

In [113], Yang et al. focus on constructing a multicast tree with zero-interference in a MCMR WMN considering the delay and energy constraints. They use an optimization technique with the objective of maximizing the number of multicast receivers that can be added to the multicast tree. This problem is known as the EDMRM problem (Energy-Delay-constrained and Maximum-Revenue-based Multicast) and is NP-hard. To solve the problem, they first propose an optimal algorithm based on Integer Linear Programming (ILP). Since the ILP-based method can only be applied in small-scale networks, they also provide a tabu-based heuristic algorithm to be used in practical networks which consist of a large number of nodes.

In [114], Papageorgiou et al. propose an optimal algorithm for the problem of least expected number of transmissions for multicast routing in WMNs. They apply graph theory and transform the network graph into an expanded graph that simplifies the point-to-multi-point transmissions in the original network graph into point-to-point transmissions in the expanded graph. Next, they calculate the weights of the expanded graph links

and include the wireless unreliable transmission characteristics of the wireless medium. Finally, by solving the Steiner tree problem for the expanded graph, they obtain the optimal solution to the original network graph. Because the optimal solution is NP-hard, they propose a heuristic algorithm.

2.5.3 Multicast Routing in MCMR WMNs

One of the most efficient methods to increase the overall network throughput in WMNs is to use multiple channels and multiple radios for each node. However, traditional multicast routing algorithms such as SPT (Shortest Path Tree) or MCT (Minimum Cost Tree) do not consider the potential of wireless broadcast communication, multiple channels or multiple radios.

Multicast routing in MCMR WMNs has been the topic of many studies [100, 104, 113–120]. Despite state-of-the-art CA algorithms that minimize interferences in MCMR WMNs, there are still other unsolved issues in such networks. For example, the distribution of traffic load in WMNs is mostly unbalanced, which leads to sub-optimal multicast trees. By distributing traffic among the nodes fairly, the number of transmissions among nodes decreases and, as a result, the interference between channels will decrease, too. In [116], Avock et al. propose the on-demand Load-balanced Multicast Tree Routing (LMTR) algorithm which provides balanced multicast trees using the new dynamic cost functions proposed in their work. When congestion happens in part of the network, LMTR does not route the traffic to that part and balances the traffic by using a load-

aware routing mechanism. Also, LMTR fairly distributes the traffic among the nodes, which reduces the interference. Further, it minimizes the number of transmissions in a MCMR WMN and prevents routing blockage on nodes by decreasing the traffic load in mesh routers, especially those that are close to the gateways.

In [117], Farzinvasht et al. propose the Bandwidth Guaranteed Minimum Cost Tree construction algorithm (BGMCT) that minimizes the total amount of bandwidth consumed by a multicast group in MCMR WMNs. Their algorithm exploits the Wireless Broadcast Advantage (WBA) property of the wireless medium and therefore yields cost effective solutions. They develop two strategies when constructing the minimum cost trees. First, they minimize the number of the relay nodes in each tree. Second, they consider the amount of overlapping between the shortest paths, which connect different destinations to their source node. Their simulation results show that the BGMCT algorithm outperforms existing solutions [116, 121, 122] in terms of bandwidth consumption and maximum load of channels. Moreover, BGMCT provides near optimal outcomes in a reasonable amount of time.

In [118], Karimi et al. address the problem of interference and bandwidth limitation of wireless channels that adversely affect multicast performance in MCMR WMNs. They use multiple mesh gateways in their work instead of a single mesh gateway and apply a CA scheme that applies the IEEE 802.11b eleven overlapping channels. The goal of the CA proposed is to minimize the interference among the nodes in MCMR WMNs. They jointly solve the problem of channel assignment and routing by using a primal-dual

optimization technique.

In [119], Avokhet al. focus on the problem of resource constraints that the multicast throughput suffers from in MCMR WMNs. They propose an analytical model based on on-demand multicast sessions and formulate the network resource utilization during each multicast session. During their analysis, they involve the CA scheme and also consider the wireless broadcast advantage and the interference constraint. The advantage of their proposed model is that it is independent of the type of multicast tree built for each session. Finally, they present a comprehensive discussion to evaluate the effects of load-balancing and number of transmissions on the network throughput.

In [41], the authors address the problem of building multicast routing trees with minimum number of transmissions in MCMR WMNs. The proposed algorithm is called MCMNT (Multicast with Minimum Number of Transmissions) and is proved to be NP-hard. Therefore, the authors propose heuristics that approximate the solution. As opposed to SPT and MCT that do not consider multi-radio and multi-channel property of nodes, MCMNT is specifically designed to work with multi-radio multi-channel networks assuming that a CA scheme is independently applied to the network beforehand. Also, the number of distinct channels assigned to a node has to be less than or equal to the number of its radios and, therefore, no channel switching is expected. Below, we describe the MCMNT algorithm by using an example followed by its formal definition.

The MCMNT Algorithm

Consider the MCMR network shown in Figure 2.14. Assume that the network is using three orthogonal channels and each node has two radios. The number associated with each link indicates the channel assigned to that link by a CA algorithm.

Assume the multicast group with source S and six destinations B, G, I, L, N and O (shaded nodes) as illustrated in Figure 2.14. The tree nodes are connected by the thick arrows whose directions indicate the data flow in a routing tree. The originating node of each arrow is called a forwarding node. The source node S is considered a forwarding node and a multicast receiver may be a forwarding node such as nodes N and O .

The problem focuses on the number of transmissions a forwarding node requires to multicast a packet to its one-hop neighbors in the routing tree. In single-channel systems, only one transmission is needed. However, in multi-channel systems, a forwarding node may need more than one transmission due to the channel diversity.

In Figure 2.14, we show two possible routing trees T_1 and T_2 for this multicast group. In this figure, each link is labelled with the assigned channel. In tree T_1 (Figure 2.14(a)), N has to transmit two copies of every packet (i.e., two transmissions), one on channel 1 to I and the other on channel 3 to K , which will forward the packet to L . On the other hand, in tree T_2 (Figure 2.14(b)), N needs to perform only one transmission on channel 1 to reach both I and M , which will forward the packet to L . This example shows that the choice of route affects the number of transmissions a node has to perform to forward a data packet.

If we sum up the numbers of transmissions that all forwarding nodes in a routing tree need to perform to deliver a packet to their multicast neighbors, the result is the total number of transmissions the tree incurs to deliver a packet from the source to all the destinations, denoted by $S(T)$. For the example trees T_1 and T_2 in Figure 2.14, $S(T_1) = 9$ while $S(T_2) = 6$. Tree T_2 is therefore preferred because it requires less transmissions per packet and thus consumes less network bandwidth. Among all possible trees connecting the source to the destinations, our goal is to find a tree with the minimum $S(T)$.

Note that the term *transmission* refers to the original transmission of a copy of a packet. In the computation of the number of multicast transmissions, re-transmissions caused by packet losses or errors are not counted due to the lack of an acknowledgement mechanism at the MAC layer in the current IEEE 802.11 standards [123].

Below, we describe the MCMNT algorithm formally:

Given C as the set of available channels in the network and Λ as a channel assignment algorithm that maps each link in E to a channel in C .

$$\begin{aligned} \Lambda : E &\rightarrow C \\ e &\mapsto \Lambda(e) = c \in C \end{aligned}$$

Let E_Λ be the set of corresponding links after Λ has been applied to E .

$$E_\Lambda = \{(e, \Lambda(e)) : \forall e \in E, \Lambda(e) \in C\}$$

Assume $G_\Lambda = (V, E_\Lambda)$ to be a graph representing a MCMR WMN and Λ as its channel assignment algorithm. Considering that S is the multicast source and $R \in V$ is

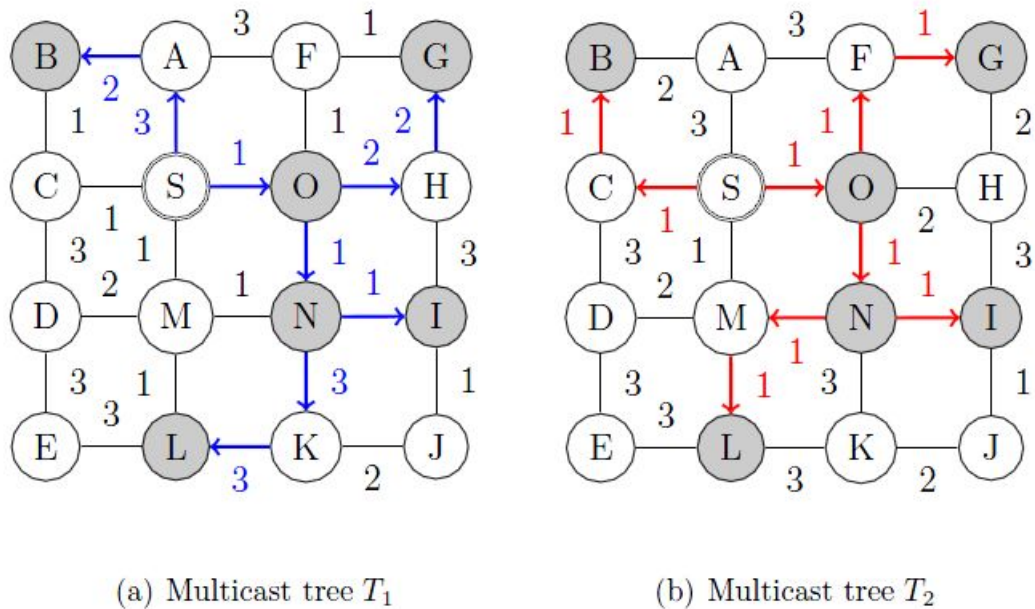


Figure 2.14: A network with two different multicast routing trees

a set of multicast destinations, the MCMNT problem is to find a multicast routing tree connecting s to all destinations in R such that the total number of transmissions required to deliver one packet from s to the destinations is minimum.

As mentioned earlier, MCMNT is proved to be NP-hard, therefore, heuristic values are used to approximate the solution. The heuristic value associated with a link (u, v) is calculated as follows:

$$w(u, v) = \frac{\mu_v(c)}{\mu_u(c)} \tag{2.3}$$

where $\mu_u(c)$ denotes the number of links that are incident on u and assigned channel c . $\mu_u(c)$ can be considered as the “channel utilization” of channel c by node u . The higher the value, the more neighbours u can reach with a single transmission on channel c . Once

the heuristic values are associated to the links, the algorithm establishes the tree starting from the source node s . Initially, the initial solution tree consists of only the source, s . Multicast destinations are then added to the tree one by one using the least cost path from each destination to the current tree.

MCMNT is designed based on the following two assumptions:

- First, the channels are orthogonal (non-overlapping).
- Second, the number of distinct channels assigned to a node has to be less than or equal to the number of its radios ($c \leq r$).

2.6 Channel Switching

When the number of assigned channels to a node is greater than the number of radios for that node ($c > r$), at least one radio has to switch among the assigned channels. In order to clarify this further, we use the following example taken from [41]. Consider a link (A,B) in an MCMR network with $r = 2$ and $c = 4$, as shown in Figure 2.15. Assume that each node is equipped with two radios r_1 and r_2 , and there are currently two unicast flows u_1 and u_2 between A and B that are assigned channels 1 and 2, respectively. Suppose that we use radio r_1 for flow u_1 on channel 1, and radio r_2 for flow u_2 on channel 2. Two multicast flow m_1 and m_2 then join the network. Suppose that link (A,B) is included in both multicast trees rooted at the two sources. It may happen that channel 3 is chosen as the best channel on link (A,B) for multicast flow m_1 , and channel 4 is assigned to multicast flow m_2 on link (A,B). Node A now has to switch two radios among four

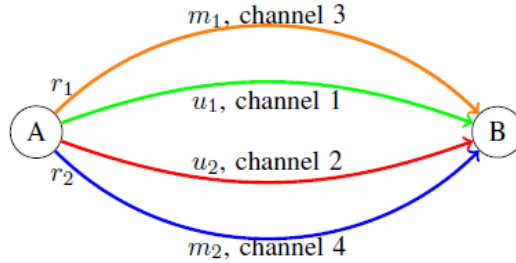


Figure 2.15: Channel switching

channels (or more, if new flows later join the network). There are several ways to divide the radios among the flows. However, at least one radio has to switch among multiple flows, given that $r = 2$ and $c = 4$. Assume that radio r_1 serves flows u_1 and m_1 while radio r_2 serves flows u_2 and m_2 . Before each transmission using radio $r_1(r_2)$, A has to tell B the channel on which B has to listen, either channel 1 or 3 (either channel 2 or 4). B then switches the radio to the specified channel waiting for the data packet.

As it can be seen in this example, existence of a channel switching scheme is necessary to synchronize the nodes about the channel on which data is sent or received. Currently, there exist several channel switching algorithms [10–13, 65], however, they do not work with multicast.

As part of their work, in [10], Kayasanur et al. propose a new channel switching protocol. They assume that there are at least two interfaces dedicated at each node and are divided into fixed interfaces and switchable interfaces. Fixed interfaces are assigned channels for long intervals of time while the switchable interfaces switch to other channels over short time scales. The main idea here is to receive data using the fixed interface

and to send data using the switchable interface. Each channel is associated with a packet queue from which the packets are taken and transmitted on different channels(see Figure 2.16). The maximum number of queued packets transmitted on every channel and before switching to another channel is equal to $BurstLength$. Furthermore, the switchable interfaces cannot remain on a channel more than $MaxSwitchTime$ seconds before switching to another channel. The advantage of their protocol is that a sender and a receiver do not require to synchronize for channel switching and therefore, a coordination algorithm is not needed.

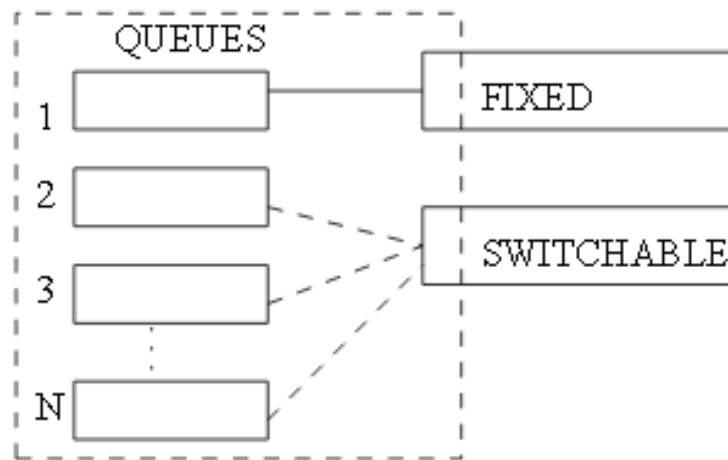


Figure 2.16: Illustration of queues associated with interfaces

In [65], Wu et. al. propose a new multi-channel MAC protocol for wireless mobile ad hoc network (MANET) that uses a Dynamic Channel Assignment algorithm (DCA).

In their work, each mobile host is assumed to have two transceivers. The overall bandwidth is divided into one control channel and n data channels, each of which having equal bandwidth. The control channel is used to resolve the contention on data channels and assign data channels to mobile hosts. For every node, one of the transceivers is called the *control transceiver* and operates on the control channel to exchange control packets with other mobile hosts and to obtain rights to access data channels. The other transceiver dynamically switches to one of the data channels and transmits data packets and acknowledgements. The main idea of their protocol is as follows. For a mobile node A to communicate with node B, A sends an RTS (Request To Send) to B carrying the free channel list of A. Next, B will match the channel list with its own channel list and identify a data channel (if any) to be used in their subsequent communication. Then, B sends this data channel through a CTS (Clear To Send) message to A. On receiving B's CTS, A notifies A's potential senders of the selected channel and inhibits them from using the same channel. All these communications happen on the control channel and finally, both A and B switch to the chosen channel and a data packet will be transmitted on the data channel.

In [11], Jain et al. propose a new multi-channel MAC protocol for multi-hop wireless networks that uses multiple channels and a dynamic channel selection method. They address the ineffectiveness of Carrier Sense Multiple Access (CSMA) in wireless medium. Propagation path loss in wireless medium causes a signal to lose power as it travels. Therefore, different neighbour nodes receive the signal at different power levels. Their

proposed algorithm divides the available bandwidth into one dedicated control channel and a predefined number of channels for data communication that is fewer than the number of nodes. The transmitter uses an exchange of RTS/CTS on the control channel to choose the best channel to send the data packet on. The best channel is selected based on the signal-to-interference plus noise ratio at the receiver side. The main objective of the protocol is to distribute the packet transmissions over time and channels, therefore, maximizing bandwidth utilization.

In [28], So et al. propose a MAC protocol that enables hosts to utilize multiple channels by switching channels dynamically and therefore, increasing network performance. The protocol requires only one transceiver per host; therefore, it can be implemented with hardware compatible to IEEE 802.11. Using simulations, they compare the performance of their scheme with a dynamic channel assignment algorithm that is explained in this work. As the simulation results show, their protocol improves network throughput significantly, especially when the network is highly congested. This work is based on an ad hoc network that does not rely on infrastructure. Therefore, it does not require a central entity for channel management. This scheme works based on time slots and requires clock synchronization among all nodes. At the start of each time slot, all nodes listen to a common channel in order to exchange traffic indication messages. During this interval, nodes do not exchange data packets and therefore this period is considered as overhead of this scheme. What distinguishes this work from the related works mentioned above is that it requires only one transceiver per host, but still solves the hidden terminal

problem in a multi-channel environment.

At first glance, the $c > r$ channel assignment approach may be perceived as a better approach than the $c \leq r$ approach, since the former provides more channels to be used in comparison with the latter and hence, potentially lowering the amount of interference around nodes in MCMR WMN. However, channel switching comes with corresponding complexities, computations and delays which are not negligible [80, 124]. To the best of our knowledge, no study has been performed previously to consider the latencies of channel switching in MCMR WMN. Also, there has not been any research that compares the network throughput achieved when using the two approaches: $c > r$ and $c \leq r$.

In this thesis, we consider evaluating the effects of channel-switching overheads on the performance of multicast in a MCMR WMN.

2.7 Chapter Summary

This chapter presented an overview of wireless communications followed by definitions and terminologies about wireless networking. We described single-channel single-radio networks along with its key limitation and maximum throughput capacity. Then, we discussed Multi-Channel Multi-Radio Wireless Mesh Network (MCMR WMN) as an alternative to increase the throughput capacity. We reviewed existing channel assignment, multicast routing and channel switching algorithms.

Chapter 3

Performance of the M4

Algorithm: Orthogonal vs.

Overlapping Channels

Zeng et al. [84] and Nguyen [125] originally designed the MCM and M4 channel assignment algorithms, respectively, with overlapping channels in mind. However, could the algorithms perform as well or even better with orthogonal channels? The research presented in this chapter aims at answering this question.

At first glance, it is easy to see the trade-offs between eleven overlapping channels and three orthogonal channels in an IEEE 802.11b network. The 11-channel option provides more channel choices for assignment, potentially reducing channel conflicts and thus interference. However, there could potentially be adjacent-channel interference among channels assigned because they can be overlapping. In a 3-channel network, there will

be no adjacent-channel interference because all the channels used are non-overlapping. However, the number of available channels for assignment is lower, three vs. eleven, hence more channel conflicts.

In this chapter, we present a simulation-based study of the performance of M4 algorithm with overlapping channels and orthogonal channels under various network settings. In all simulations, we use SPT (Shortest Path Tree) as the multicast tree. Next, we apply the M4 algorithm to assign channels to the multicast links/edges in the tree (i.e., using the routing-first, CA-second approach). We first describe the simulation parameters and performance metrics in Sections 3.1 and 3.2, respectively. We then discuss the simulation scenarios and results in Sections 3.3 and 3.4, respectively.

3.1 Simulation Parameters

We simulated a medium-size and a large-size network consisting of 49 and 100 nodes, respectively. The nodes are uniformly distributed in a $1200\text{m} \times 1200\text{m}$ area and a $1700\text{m} \times 1700\text{m}$ area for the medium and large-size network, respectively. Figure 3.1 illustrates one example topology of a medium-size network with 49 nodes (represented by the circles) uniformly distributed in the area. The transmission power and the transmission range of wireless routers are 20dBm and 315m, respectively, according to the specifications of wireless routers manufactured by Tropos [126]. The data transmission rate at the physical layer is 11 Mbps. The IEEE 802.11 CSMA/CA protocol without RTS/CTS exchange is the medium access control protocol for multicast transmissions as explained

in Section 2.2.

In our simulations, we use two radios per node (as done by the M4 channel assignment algorithm proposed in [41]), one to send and the other to receive multicast data packets (although a node may have more than two radios).

At the transport layer, we do not use any flow or congestion control mechanisms in order to test the network performance under very high loads. The multicast group has one source placed at the centre of the network, while the destinations are randomly selected. We assume that each source or destination is connected to a different wireless mesh router. That is, a multicast group with d destinations consists of d destination routers and one source router, since we are interested in the multicast performance of routers in the mesh backbone. All destinations joined a multicast group at the beginning and stayed until the end of the simulation. In each experiment, the source transmits at a specified constant bit rate (CBR) for 600 seconds of simulated time. The simulator then continues to run for 100 seconds of simulated time to give the last packets time to be routed. Each data point in the graphs is averaged from 50 runs using different network topologies and random seeds, and plotted with a confidence interval of 95%.

We use the two-ray propagation model [127] when the distance between two nodes is 250 m or more. Otherwise, we use the free space model to avoid the oscillation caused by the constructive and destructive combination of the two rays over short distances. The above distance threshold for switching between the two models is specified by the QualNet software [128].

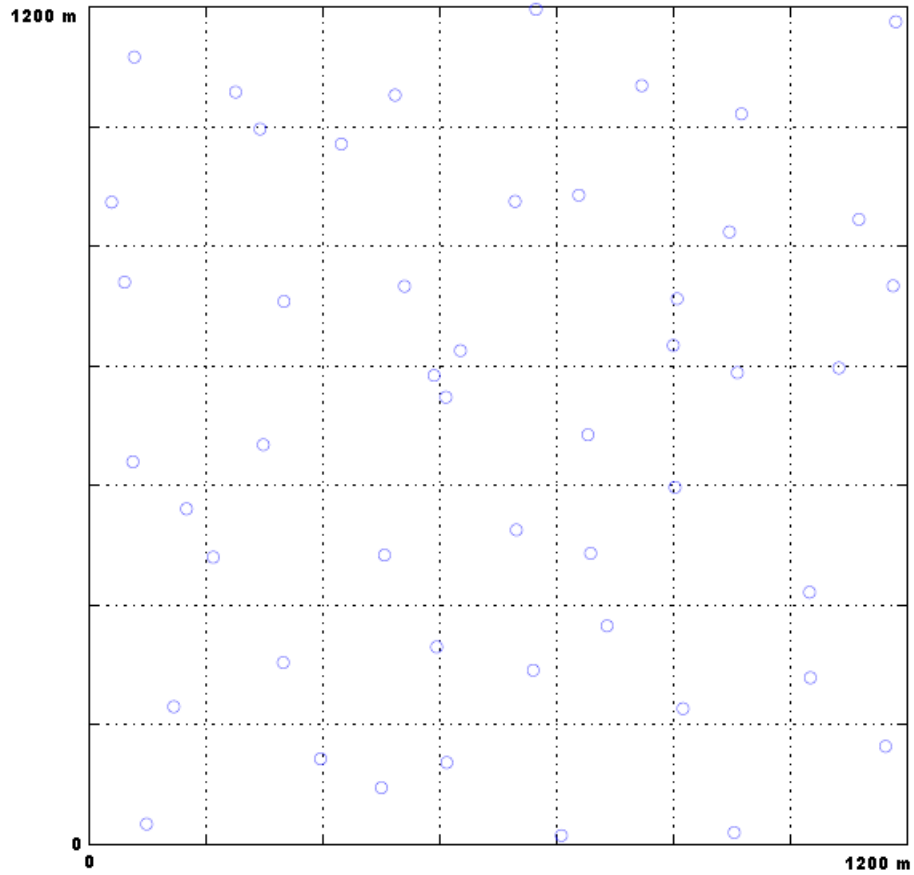


Figure 3.1: Node placement with 49 nodes in a 1200m \times 1200m area

The size of data packets is 512 bytes excluding the header. The size of the queue at every node is 50 Kbytes. Also, packets in a queue are scheduled for transmission on a first-in-first-out basis.

The parameters common to all experiments are summarized in Table 3.1.

Table 3.1: Common simulation parameters

Parameter	Value
Network size	49 nodes in a 1200m x 1200m area 100 nodes in a 1700m x 1700m area
Path loss model	free source for distances shorter than <250m two-ray for distances longer than >250m
Fading model	non
Transmission range	315m
Transmission rate at physical layer	11 Mbits/s
Physical layer protocol	PHY802.11b
Medium access control	MAC 802.11 with DCF
MAC for multicast flow	CSMA/CA
Packet size (excluding header size)	512 bytes
Queue size at routers	50 Kbytes
Queueing policy at routers	first-in-first-out
Traffic model of sources	constant bit rate (CBR)
Duration of each experiment	600 seconds of simulated time
Number of runs per data point	50
Confidence interval	95%

3.2 Performance Metrics

We use the following performance metrics:

- **Average packet delivery ratio.** The packet delivery ratio (PDR) of a destination in the multicast group is the number of data packets actually delivered to the destination over the number of data packets sent by the source. The average PDR of a multicast group is the average of the PDRs of all the destinations in the group. This measures the delivery reliability of a multicast protocol.
- **Average end-to-end delay.** The end-to-end delay (EED) of every packet received at every destination is recorded; the average over all the packets correctly received is then computed. This metric is important in real-time interactive applications such as on-line multi-player games and audio/video conferencing.
- **Average throughput.** The throughput of a destination is defined as the total number of data packets a destination actually receives divided by the time between the receipt of the first packet and the last packet. The average taken over all the destinations is the average throughput of the multicast group.
- **Average delay jitter.** Delay jitter is the variation (difference) of the inter-arrival intervals from one packet received to the next packet received. Each destination calculates the average delay jitter from the received packets. The average delay jitter is the average of the per-destination delay jitters taken over all the destinations. This is an important metric in audio/video applications and lower jitter values

result in better quality of service.

3.3 Experiment Scenarios

We divide all experiments into two sets: (i) those with three orthogonal channels and (ii) those with eleven overlapping channels. For each set, we run the simulations for two different network sizes: 49 nodes and 100 nodes. For each set, we conduct several experiments and measure the above performance metrics as functions of:

- *Multicast traffic load.* The multicast source rate at the application layer varies from 100 to 350 packets/sec. The multicast groups consist of 30 and 50 destinations in the 49-node and 100-node networks, respectively.
- *Multicast group size.* The number of multicast destinations varies from 10 to 40 in the 49-node network and from 10 to 70 in the 100-node network. The source transmits at a rate of 250 packets/sec and 200 packets/sec in the 50-node and 100-node networks, respectively. The source rates were chosen so that we can observe the performance degradation as the group size increases, and the PDRs still stay at acceptable values (e.g., above 60%).

A summary of the parameters of the above simulation scenarios is shown in Table 3.2.

3.4 Experimental Results

In this section, we discuss and analyze the results that we obtained from our simulations.

Table 3.2: Parameter setting for the simulations

Function of	Parameters	49-node network	100-node network
Multicast source rate	source rate	100 to 350 packets/s	
	group size	30 nodes	50 nodes
Multicast group size	source rate	250 packets/s	
	group size	10 to 40 nodes	10 to 70 nodes

3.4.1 Function of Multicast Traffic Load

In this set of experiments, the sender’s rate varies from 150 to 350 packets/s. The size of the multicast group in the 49-node and 100-node networks are 30 and 50, respectively. The results are illustrated in Figures 3.2 and 3.3.

The results show that as the traffic load increases, the average PDR decreases (see Figures 3.2(a) and 3.3(a)). The reason is that higher medium contention and more interference (both co-channel and adjacent-channel) result from higher traffic loads. However, in the network with three orthogonal channels, as traffic load increases, the average PDR drops more rapidly in comparison with the network using eleven overlapping channels. The reason is that in the network with three orthogonal channels, each channel is shared by more nodes than in the 11-channel network, which leads to higher medium contention and co-channel interference. Therefore, the PDR reduces faster in the 3-channel network. Specifically, when the traffic load is 300 packets/s, the PDRs of the 100-node network when using overlapping channels and orthogonal channels are 63% and 50%, respectively,

a difference of 13% (Figure 3.3(a)).

The results for average end-to-end delay under different traffic conditions are illustrated in Figures 3.2(b) and 3.3(b). As the traffic load increases, the average end-to-end delay increases due to higher medium contention and longer queues in routers. However, in the network with three orthogonal channels, the contention on each channel is higher in comparison with the network using eleven overlapping channels (due to a higher level of channel sharing mentioned above). In particular, in our 100-node network, when the traffic load is 350 packets/sec, the average end-to-end delay for the cases of overlapping channels and orthogonal channels is 0.05 s and 0.14 s, respectively (see Figure 3.3(b)).

Figures 3.2(c) and 3.3(c) illustrate the simulation results for the average throughput. In both 100-node and 49-node networks, as the traffic load increases, the throughput for both cases increases. However, when three orthogonal channels are used, the growth rate of throughput is slower than in the case where eleven overlapping channels are used. The reason is higher contention and more co-channel interference that occur in the network using three orthogonal channels. Specifically, in the 100-node network, when the traffic load is 350 packets/sec, the average throughput for the cases where overlapping and orthogonal channels are used is 0.894 Mbps and 0.637 Mbps, respectively (see Figure 3.3(c)).

Figures 3.2(d) and 3.3(d) correspond to simulation results for the average jitter. As illustrated in these figures, with the traffic load increase, the average jitter increases. However, the network that uses three orthogonal channels offers higher values of jitter in comparison with the one that uses eleven overlapping channels. The reason is higher

medium contention due to more channel sharing in the network that uses three orthogonal channels.

In summary, in both 49-node and 100-node networks, as the traffic load increases, the PDR decreases and the throughput, average end-to-end delay and jitter increase. The higher the traffic load, the more medium contention and interference among nodes. However, the performance of the network using three orthogonal channels degrades at a faster rate in comparison with the same network using eleven overlapping channels. The reason is that in a network with three orthogonal channels in use, more nodes share a channel, which leads to higher interference and higher medium contention in comparison with the same network using eleven overlapping channels. In conclusion, given the same routing tree and CA scheme, using eleven overlapping channels along with an intelligent CA scheme provides better performance than using three orthogonal channels. (This conclusion is no longer true if a different routing or CA algorithm is used, as will be shown in Chapter 5.)

3.4.2 Function of Multicast Group Size

In the 49-node and 100-node network, the multicast group size is varied from 10 to 40 and from 10 to 70, respectively. The multicast source rate is set to 250 packets/sec. The results for this set of experiments are given in Figures 3.4 and 3.5.

The graphs in Figures 3.4(a) and 3.5(a) indicate that using eleven overlapping channels provides better PDR than using three orthogonal channels. For instance, in the

49-node network, when the number of receivers is 40, the average PDRs are 77% and 67% when overlapping and orthogonal channels are used, respectively. As the multicast group size increases, the PDR has a slight increase when overlapping channels are used while the PDR goes down when orthogonal channels are used. This can be explained as follows. In a multicast routing tree, each forwarder acts as a relay that forwards any new multicast packet it receives. The number of forwarders in a routing tree grows with the multicast group size. Having more forwarders in both networks increases the PDR because of the overhearing effect explained in Section 2.1. However, in the case of three orthogonal channels, the improving effect of overhearing is negated by the increase in medium contention and co-channel interference that occurs among nodes. Therefore, the PDR in the network using three orthogonal channels goes down as the multicast group size increases, as illustrated in Figure 3.4(a).

Figures 3.4(b) and 3.5(b) illustrate the results for the average end-to-end delay. As the multicast group size increases, the average end-to-end delay increases rapidly when three orthogonal channels are used due to higher medium contention within a channel. When eleven overlapping channels are used, the situation is better: more channels are shared, hence, lower medium contention. Therefore, the end-to-end delay does not increase much as the multicast group size grows. Specifically, in the 100-node network with a multicast group of 70 destinations, the average end to end delay values for the two cases (three orthogonal channels and eleven overlapping channels) are 0.15 s and 0.04 s, respectively.

Figure 3.4(c) and 3.5(c) illustrate the results for the average throughput. In the 49-

node network, as the multicast size grows, the throughput of the network that uses eleven overlapping channels increases. The explanation is that the throughput is a function of PDR and end-to-end delay as defined in Section 3.2. Therefore, as the multicast group size grows, with an almost constant end-to-end delay and increasing PDR, the throughput increases as a result. For instance, in the 49-node network using eleven channels, as the multicast group size goes up from 10 to 40, the average throughput increases from 0.86 Mbps to 0.9 Mbps. As for the network that uses three orthogonal channels, as the multicast group size grows, the average end-to-end delay increases and the PDR decreases; therefore, the throughput decreases. For example, when three channels are used, the average throughput decreases from 0.82 Mbps to 0.7 Mbps.

In the 100-node network, when either three or eleven channels are used, as the multicast group size increases, the average PDR goes down and the average end-to-end delay increases and as a result, the average throughput decreases. Specifically, in the network with eleven overlapping channels, as the multicast group size varies from 10 to 70, the average throughput decreases from 0.79 Mbps to 0.74 Mbps. In the same situation, when using three orthogonal channels, the average throughput goes down from 0.76 Mbps to 0.59 Mbps.

The results for the average jitter are presented in Figures 3.4(d) and 3.5(d). The results show that in both 49-node and 100-node networks, as the multicast group size increases, the average jitter values increase, and the network that uses eleven overlapping channels offers lower values of average jitter. The reasons are the same as those given

above for the average end to end delay.

In conclusion, the network using eleven overlapping channels performs better than the network using three orthogonal channels given the same routing tree and CA scheme.

Readers may note that when using overlapping channels, in the 100-node network, as multicast group size increases, the PDR has a slight decrease as opposed to the 49-node network in which the PDR increases (see Figures 3.5(a) and 3.4(a)). This can be explained as follows. In the 100-node network, paths from the source to destinations are longer than those in the smaller network (see Tables 3.3 and 3.4). As the path between a source and a destination becomes longer, the probability that a packet will be lost on the path increases. We call this the negative effect of path length on the PDR.

On the other hand, as the multicast group size increases, more forwarders are added to the multicast routing tree. More forwarders enhance the overhearing effect, defined in Section 2.1, a factor that can potentially improve the PDR. In the 100-node network, the negative effect of long paths on the PDR outweighs the positive effect of overhearing. Therefore, as the multicast group size increases, the PDR decreases in the 100-node network.

3.5 Chapter Summary

In this chapter, we present a simulation-based study on the performance of multicast in MCMR WMNs under two channel configurations: eleven overlapping channels and three orthogonal channels as defined in IEEE 802.11b. We created various simulation scenar-

Table 3.3: Path lengths in the 49-node network

Multicast Group	Average Path Length
10	2.04
20	2.01
30	2.00
40	2.1

Table 3.4: Path lengths in the 100-node network

Multicast Group	Average Path Length
10	2.81
30	2.82
50	2.79
70	2.79

ios with different configurations. Specifically, we varied the traffic load and multicast group size and measured the average PDR, throughput, jitter and end-to-end delay. The simulation results indicate that using eleven overlapping channels offers higher multicast performance than using three orthogonal channels, assuming the same multicast trees and the M4 CA algorithm. As a result, in the subsequent chapters, we use eleven overlapping channels with the M4 algorithm.

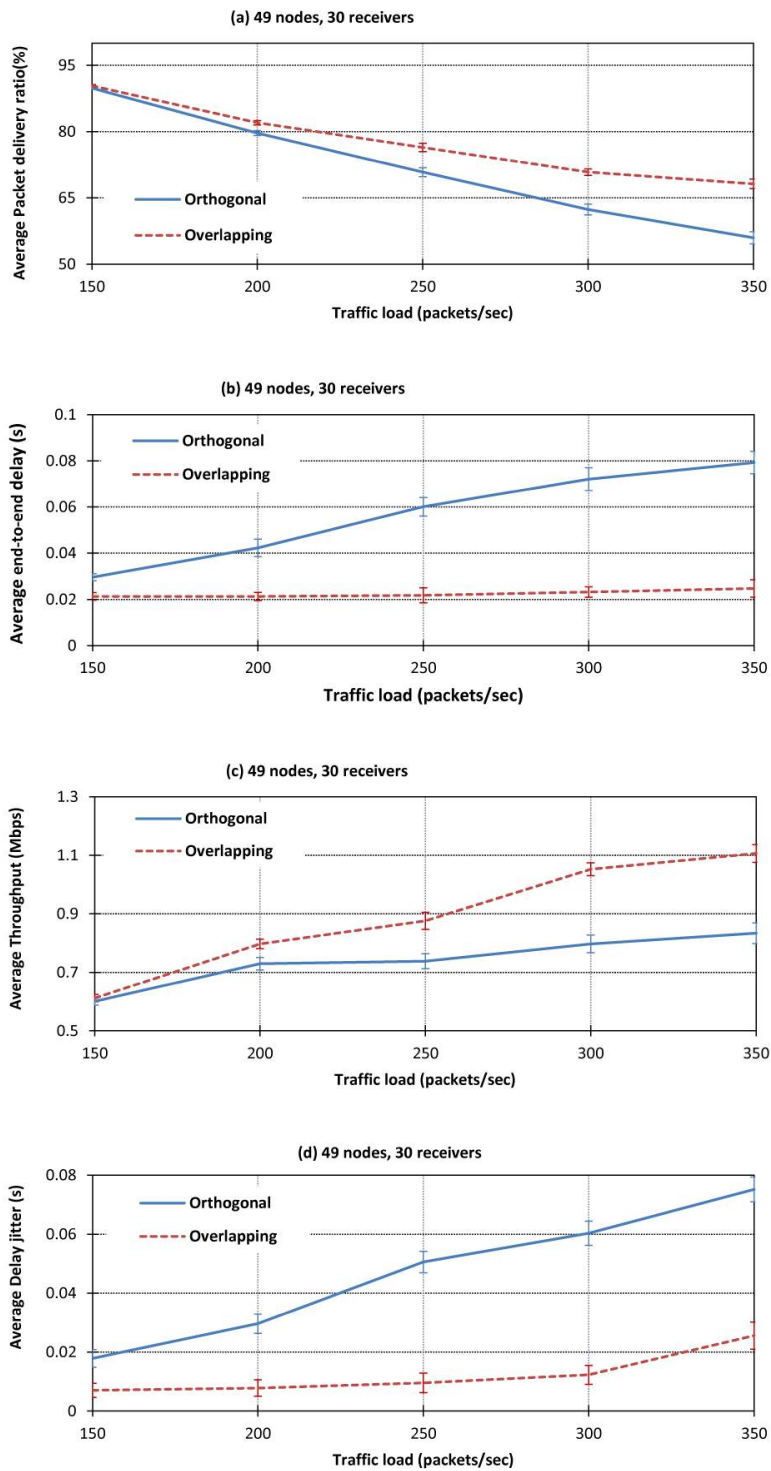


Figure 3.2: Functions of traffic load - 49-node network

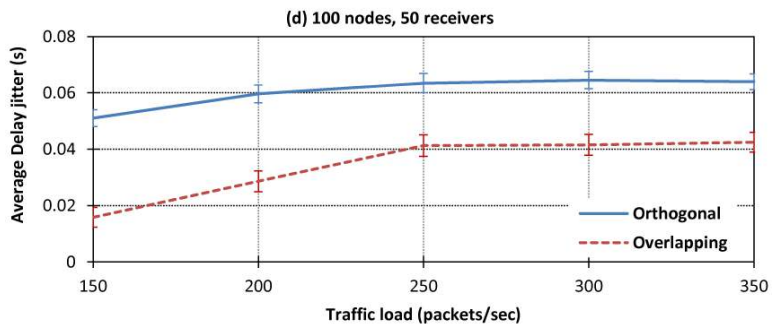
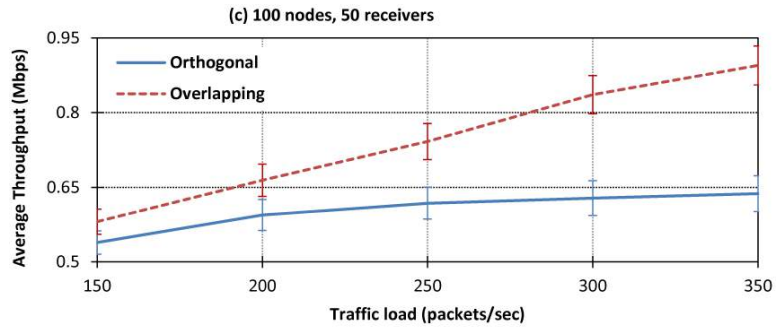
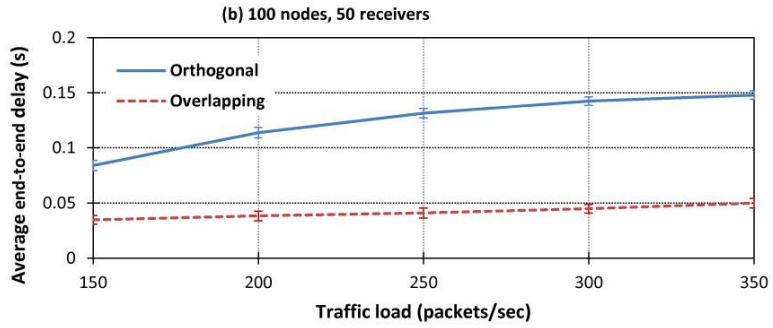
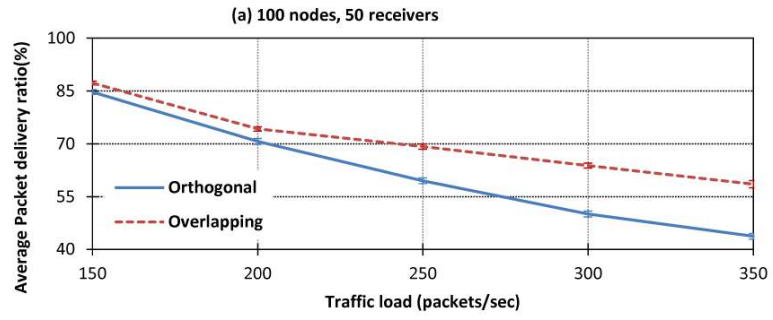


Figure 3.3: Functions of traffic load - 100-node network

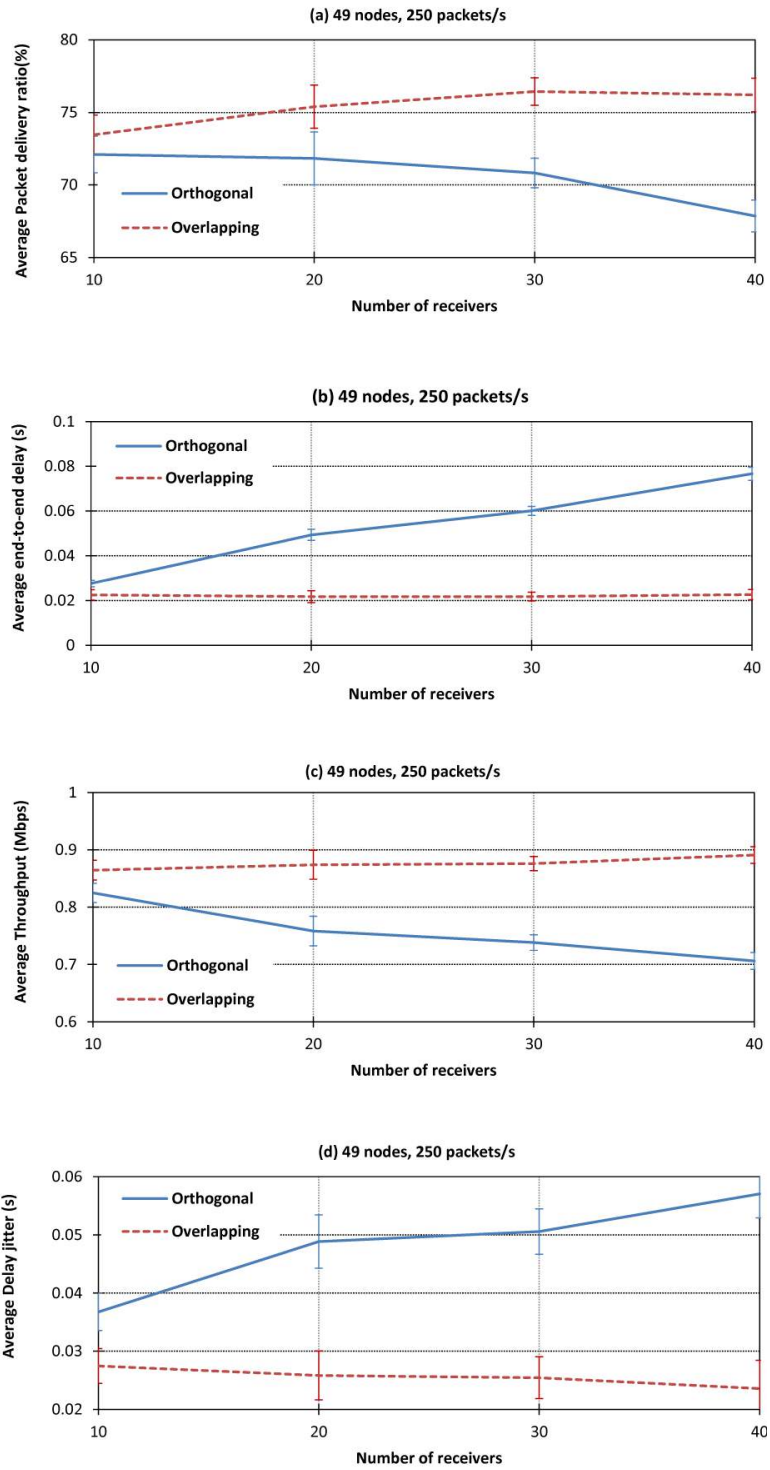


Figure 3.4: Functions of group size - 49-node network (250 packets/sec)

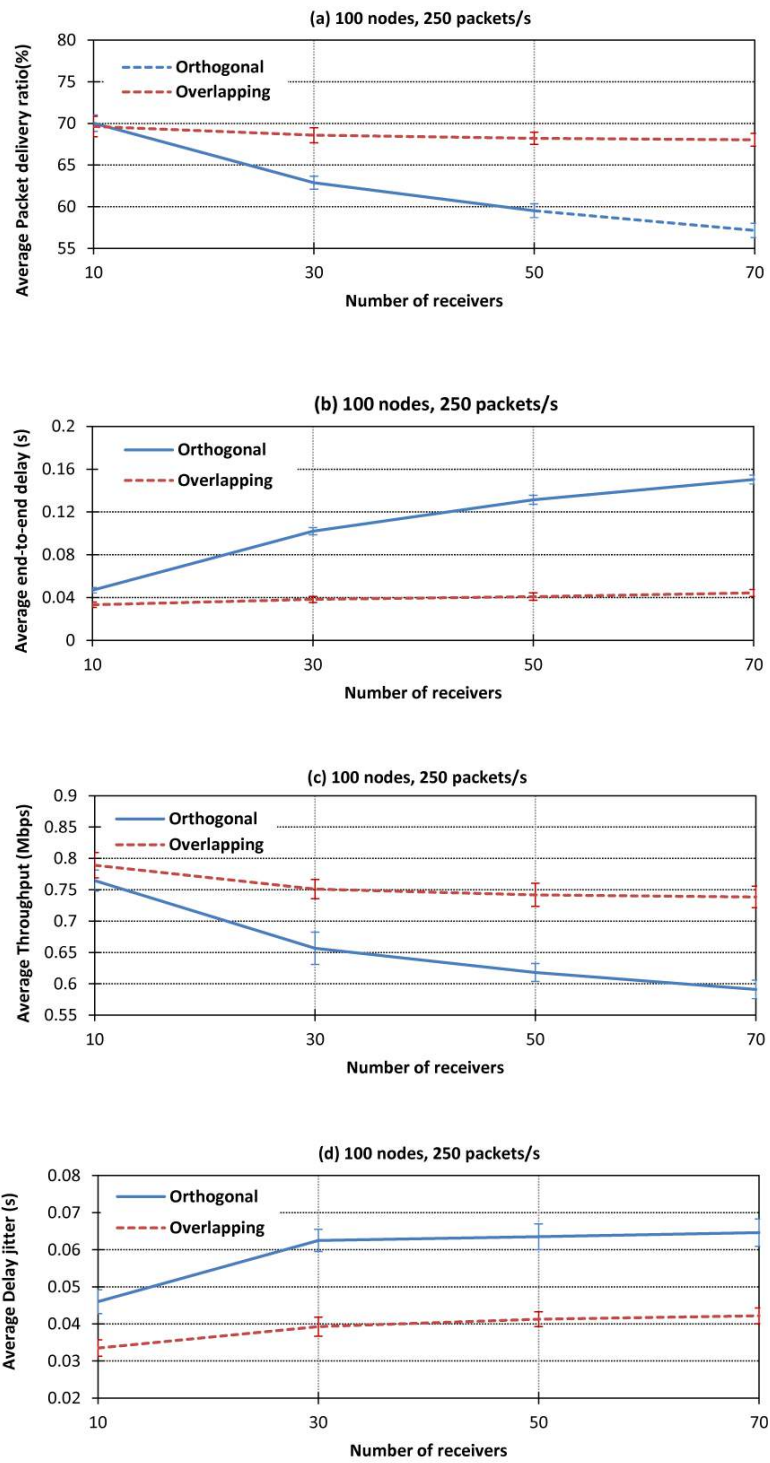


Figure 3.5: Functions of group size - 100-node network (250 packets/sec)

Chapter 4

Impacts of Channel Switching Latency on the Performance of Multicast in MCMR WMNs

In a MCMR WMN, when the number of channels assigned to a node is higher than the number of its radios ($c > r$), at least one radio is required to switch among multiple channels as discussed in Section 2.6. Channel switching has the potential to increase the network performance by reducing medium contention and interference and increasing the number of simultaneous transmissions. However, channel switching has different associated costs such as switching time, bottleneck of a common control channel and required synchronizations between a sender and the corresponding receiver (see Section 2.6). Channel switching overheads are categorized as hardware and software latencies. Hardware latency refers to the time required for a radio to switch from one channel to another

and varies from a few milliseconds to hundreds of microseconds depending on the radio specifications [8, 129]. Software switching latency refers to the time required for a channel switching algorithm to be executed and varies depending on the algorithm [25]. In this chapter, we present a simulation-based study to evaluate the effects of channel switching latency on the performance of multicast in MCMR WMNs using the M4 channel assignment algorithm proposed in [41].

4.1 Experiment Scenarios

In our simulations, we use the simulation parameters presented in Section 3.1 and summarized in Table 4.1. Such simulation parameters which are used in this chapter and other chapters are obtained from many researches that have been accomplished in this field [125, 130–132]. Also, for all experiments in this chapter, the number of overlapping channels is eleven as defined in IEEE 802.11b standards unless otherwise stated. The performance metrics that we consider here consist of average packet delivery ratio, average end-to-end delay, average throughput and average delay jitter as defined in Section 3.2. Finally, we measure the specified metrics as functions of:

1. *Multicast traffic load.* The multicast source rate at the application layer increases from 100 packets/sec to 350 packets/sec for both 49-node and 100-node networks. The multicast group size is 30 and 50 for the 49-node and 100-node networks, respectively.
2. *Multicast group size.* The number of multicast destinations varies from 10 to 40,

and from 10 to 70 in the 49-node and 100-node networks, respectively.

3. *Number of channels.* The total number of overlapping channels varies from 3 to 11.

In the medium and large size networks, the number of multicast destinations is set to 30 and 50, respectively.

In the sets of experiments (2) and (3) just mentioned above, we ran experiments under various traffic conditions: 150 packets/sec, 200 packets/sec and 250 packets/sec. Also, we ran each of the above scenarios for two cases, with and without channel switching in effect in order to observe the effects of channel switching. A summary of the above specified parameters is shown in Table 4.2.

4.2 Implementation Details

In our simulations, we use three radios per node as follow. The first radio is used to receive multicast data; the second radio is used to forward multicast data; the third radio is fixed on a common channel, namely the control channel. The control channel is dedicated to control messages used in our channel switching algorithm, which works as follows.

For every forwarder s in the multicast tree, before sending a multicast packet, s broadcasts an announcement (ANC) message on the control channel (using the CSMA/CA protocol) to announce the channel on which the next data packet will be multicast. Upon receiving the ANC, multicast neighbours of s tune to the announced channel to receive the multicast packet. (There is a chance that one or more neighbours of s do not receive the ANC message on the control channel (e.g., due to packet collision or bit errors), and

Table 4.1: Common simulation parameters

Parameter	Value
Network size	49 nodes in a 1200m x 1200m area 100 nodes in a 1700m x 1700m area
Path loss model	free source for distances shorter than <250m two-ray for distances longer than >250m
Fading model	non
Transmission range	315m
Transmission rate at physical layer	11 Mbits/s
Physical layer protocol	PHY802.11b
Medium access control	MAC 802.11 with DCF
MAC for multicast flow	CSMA/CA
Packet size (excluding header size)	512 bytes
Queue size at routers	50 Kbytes
Queueing policy at routers	first-in-first-out
Traffic model of sources	constant bit rate (CBR)
Duration of each experiment	600 seconds of simulated time
Number of runs per data point	50
Confidence interval	95%

Table 4.2: Parameters used for our simulations

Function of	Parameters	49-node	100-node
Multicast traffic load	source rate	150 to 350 packets/s	
	number of channels	11	
	group size	30 nodes	50 nodes
multicast group size	source rate	150, 200, 250 packets/s	
	number of channels	11	
	group size	10 to 40 nodes	10 to 70 nodes
number of channels	source rate	150, 200, 250 packets/s	
	number of channels	3 to 11	
	group size	30 nodes	50 nodes

thus miss the subsequent data packet. Therefore, this channel switching scheme follows the current best-effort philosophy of medium access control for multicast in IEEE 802.11 WMNs as offered by the CSMA/CA protocol.) The sender then transmits the data packet on the announced channel, also using the CSMA/CA protocol.

Once an ANC message is received, the receiver enters into the channel switching period during which it cannot receive any packet, nor data neither control messages. Therefore, right after sending an ANC message, the sender has to wait for some time interval (about the duration of channel switching latency) before transmitting the next data packet. Otherwise, there is a high probability that the receiver loses the packet

since its receiving radio is inactive during the channel switching period.

In order to better understand the effects of channel switching in our simulations, we used two different values for hardware channel switching delays, 2 milliseconds and 5 milliseconds. In our simulations, the size of an ANC message and a multicast data packet is 64 bytes and 512 bytes, respectively, including the header.

Excluding the IEEE 802.11b overheads (medium contention, random backoff, collisions and retransmissions), the required time to transmit a single data packet from a forwarder node s to its multicast neighbours is equal to one cycle as just described and is computed as follows:

$$T_{total} = T_{ANC} + T_{CSW} + T_{data} \quad (4.1)$$

In the above equation,

T_{ANC} is the time required to transmit an ANC message to the neighbours of s ;

T_{CSW} is the summation of software and hardware switching delay that is hardware specific. Hardware switching delay varies from a few milliseconds to hundreds of microseconds. The maximum software switching latency measured in our simulations is 0.05 milliseconds.

T_{data} is the required time to transmit the actual data packet to the neighbours of s .

T_{Total} is the total time required to transmit a multicast data packet from s to its one-hop neighbours and the sum of the three above components.

Considering that in IEEE 802.11b we can transmit at a rate of 11 Mbps at the physical

layer using a 2.4 GHz band, the total transmission delay of an ANC message and the corresponding data packet at the physical layer is calculated as follows:

$$\frac{(64 \text{ bytes} + 512 \text{ bytes}) \times 8}{11 \text{ Mbps}} = 0.42 \text{ ms} \quad (4.2)$$

Since the value of software switching latency is negligible in comparison with the hardware switching values we used (2 ms or 5 ms), we do not include it in our calculations. However, for the cases where the hardware switching latency is in the range of hundreds of microseconds, this value should be considered.

Using Eq. 4.1 and considering the case where the channel switching delay is 5 ms, it takes 5.42 ms (5 ms + 0.42 ms) for each data packet to be transmitted from a multi-cast sender to its neighbours (excluding the delay due to medium contention and back-off time in the CSMA/CA algorithm). Spending 5.42 ms per data packet limits a forwarder's transmission rate to less than 184 data packets per second (1 sec / 5.42 ms per packet \approx 184 packets/sec). This means that in our simulations, when the hardware channel switching delay is 5 ms, the source rate at the application layer cannot exceed 184 packets/sec. Therefore, when setting the source rate to less than 184 packets/sec, we are able to run simulations with hardware switching delay values equal to 5 ms as well as 2 ms. Using the same logic, when hardware switching delay is equal to 2 ms, the maximum transmission rate for a source is 413 packets/sec (1 sec / 2.42 ms per packet \simeq 413 packets/sec).

In our implementation, we first use the breadth first search algorithm (SPT) to build

a multicast tree. Next, using eleven overlapping channels specified in IEEE 802.11b standard and the M4 algorithm [41], we assign channels to the links in the tree.

4.3 Experimental Results

The graphs obtained from the simulations are shown in Figures 4.1 to 4.14. Below we analyze the results obtained from our simulations.

4.3.1 Function of Multicast Traffic Load

In this set of experiments, the traffic load varies from 150 packets/sec to 350 packets/sec. For all these experiments, the hardware switching delay is 2 ms. The multicast group size in the 49-node and 100-node networks are 30 and 50, respectively. The results are given in Figures 4.1 and 4.2. Below, we analyze the effect of channel switching on the performance metrics.

- *Average packet delivery ratio.* The PDR results for the 49-node and 100-node networks are illustrated in Figures 4.1(a) and 4.2(a), respectively. Under light traffic conditions, medium contention, collision and channel sharing are low. As the traffic load increases, the network gets busier and the PDR drops, but the difference between channel switching multicast (CS multicast) and regular multicast (non-CS multicast) is not noticeable. Specifically, in our large-size network, when the traffic load is 150 packets/sec, the PDR for non-CS multicast and CS multicast is 86% and 83%, respectively (see Figure 4.2(a)). Under heavy traffic loads, medium contention

and collisions increase, the network gets even more busy and the effect of channel switching on the PDR becomes more pronounced. For instance, in the large-size network, when the traffic load is 350 packets/sec, the values of PDR for non-CS and CS multicast are 58% and 49%, respectively (see Figure 4.2(a)). When the source rate increases, not only the number of data packets per second goes up, but the number of ANC messages also increases, causing CS multicast to lose more data packets. In the 49-node network, when there is no channel switching, as the traffic load increases from low to high, the PDR values for regular multicast decreases from 90% to 70%. When channel switching is involved, these values reduce to 89% and 64%, respectively (see Figure 4.1(a)).

- *Average end-to-end delay.* The results for the average end-to-end delay in the 49-node and 100-node networks are presented in Figures 4.1(b) and 4.2(b). The results indicate that as the traffic load goes higher, the average end-to-end delay increases, as expected. High traffic load results in high medium contention and long queues in routers and consequently leads to longer end-to-end delay. In our 100-node network, when the traffic load is 150 packets/sec, the average end-to-end delay for non-CS multicast is about 3 milliseconds. When channel switching is in effect, the average end-to-end delay increases to 7 milliseconds. When the traffic load is 350 packets/sec, the average end-to-end delay values for non-CS and CS multicast are 4 milliseconds and 8 milliseconds, respectively (see Figure 4.2(b)).
- *Average throughput.* The average throughput results for 49-node and 100-node net-

works are shown in Figures 4.1(c) and 4.2(c), respectively. As the multicast source rate increases, the throughput increases as expected. Under ideal conditions where the packet loss is zero, the throughput increase has a linear relation with the traffic load. In practise, due to packet loss and medium contention, the throughput graph does not follow a linear pattern and the growth rate of the throughput decreases as the traffic load increases (see Figures 4.1(c) and 4.2(c)).

In the 100-node network, when the traffic load is 150 packets/sec, the throughput values for non-CS multicast and CS multicast are 0.50 Mbps and 0.48 Mbps, respectively. When the traffic load increases to 350 packets/sec, the throughput values are 0.75 Mbps and 0.67 Mbps, respectively.

- *Average jitter.* The results obtained for the average jitter for both 49-node and 100-node networks are illustrated in Figures 4.1(d) and 4.2(d), respectively. As the traffic load goes up, the network gets busy and the jitter values increase. Specifically, in the large network, when the traffic load reaches 350 packets/sec, the jitter values for non-CS multicast and CS multicast are 5.8 ms and 6.5 ms, respectively.

In summary, under all traffic conditions, channel switching has the most significant impacts on the average end-to-end delay. For instance, in the large network, when the traffic load is 350 packets/sec, the PDR difference due to channel switching is about 9% (58% for non-CS multicast and 49% for CS multicast). In the same scenario, the difference in the average end-to-end delay due to channel switching is about 4 milliseconds (8 milliseconds for CS multicast and 4 milliseconds for non-CS multicast, a difference of

100%).

The reason for the big difference in the end-to-end delay between CS multicast and non-CS multicast is the switching delay incurred by each packet at every hop on the path from the source to the destination. As we can see from the graphs in Figures 4.1(b) and 4.2(b), the longest average end-to-end delay of a non-CS multicast packet is about 4 ms. Given a channel switching delay of 2 ms and a path length of only two hops, the total channel switching delay is 4 ms. That is, the average end-to-end delay of a CS multicast packet is about 8 ms, doubling that of a non-CS multicast packet.

4.3.2 Function of Multicast Group Size

In this set of simulations, we vary the multicast group size from 10 to 40 in the 49-node network and from 10 to 70 in the 100-node network. The results for the 49-node network are illustrated in Figures 4.3 to 4.5, and the results for the 100-node network are shown in Figures 4.6 to 4.8 for different source rates of 150, 200 and 250 packets/sec. As explained in Section 4.2, when the hardware channel switching delay is 2 ms, the traffic load can be increased as high as 413 packets/sec. When the hardware channel switching delay is 5 ms, the traffic load can not be increased to more than 184 packets/sec. Therefore, in the graphs corresponding to a source rate of 150 packets/sec traffic, we consider hardware switching delay of both 2 ms and 5 ms. For rates higher than 150 packets/sec (i.e., 200 and 250 packets/sec), we only consider hardware switching delay equal to 2 ms.

Following is the analysis of the effect of channel switching on each metric as the

multicast group size varies.

- *Average packet delivery ratio.* The PDR simulation results are illustrated in Figures 4.3(a) to 4.5(a) and in Figures 4.6(a) to 4.8(a) for the medium size and large size networks, respectively. In the medium size network, as the multicast group size increases, the PDR goes up slightly. On the other hand, for the large size network, as the multicast group size increases, the PDR goes down slightly. (A detailed explanation for these results will be provided at the end of this section.) However, under all different multicast group sizes, non-CS multicast offers higher PDR than CS multicast.

Using longer values for hardware channel switching delay results in lower PDR for all multicast group sizes. Specifically, in the medium size network, with a source rate of 150 packets/sec, the PDR value for non-CS multicast varies from 88% to 91% as the multicast group size varies from 10 to 40 (see Figure 4.3(a)). When channel switching is involved and the hardware switching delay is 2 ms, the PDR values vary between 88% to 90%. When the switching delay is 5 ms, these PDR values go down to 87% and 88%, respectively.

Running the same set of experiments with higher traffic loads and for different multicast group sizes shows that in all conditions, the conclusion is the same: CS multicast has lower PDR than non-CS multicast. Also, in CS multicast, longer hardware switching delay results in lower PDRs.

- *Average end-to-end delay.* The effect of channel switching on the average end-to-end delay is illustrated in Figures 4.3(b) to 4.5(b) and in Figures 4.6(b) to 4.8(b) for the 49-node and 100-node networks, respectively. In all cases, as the multicast group size increases, the average end-to-end delay increases. The reason is that more forwarders are required to support the multicast receivers and therefore, the multicast tree grows larger. As a result, source-to-destination path lengths also become longer and medium contention in the tree also increases. As our simulation results indicate, the average end-to-end delay for CS multicast is longer than that of non-CS multicast. Specifically, in the large network, when the multicast group size is 10 and under traffic load of 200 packets/sec, the values for the average end-to-end delay are 3 ms and 7 ms for non-CS multicast and CS multicast, respectively. When the multicast group size grows to 70, such values increase to 3.6 ms and 7.6 ms, respectively (see Figure 4.7(b)). Moreover, longer hardware switching delay (5 ms vs. 2 ms) results in longer average end-to-end delay. In the 100-node network, when the multicast group size is 10 and under 150 packets/sec traffic, the average end-to-end delay for CS multicast with hardware switching delays of 2 ms and 5 ms are 6 ms and 15 ms, respectively. When the multicast group size is 70, these values are 8 ms and 17 ms, respectively (see Figure 4.6(b)).
- *Average throughput.* Figures 4.3(c) to 4.5(c) and in Figures 4.6(c) to 4.8(c) illustrate the results of our experiments for the average throughput of the 49-node network and 100-node networks, respectively. For the medium size network, the throughput

goes higher as the multicast group size grows. For the large size network, the situation is reverse and the average throughput goes down as the multicast group size increases (a detailed explanation for these results will be provided at the end of this section). However, for both medium and large size networks and for all multicast group sizes, CS multicast has lower throughput than non-CS multicast. In the large size network, given a hardware channel switching delay of 2 ms, a source rate of 250 packets/sec and a multicast group size of 10, the throughput values for non-CS multicast and CS multicast are 0.6 Mbps and 0.58 Mbps, respectively. Under the same condition, as the multicast group size grows to 70, these values reach 0.553 Mbps and 0.524 Mbps, respectively (see Figure 4.8(c)).

- *Average delay jitter.* The simulation results obtained for the average delay jitter are illustrated in Figures 4.3(d) to 4.5(d) and in Figures 4.6(d) to 4.8(d) for the 49-node and 100-node networks, respectively. As the results indicate, in both networks, the average jitter delay increases as the multicast group size increases. The reason is that a higher number of multicast receivers create a larger multicast tree and thus higher medium contention among the nodes, resulting in larger average jitter values. We can also observe that in all cases, CS multicast has higher values of jitter in comparison with non-CS multicast.

It may be noted that in our medium size network, the average PDR and throughput increase as the multicast group size grows. The reason is that more multicast receivers require a larger multicast tree with more multicast forwarders. More forwarders in a tree

increases the chance of overhearing for multicast nodes. As explained in section 2.1, the overhearing effect improves the delivery rate among nodes and thus leads to a higher PDR in the tree. However, in the large-size network, the PDR goes down as the multicast group size increases (as opposed to the scenario in the medium-size network). The reason is that longer path lengths negate the positive effect of overhearing. Tables 4.3 and 4.4 show the average source-to-destination path lengths and the average number of forwarders for the medium and large size networks. As illustrated in these tables, source-to-destination paths in the 100-node network are longer and the number of forwarders is higher when compared to the 49-node network.

The simulation results show that the overhead of channel switching is most significant for the average end-to-end delay metric. (The explanation for this result is provided in the summary of Section 4.3.1.) Specifically, in the large network, the difference in average end-to-end delay of non-CS and CS multicast is 4.2 ms vs. 7.8 ms, an increase of 85.7%.

Table 4.3: Average path lengths and number of forwarders in the medium size network

Multicast Group	Average Path Length	Average Number Of Forwarders
10	2.04	8.2
20	2.01	11.6
30	2.00	14
40	2.1	16.5

Table 4.4: Average path lengths and number of forwarders in the large size network

Multicast Group	Average Path Length	Average Number Of Forwarders
10	2.81	13.3
30	2.82	25.13
50	2.79	32
70	2.79	36

4.3.3 Function of Number of Channels

The number of overlapping channels in this set of experiments varies from 3 to 11 and the multicast group size is 30 and 50 for the medium-size and large-size networks, respectively. The simulation results for the 49-node network are shown in Figures 4.9, 4.10 and 4.11. The results for the 100-node network are presented in Figures 4.12, 4.13 and 4.14. We ran simulations with traffic loads of 150 packets/sec, 200 packets/sec and 250 packets/sec. When the traffic load was 150 packets/sec, we were able to run simulations with both hardware switching delay values of 2 ms and 5 ms. With traffic loads of 200 packets/sec and 250 packets/sec, we could only use a hardware switching delay of 2 ms as explained in Section 4.2. Following is an analysis of the performance of CS multicast and non-CS multicast as functions of the number of channels used.

- *Average packet delivery ratio.* The PDR results for the 49-node and 100-node networks are illustrated in Figures 4.9(a) to 4.11(a) and in Figures 4.12(a) to 4.14(a),

respectively. Deploying more channels in a network reduces channel sharing, interference and medium contention among nodes, which in turn improves the PDR. For instance, when using three channels in the large network with a traffic load of 250 packets/sec and a hardware switching delay of 2 ms, the PDR values for non-CS multicast and CS multicast are 59% and 56%, respectively. When eleven channels are used, these values increase to 73% and 70%, respectively (see Figure 4.14(a)). Furthermore, the results show that in all cases, CS multicast offers lower PDRs than non-CS multicast. Moreover, longer hardware switching latency results in lower PDRs.

- *Average end-to-end delay.* Figures 4.9(b) to 4.11(b) and Figures 4.12(b) to 4.14(b) illustrate the performance of CS and non-CS multicast in terms of average end-to-end delay as a function of the number of channel in the 49-node and 100-node networks, respectively. The results indicate that as the number of channels increases, the average end-to-end delay is shortened. Using fewer channels increases channel sharing and medium contention among nodes, which leads to longer average end-to-end delay. Specifically, in the large size network, given three channels, a hardware switching delay of 2 ms and a traffic load of 250 packets/sec, the average end-to-end delay is about 13 ms and 9 ms for CS multicast and non-CS multicast, respectively. Under the same conditions, with eleven channels in use, such values are reduced to 7 ms and 4 ms, respectively (see Figure 4.14(b)).
- *Average throughput.* The results obtained from our simulations are illustrated in

Figures 4.9(c) to 4.11(c) and in Figures 4.12(c) to 4.14(c) for the 49-node and 100-node networks, respectively. The results show that as the number of channels increases, the average throughput also increases. Moreover, for all channel configurations in our simulations, CS multicast offers lower throughput than non-CS multicast. Furthermore, as the hardware channel switching delay increases, the throughput decreases. For instance, in the large-size network with a traffic load of 250 packets/sec, when three overlapping channels are used, the average throughput for non-CS multicast and CS multicast are 0.59 Mbps and 0.578 Mbps, respectively. Under the same conditions, when 11 overlapping channels are used, the throughput values go up to 0.725 Mbps and 0.705 Mbps (see Figure 4.14(c)), respectively.

- *Average delay jitter.* The simulation results for average delay jitter are illustrated in Figure 4.9(d) to 4.11(d) and in Figures 4.12(d) to 4.14(d) for the 49-node and 100-node networks, respectively. Our simulation results indicate that the jitter values decrease as the number of channels increases. The reason is that using more channels in a network reduces interference, medium contention and channel sharing, which results in smaller jitter values. Also, CS multicast incurs higher jitter values than non-CS multicast.

4.4 Chapter Summary

We performed a simulation-based study to evaluate the impact of channel switching on the performance of multicast in MCMR WMNs. We considered different simulation scenarios

with and without channel switching. We measured the average PDR, throughput, end-to-end delay and delay jitter as functions of multicast group size, number of channels used in the network and traffic load. The results obtained from the simulations show that CS multicast performs worse than non-CS multicast in all scenarios due to channel switching delay. The latency of channel switching has the most significant effect on the average end-to-end delay.

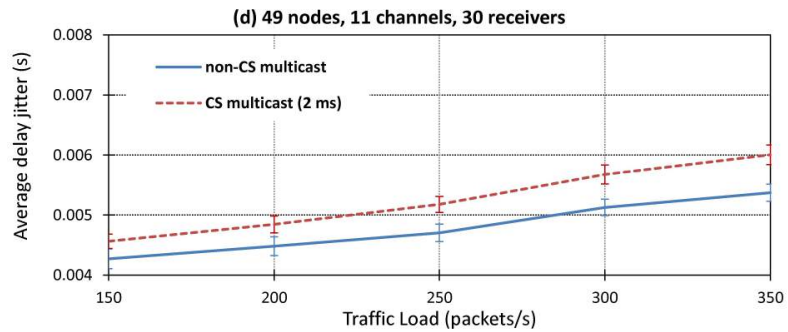
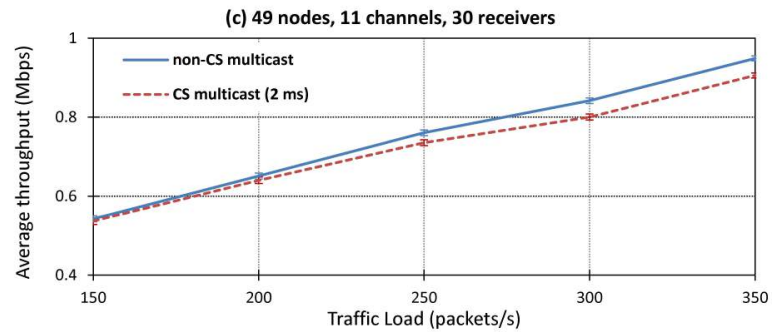
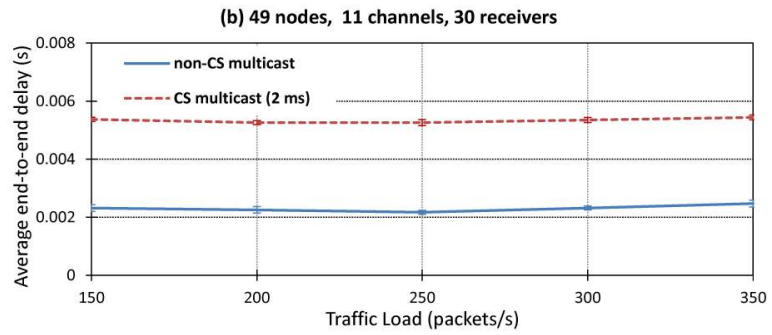
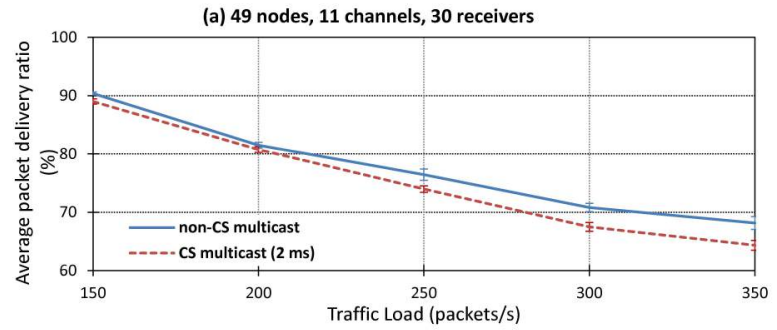


Figure 4.1: Functions of traffic load - 49-node network (hardware switching delay is 2 ms)

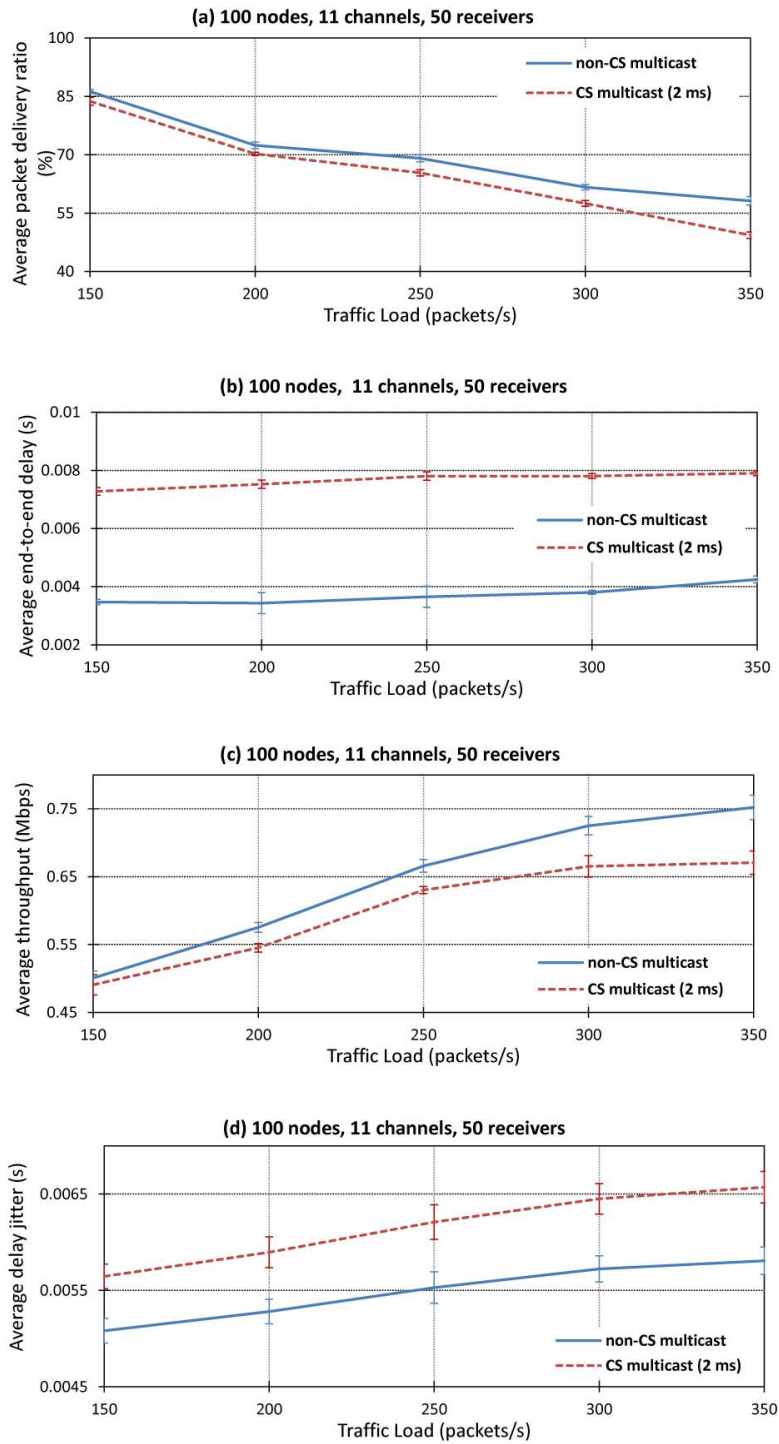


Figure 4.2: Functions of traffic load - 100-node network (hardware switching delay is 2 ms)

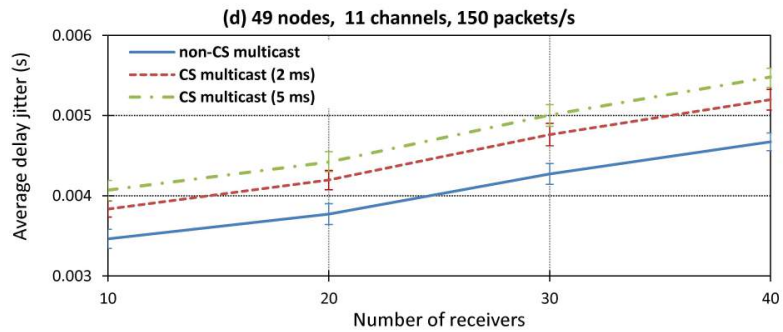
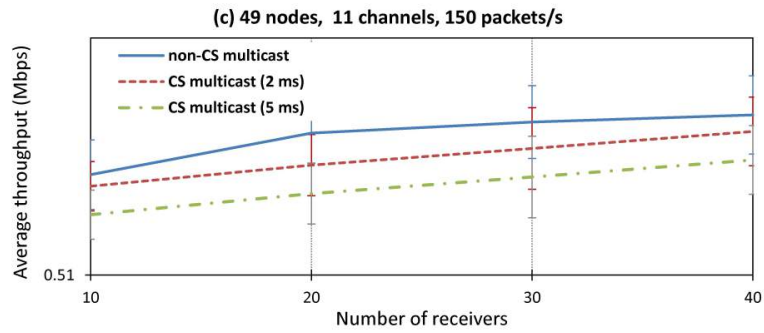
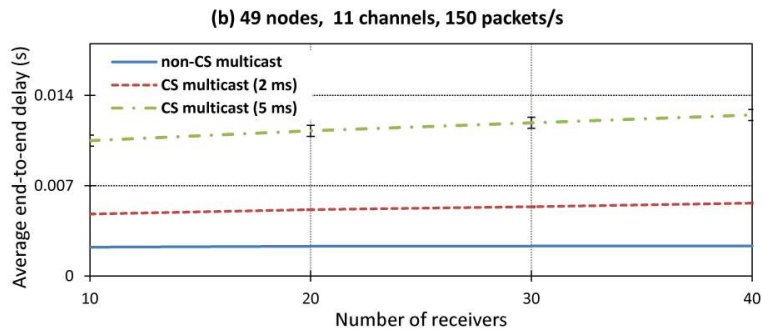
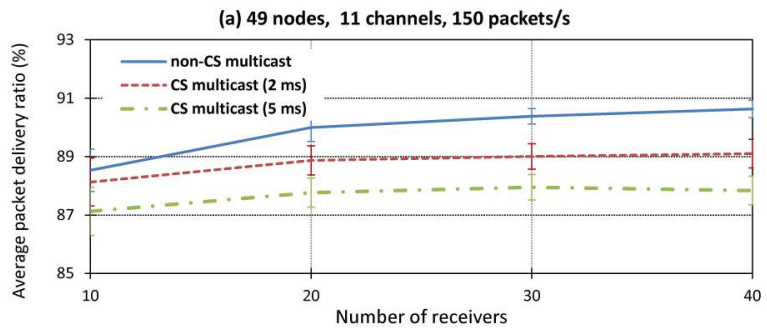


Figure 4.3: Functions of group size - 49-node network (150 packets/sec)

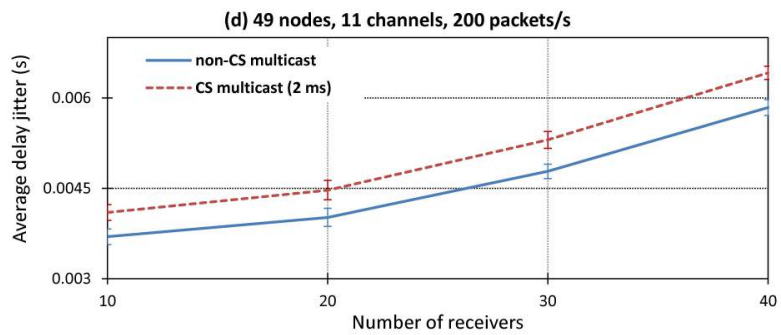
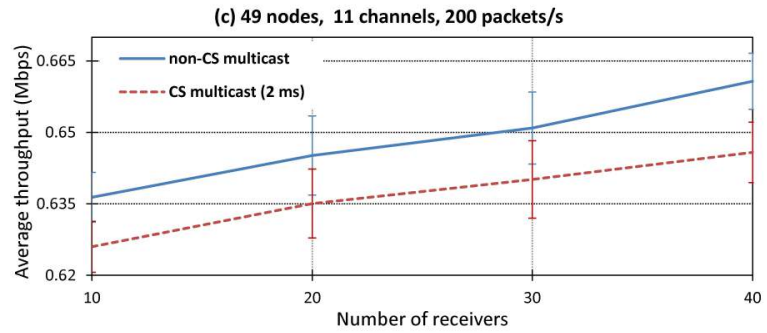
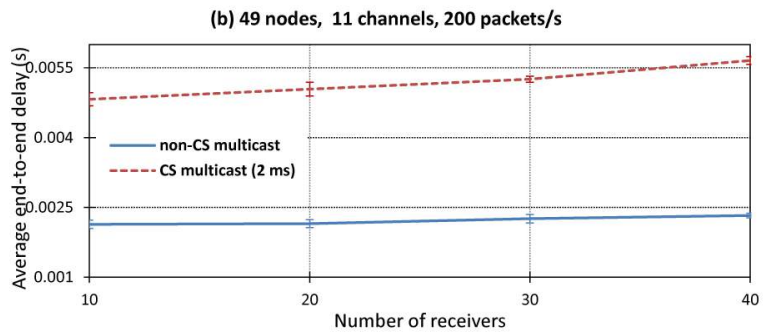
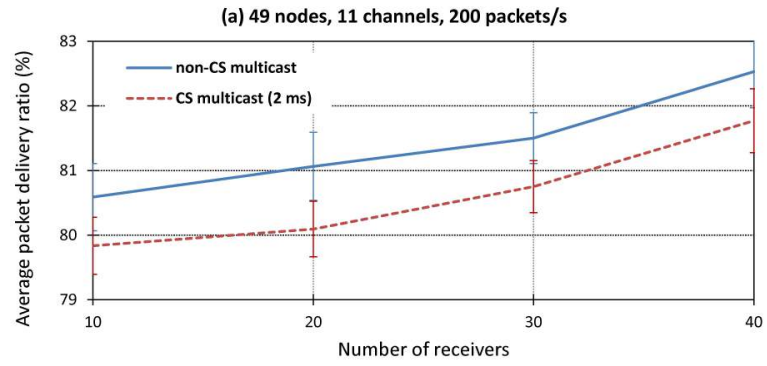


Figure 4.4: Functions of group size - 49-node network (200 packets/sec)

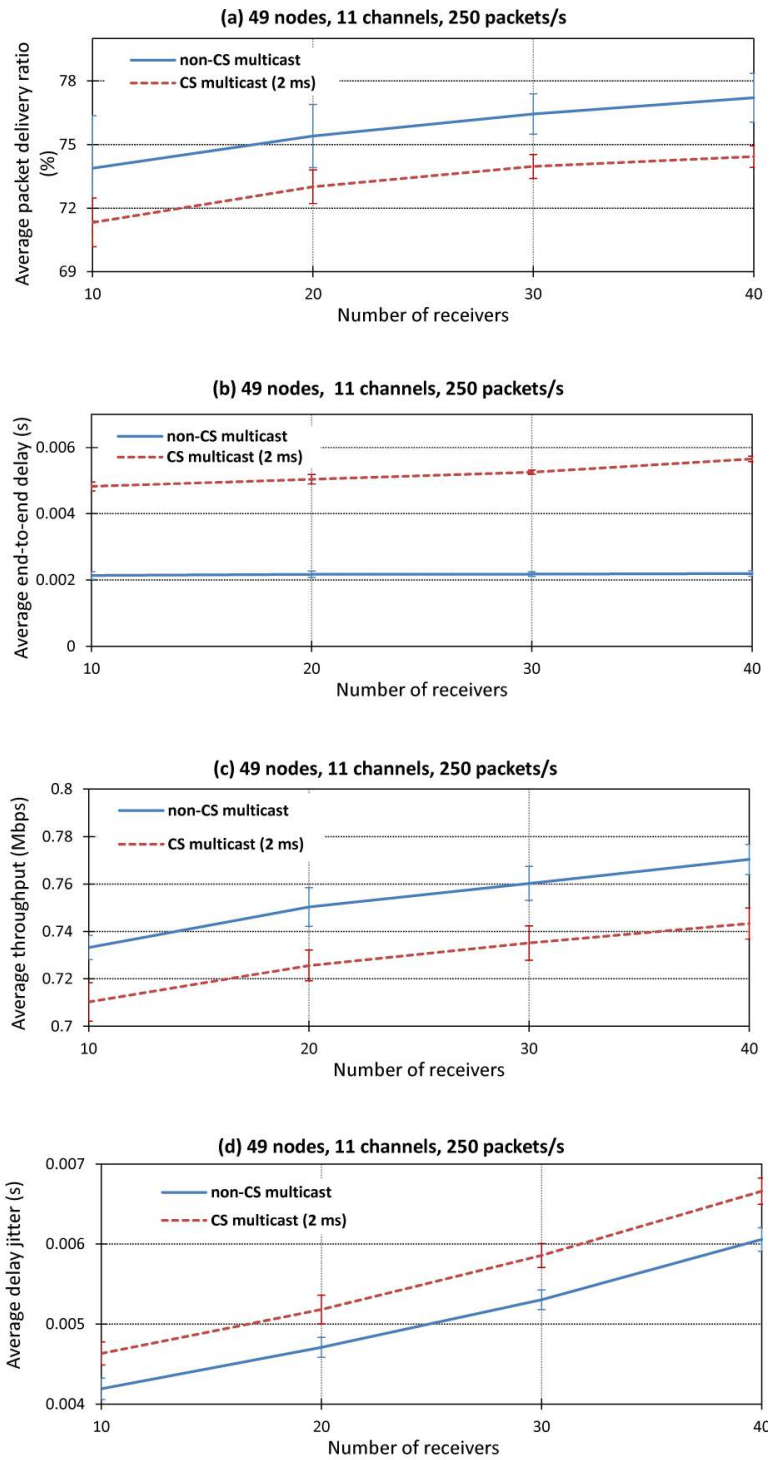


Figure 4.5: Functions of group size - 49-node network (250 packets/sec)

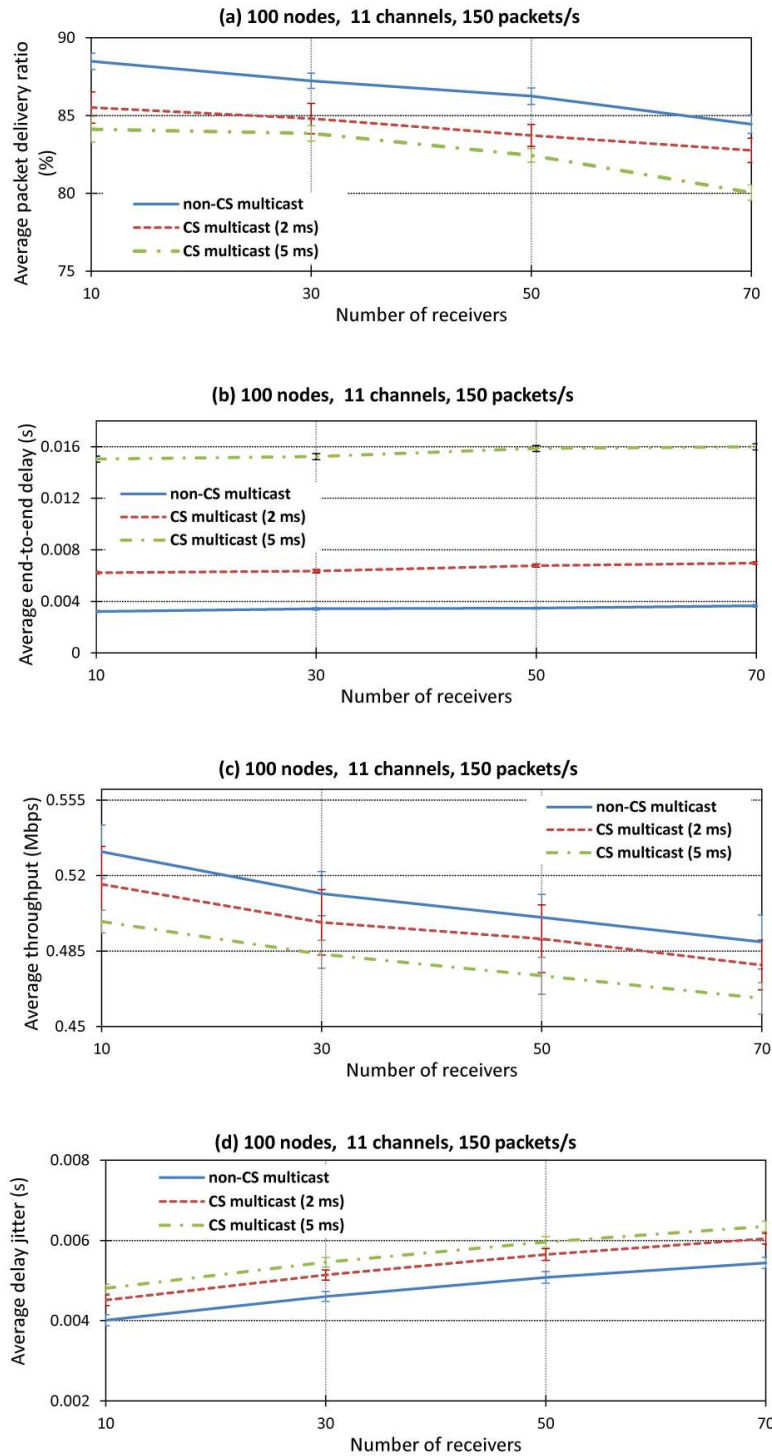


Figure 4.6: Functions of group size - 100-node network (150 packets/sec)

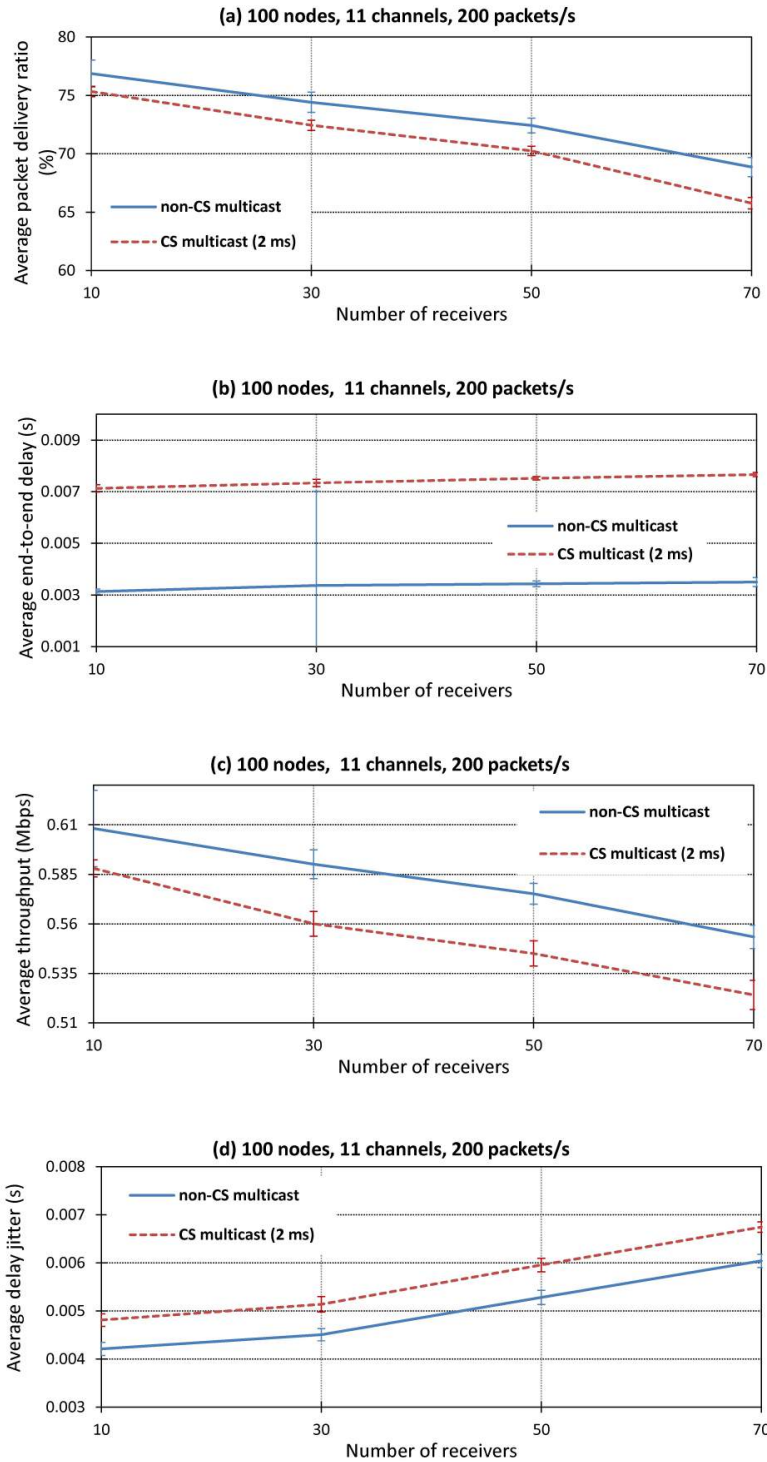


Figure 4.7: Functions of group size - 100-node network (200 packets/sec)

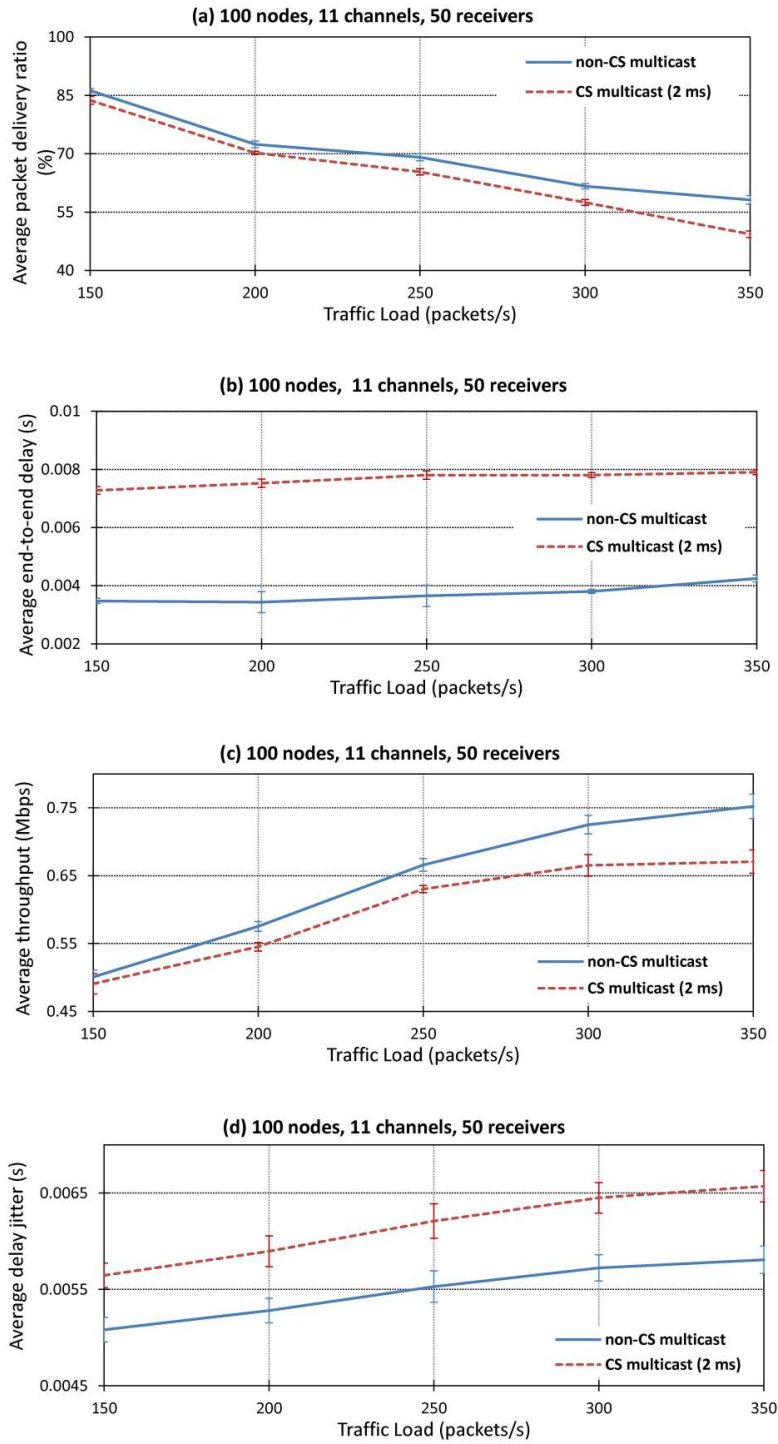


Figure 4.8: Functions of group size - 100-node network (250 packets/sec)

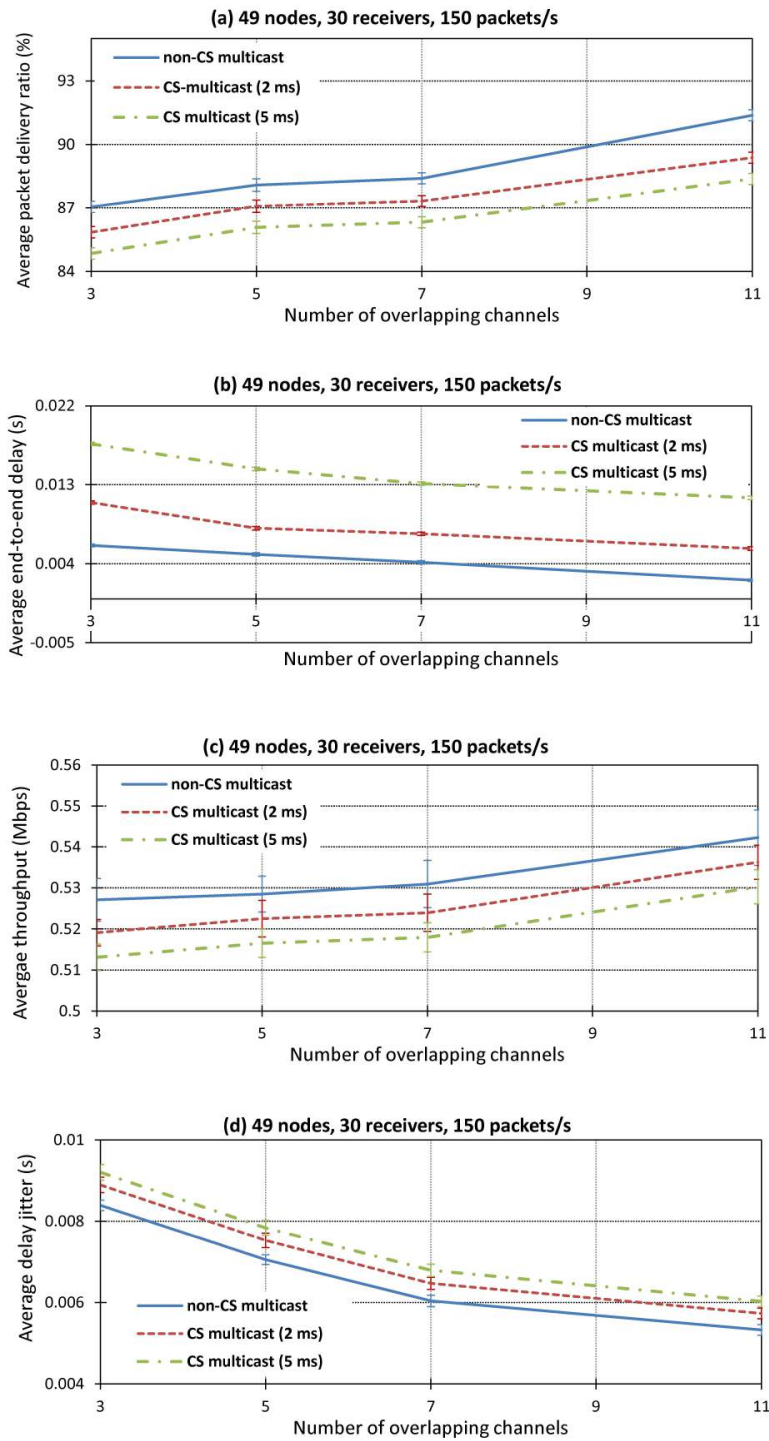


Figure 4.9: Functions of number of channels - 49-node network (hardware switching delay is 2 ms)

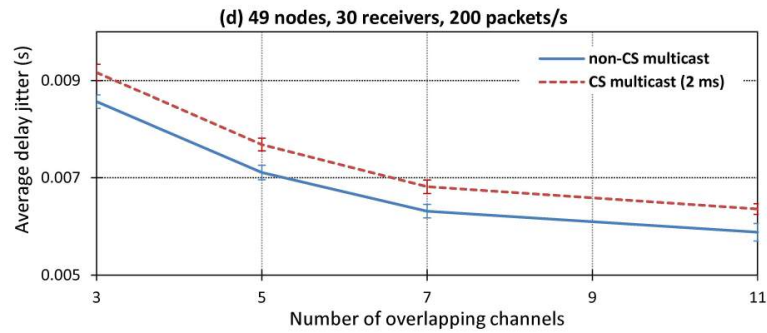
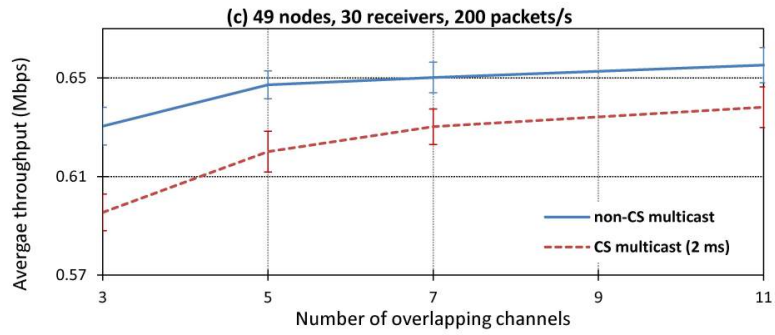
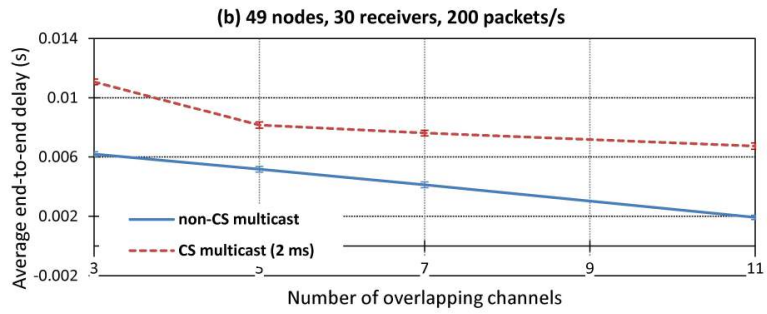
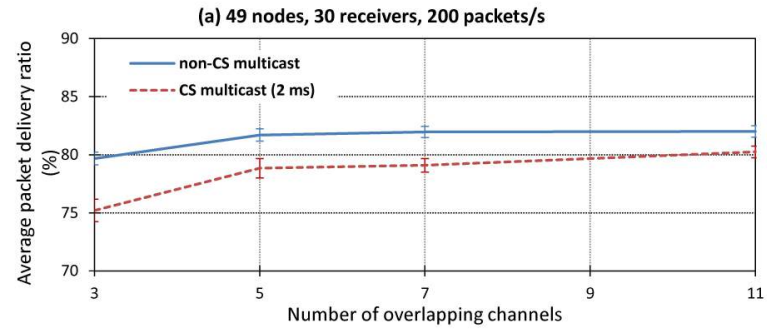


Figure 4.10: Functions of number of channels - 49-node network

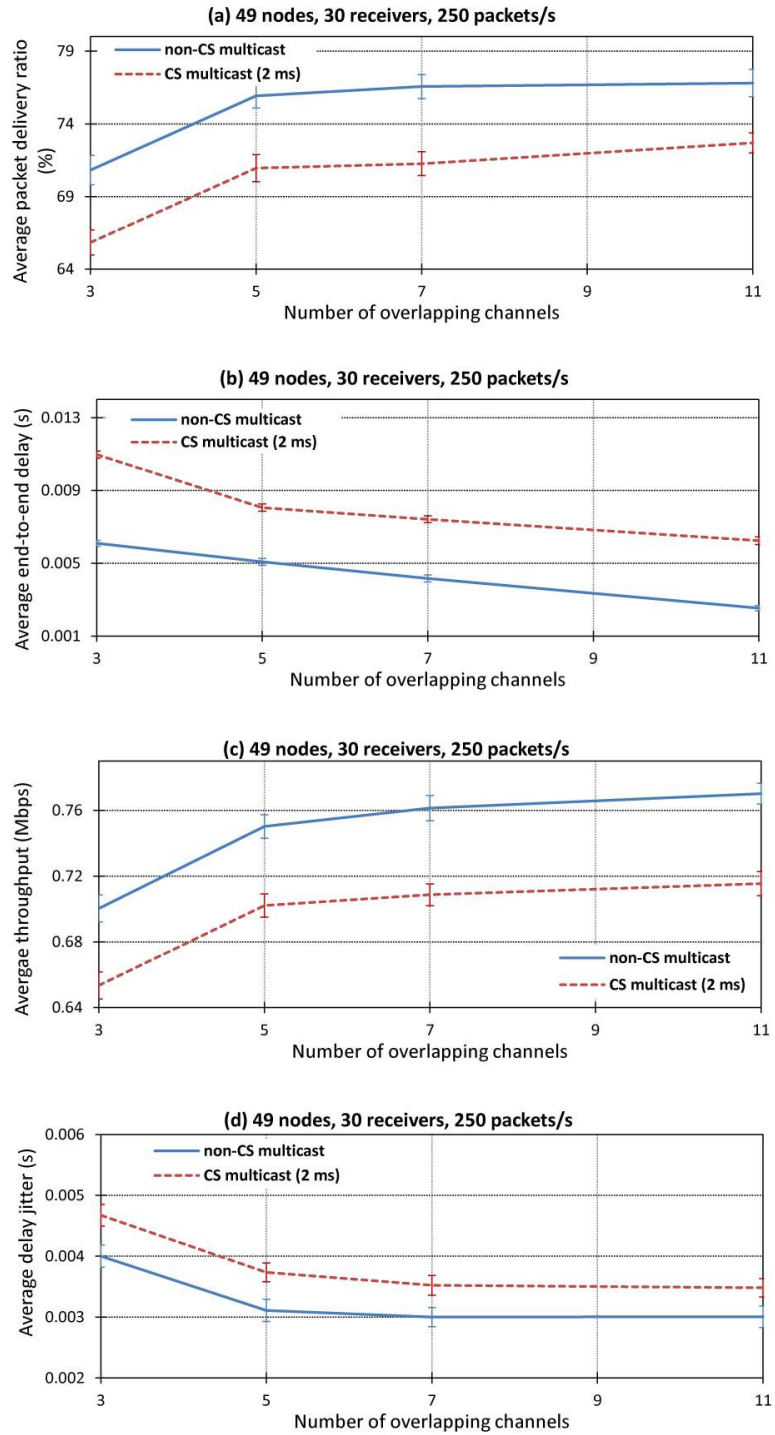


Figure 4.11: Functions of number of channels - 49-node network

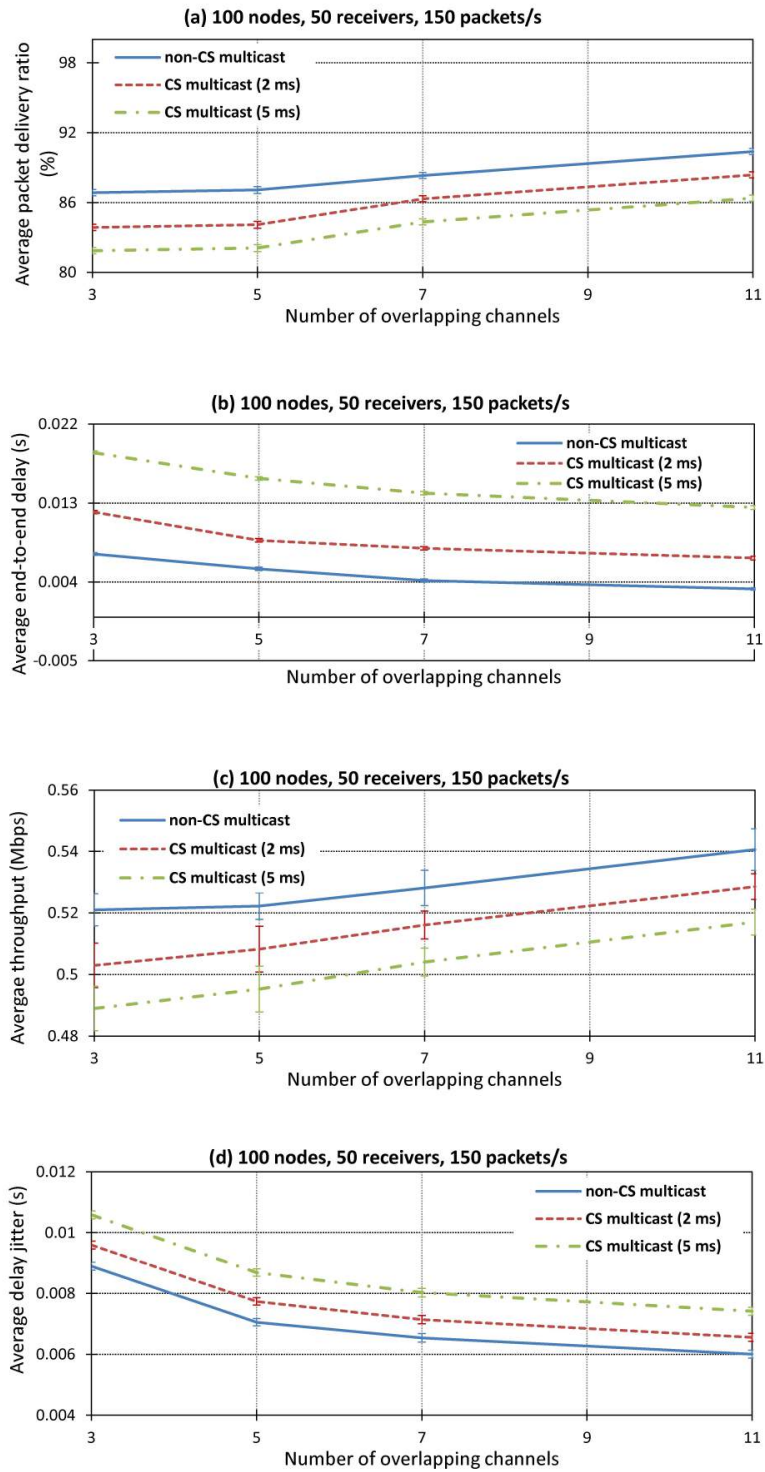


Figure 4.12: Functions of number of channels - 100-node network

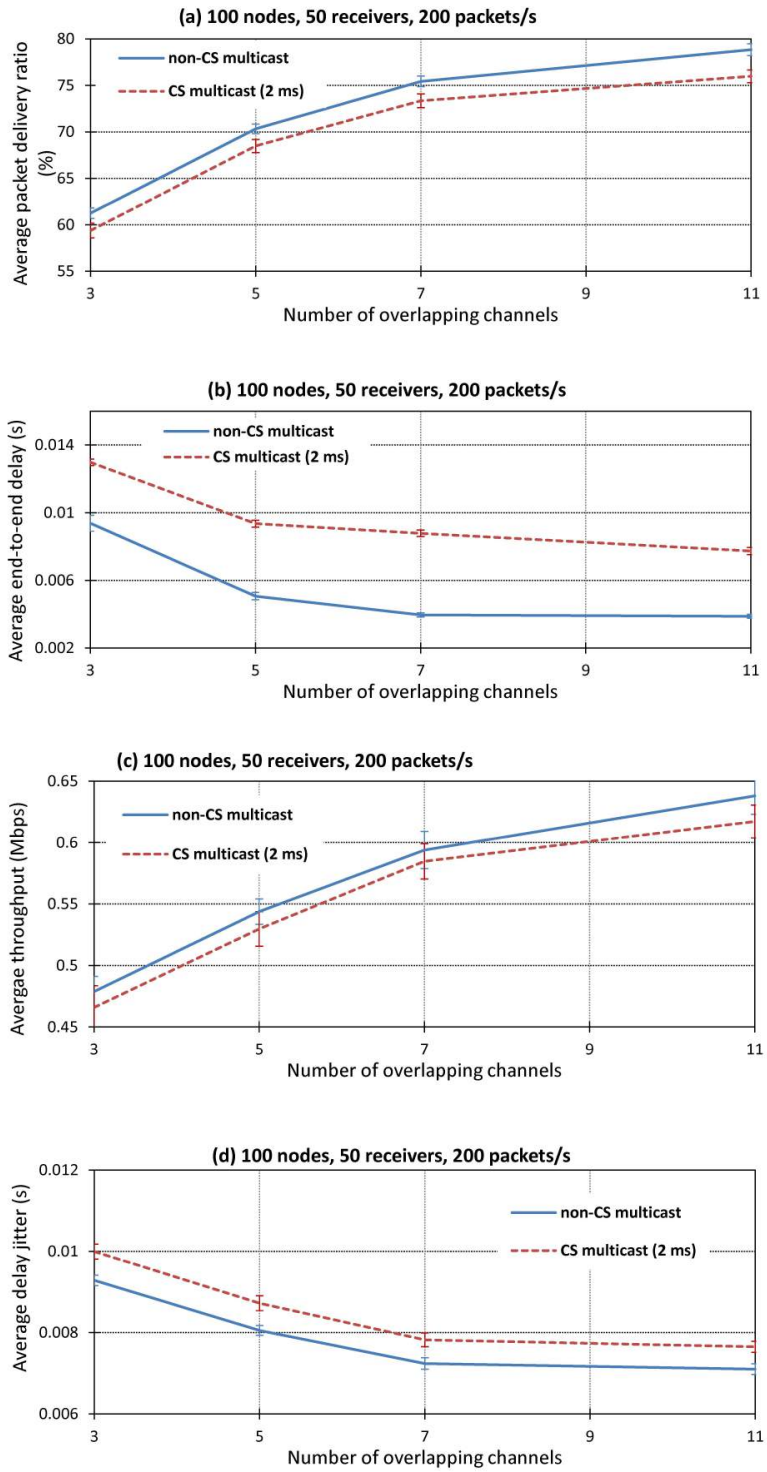


Figure 4.13: Functions of number of channels - 100-node network

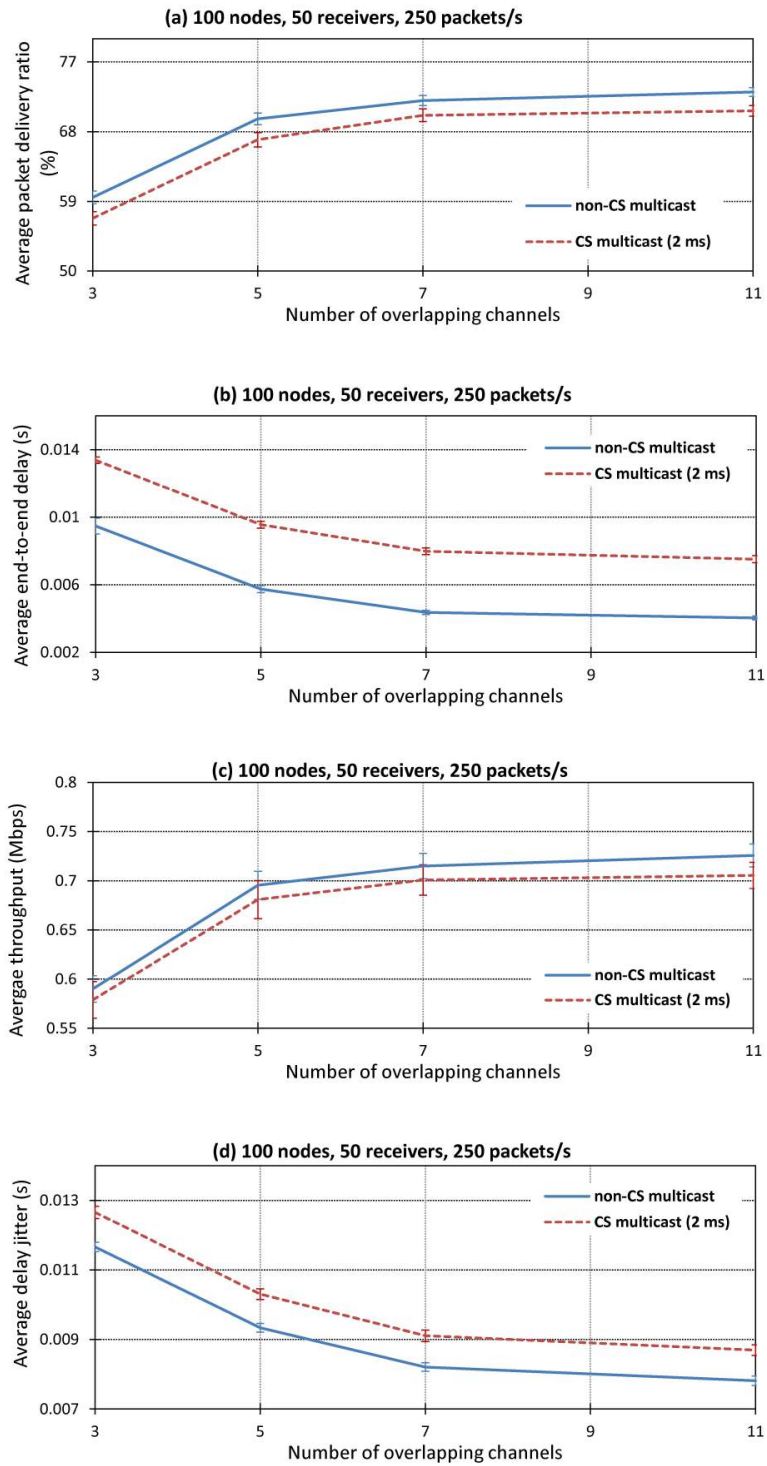


Figure 4.14: Functions of number of channels - 100-node network

Chapter 5

Comparison between the $c \leq r$ and $c > r$ Approaches

As discussed in Section 2.4, the $c \leq r$ approach does not require channel switching and therefore, benefits from a simple implementation. However, using a low number of channels in a network increases medium contention, channel sharing and interference, which in turn reduces the number of simultaneous transmissions, hence lowers the network throughput. As a result, the $c \leq r$ approach may be perceived as offering lower performance than the $c > r$ approach. On the other hand, the $c > r$ approach requires efficient channel switching schemes and carries additional channel switching costs, which is not negligible as shown in [30, 31] and demonstrated in Chapter 4. In this chapter, we perform a simulation-based study to compare the performance of multicast for the two cases: $c \leq r$ and $c > r$. Specifically, our goal here is to compare the performance of multicast between two groups of networks. The first group uses the $c > r$ approach and

the M4 algorithm for channel assignment. The second group uses the $c \leq r$ approach for channel assignment and the MCMNT algorithm [41] for multicast routing.

5.1 Implementations

In this chapter, our goal is to compare the performance of multicast using the $c \leq r$ and $c > r$ approaches. The implementations of the two approaches are described below:

- $c \leq r$: In this set of experiments, every node is equipped with three radios to receive and to forward multicast data packets. The number of channels assigned to a node is less than or equal to the number of radios it possesses; therefore channel switching is not required. To build the multicast routing tree, we apply the MCMNT algorithm [41] which follows the $c \leq r$ channel assignment (CA) approach. The MCMNT multicast routing tree connects the multicast source to all destinations such that the total number of transmissions required to deliver one packet from the source to all destinations is minimum (see Section 2.5). The MCMNT uses the “CA-first, routing-second” approach and therefore, we need to perform channel assignment first. We use a random CA scheme that complies with the constraint $c \leq r$. In this set of experiments, we assume three orthogonal channels as specified in IEEE 802.11b. Throughout this chapter (including the graphs), the experiments based on the $c \leq r$ CA approach are denoted by “MCMNT”, the multicast routing algorithm used in these experiments.
- $c > r$: In this set of simulations, we use the shortest-path-tree (SPT) algorithm

to build multicast routing trees. The SPT connects the multicast source to each destination via a minimum hop count path. Next, we use the M4 CA algorithm (see Section 2.4.4) to assign channels to the links in the multicast tree. The M4 CA belongs to the $c > r$ approach and its goal is to minimize the interference among nodes in a given MCMR WMN. It is applied on top of a pre-built multicast routing tree.

For this set of simulations, each node has three radios that are used for receiving data, sending data and managing control messages, respectively. Furthermore, since a node can be assigned more channels than the number of radios it possesses, we require a channel switching scheme which is implemented as follows. Before transmitting a data packet, a forwarder s in the multicast tree broadcasts an announcement (ANC) message on the control channel (using the CSMA/CA protocol) to announce the channel on which it will multicast the next data packet. Upon receiving the ANC, multicast neighbours of s tune to the announced channel to receive the multicast packet. (It may happen that not all neighbours receive the ANC message and thus may not be able to capture the data packet following the ANC message. Therefore, this channel switching scheme follows the current “best-effort” philosophy of medium access control for multicast in IEEE 802.11 WMNs as offered by the CSMA/CA protocol.) Finally, the forwarder transmits the data packet on the announced channel, also using the CSMA/CA protocol. To better demonstrate the effect of channel switching delay on the performance metrics, we

use two different hardware switching delay values of 2 ms and 10 ms. Since the value of software switching latency (about 0.05 milliseconds as measured in our simulations) is negligible in comparison with the hardware switching used (2 ms or 10 ms), we do not include it in our simulations. (However, in cases where the hardware switching latency is comparable to the software switching latency, the software switching latency must be considered.)

We emphasize here that the M4 algorithm always require a channel switching (CS) scheme because a node may be assigned more channels than the number of radios it possesses. Therefore, in practise, the M4 algorithm is usually used in combination with a CS scheme. The only reason that we simulated M4 without CS here is to provide a theoretical comparison of M4 with the MCMNT algorithm, assuming an ideal condition in which the number of radios is unlimited. Throughout this chapter, the scenarios of M4 without CS are identified by “non-CS M4” and the scenarios of M4 with channel switching are referred to as “CS M4”.

Furthermore, in all figures, the graphs corresponding to “CS M4” with 2 ms and 10 ms switching delay are indicated by “CS M4 (2ms)” and “CS M4 (10ms)”, respectively.

5.2 Simulation Parameters and Performance Metrics

The simulation parameters are the same as those described in Section 3.1, unless otherwise stated. Table 5.1 lists the common parameters. In our simulations, we randomly

distribute the nodes in the network area using a uniform distribution and place the multicast source in the centre of the area. (Figures B.1 to B.8 in the Appendix B show the examples of simulation topologies along with the corresponding multicast routing trees. In these figures, the multicast receivers are highlighted in red and the multicast source is node 1).

The performance metrics consist of average packet delivery ratio, average end-to-end delay, average throughput and average delay jitter as defined in Section 3.2. Specifically, we measure these metrics as functions of:

- *Multicast group size.* The number of multicast destinations varies from 10 to 40 in the 49-node network and from 10 to 70 in the 100-node network. The source transmits at a rate of 90 packets/s in the 100-node network and 250 packets/s in the 49-node network. The traffic rates are selected based on the calculations presented in Section 4.1 and the channel switching delay used for each scenario.
- *Multicast traffic load.* The multicast source rate at the application layer increases from 100 to 350 packets/s for both 49-node and 100-node networks. The multicast group size is 30 and 50 for 49-node network and 100-node networks, respectively.

Table 5.2 summarizes the parameters of the above simulation scenarios.

5.3 Experimental Results

The graphs obtained from the simulations are shown in Figures 5.1 to 5.4. Below we discuss and analyse the results.

Table 5.1: Common simulation parameters

Parameter	Value
Network size	50 nodes in a 1200m x 1200m area 100 nodes in a 1700m x 1700m area
Path loss model	free source for distances shorter than 250m two-ray for distances longer than 250m
Fading model	non
Transmission range	315m
Transmission rate at physical layer	11 Mbits/s
Physical layer protocol	PHY802.11b
Medium access control	MAC 802.11 with DCF
MAC for multicast flow	CSMA/CA
Packet size (excluding header size)	512 bytes
Queue size at routers	50 Kbytes
Queueing policy at routers	first-in-first-out
Traffic model of sources	constant bit rate (CBR)
Duration of each experiment	600 seconds of simulated time
Number of runs per data point	50
Confidence interval	95%

Table 5.2: Parameter setting for the simulations

Function of	Parameters	49-node network	100-node network
Multicast source rate	source rate	100 to 350 packets/s	
	group size	30 nodes	50 nodes
Multicast group size	source rate	250 packets/s	
	group size	10 to 40 nodes	10 to 70 nodes

5.3.1 Function of Traffic Load

The simulation results for the 49-node and 100-node networks are shown in Figures 5.1 and 5.2, respectively. We analyze and compare the performance of the M4 and MCMNT algorithms as the multicast group size varies:

- *Average packet delivery ratio:* Figures 5.1(a) and 5.2(a) illustrate the average packet delivery ratio as a function of the traffic load for 49-node and 100-node networks, respectively. In all cases, as the traffic load increases, the PDR decreases, as expected. However, in both 49-node and 100-node networks, MCMNT offers higher PDRs than non-CS M4 and CS M4 (2ms). The reason is the lower numbers of transmissions in MCMNT, which result in less medium contention, channel sharing and interference among nodes in the routing trees. Specifically, in the 100-node network, when the traffic load is 150 packets/sec, the PDR values corresponding to MCMNT, non-CS M4 and CS M4 (2ms) are 92%, 86% and 83%, respectively.

When the traffic load is 350 packets/sec, the PDR values corresponding to MCMNT, non-CS M4 and CS M4 (2ms) are 62%, 55% and 50%, respectively.

Although MCMNT uses only three channels, it provides higher PDRs than the M4 algorithm that uses eleven overlapping channels. The reason is that lower numbers of transmissions of MCMNT outperform the channel diversity effect of eleven channels in M4.

- *Average end to end delay:* Figures 5.1(b) and 5.2(b) show the average end-to-end delay as a function of the traffic load for the 49-node and 100-node networks, respectively. For all traffic conditions, M4 without CS offers smaller values of average end-to-end delay than MCMNT. The reason is shorter path lengths (hop counts) in M4 routing trees, which use SPT as their routing algorithm(See Table 5.3 for a comparison of average path lengths in routing trees produced by the SPT and MCMNT algorithms.) Note, however, that in practice M4 requires channel switching. Thus, the above result does not apply in real life, but is provided for a theoretical comparison to illustrate the effect of path length on the end-to-end delay.

Among all, CS M4 incurs the longest average end-to-end delays due to channel switching delays as explained at the end of Section 4.3.3. Specifically, in our 49-node network, when the multicast source rate is 350 packets/sec, the average end-to-end delay values for MCMNT, M4 and CS M4 are 3.6 ms, 2.8 ms and 6.5 ms, respectively. When the multicast source rate is 150 packets/sec, these values are 2.8 ms, 2.0 ms and 5.3 ms, respectively.

- *Average throughput:* The simulation results for the average throughput for the 49-node and 100-node networks are illustrated in Figures 5.1(c) and 5.2(c), respectively. In all scenarios for both 49-node and 100-node networks, MCMNT provides better throughput than M4 and CS M4. Specifically, in the 100-node network, when the multicast source rate is 350 packets/sec, the average throughput values for the MCMNT, M4 and CS M4 are 0.87 Mbps, 0.75 Mbps and 0.71 Mbps, respectively. When the multicast source rate is 150 packets/sec, these values are 0.55 Mbps, 0.50 Mbps and 0.49 Mbps, respectively. MCMNT provides higher throughput than non-CS M4 and CS M4 thanks to its higher PDRs. Although the throughput is a function of the PDR and end-to-end delay, the higher PDR of MCMNT outweighs its longer end-to-end delay and, as a result, the throughput of MCMNT is higher than that of non-CS M4 and CS M4.
- *Average delay jitter:* Figures 5.1(d) and 5.2(d) illustrate the average delay jitter as a function of the traffic load for the 49-node and 100-node networks, respectively. MCMNT has longer jitter values than non-CS M4 and CS M4. The reason lies in the longer paths of MCMNT when compared to M4 and CS M4 (see Table 5.3). In general, longer paths introduces larger number of forwarders to the multicast tree. With more forwarders, network gets more busy; therefore, channel sharing and medium contention increases and as a result, the delay jitter values increase. Specifically, in our 100-node network, when the traffic load is 350 packets/sec, the average delay jitter values for MCMNT, CS M4 and M4 are 8.7 ms, 6.6 ms and 5.8

ms, respectively.

In conclusion, MCMNT provides better PDR and throughput than non-CS M4 and CS M4. MCMNT also gives shorter end-to-end delay in comparison with CS M4. Non-CS M4 provides better performance than MCMNT in terms of average end-to-end delay and average delay jitter and under all traffic loads (However, M4 without CS will not be used in practice, because the M4 algorithm always requires channel switching). Finally, among all, CS M4 has the lowest performance due to switching delay.

5.3.2 Function of Multicast Group Size

In this section, we run each simulation using two different hardware channel switching delay values, 2 ms and 10 ms. The graphs in Figures 5.3 and 5.4 show the results for the 49-node and 100-node networks, respectively. We analyse the performance of the three schemes: MCMNT, non-CS M4 and CS M4.

- *Average packet delivery ratio.* Figures 5.3(a) and 5.4(a) illustrate the average packet delivery ratio as a function of the number of multicast destinations for 49-node and 100-node networks, respectively. In both networks, MCMNT provides better delivery ratios for different multicast group sizes. Low numbers of transmissions enable MCMNT to outperform non-CS M4 and CS M4. Specifically, in our 100-node network (Figure 5.4(a)), when the group-size is 10, the values of PDR for MCMNT, non-CS M4 and CS M4 (10 ms) are 96%, 93% and 82%, respectively. As the group size increases to 70, such values decrease to 90%, 84% and 79%.

- *Average end-to-end delay.* The results for the average end-to-end delay for 49-node and 100-node networks are illustrated in Figures 5.3(b) and 5.4(b), respectively. In all simulations for both 49-node and 100-node networks, non-CS M4 has shorter average end-to-end delay in comparison with the MCMNT. The reason is shorter path lengths in M4 routing trees when compared with path lengths in MCMNT trees (see Table 5.3). (Note that, in practice, M4 requires channel switching and the results for the comparison between MCMNT and non-CS M4 are only provided to demonstrate the effect of path length on the end-to-end delay). Among all, CS M4 with 10 ms switching delay has the longest average end-to-end delay and the reason is the channel switching delay that occurs between every two consecutive data packets.

Specifically, in our 100-node network, when the multicast group size is 70, average end-to-end values for the non-CS M4, MCMNT and CS M4 (10 ms) hardware switching delay are 3.8 ms, 5.4 ms and 33 ms, respectively (see Figure 5.4(b)).

Table 5.3: Average path lengths for the 49-node network

Group size	Average path length (SPT)	Average path length (MCMNT)
10	2	3.4
20	1.95	3.34
30	1.90	3.12
40	1.85	2.84

- *Average throughput.* Figures 5.3(c) and 5.4(c) illustrate the average throughputs for the 49-node and 100-node networks, respectively. In all cases, MCMNT provides higher throughputs than non-CS M4 and CS M4. For instance, in the 100-node network, when the group size is 10, the values of the average throughput for MCMNT, non-CS M4 and CS M4 with 10 ms hardware switching delay are 0.345 Mbps, 0.33 Mbps and 0.299 Mbps, respectively. When the group size is 70, these values are 0.308 Mbps, 0.289 Mbps and 0.266 Mbps, respectively. Following is the explanation for this result. The throughput is a function of the PDR and end-to-end delay as defined in Section 3.2. In comparison with CS M4, MCMNT has higher PDR values and shorter end-to-end delays, and therefore, provides higher values of throughput. In comparison with non-CS multicast, MCMNT offers higher values of PDR, but longer end-to-end delay. However, the higher PDR of MCMNT outweighs its longer end-to-end delay. Therefore, MCMNT has higher throughput than non-CS multicast.
- *Average delay jitter.* Figures 5.3(d) and 5.4(d) illustrate the average delay jitter for the 49-node and 100-node networks, respectively. MCMNT has longer delay jitter values than non-CS M4 and CS M4. MCMNT has longer path lengths (measured in hops) in comparison with M4 and CS M4 (see Table 5.3) and longer paths introduces larger number of forwarders to the multicast tree. With larger number of nodes, network gets more busy; therefore, channel sharing and medium contention increases and as a result, the delay jitter values increase.

Specifically, in the 100-node network, when the group size is 10 and hardware switching delay is 2 ms, the average delay jitter values for the MCMNT, M4 and the CS M4 are 7.5 ms, 4.3 ms and 6 ms, respectively. When group size is 70, these numbers increase to 9.2 ms, 4.8 ms and 8 ms, respectively.

In summary, as the multicast group size grows, MCMNT provides better throughput and PDRs than M4 and CS M4. The reason is that MCMNT benefits from lower numbers of transmissions. CS M4 incurs the longest values of average end to end delay because of the channel switching overheads.

MCMNT and non-CS M4 have the longest and the shortest values of average delay jitter, respectively. The reason is that in all M4 simulations, we use the SPT algorithm to build multicast trees. SPT uses the shortest path when delivering a packet from a source to a destination (while MCMNT paths are longer), resulting in lower jitter values as explained above.

5.4 Chapter Summary

In this chapter, we conduct a simulation-based study to compare the performance of multicast for the two cases where $c \leq r$ and $c > r$. For the first approach ($c \leq r$), we use the MCMNT routing algorithm and random channel assignment. For the second approach ($c > r$), we use the SPT routing algorithm and the M4 CA algorithm to build multicast routing trees and assign channels to links, respectively. We measure the average packet delivery ratio, throughput, end-to-end delay, and delay jitter as functions of the

group size and traffic load. Our simulation results show that in all cases

- MCMNT provides higher average PDRs and throughput than CS M4 because of its lower numbers of transmissions.
- MCMNT offers shorter end-to-end delay than CS M4 due to the channel switching overhead that CS M4 incurs.
- Non-CS M4 and CS M4 have lower jitter than MCMNT, thanks to shorter paths in their multicast routing trees.

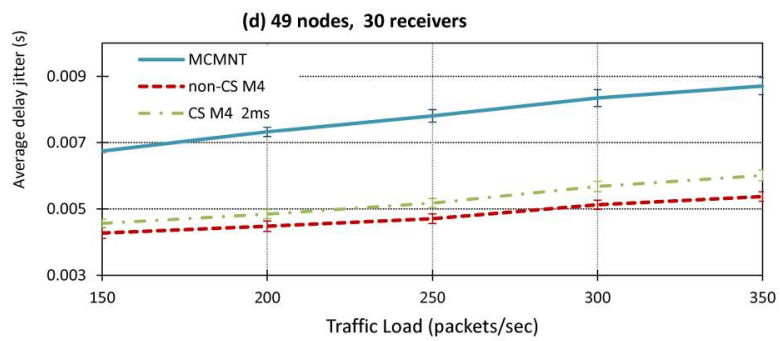
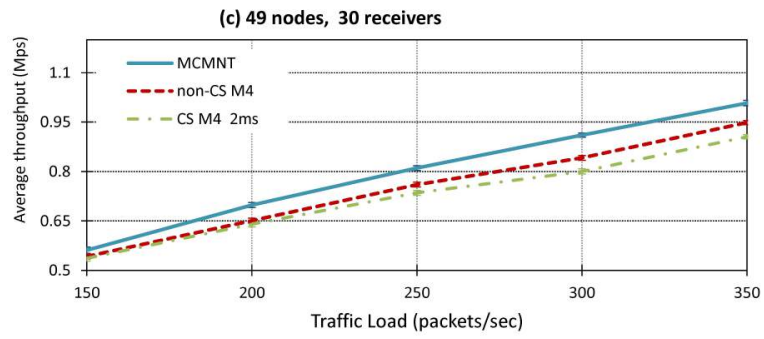
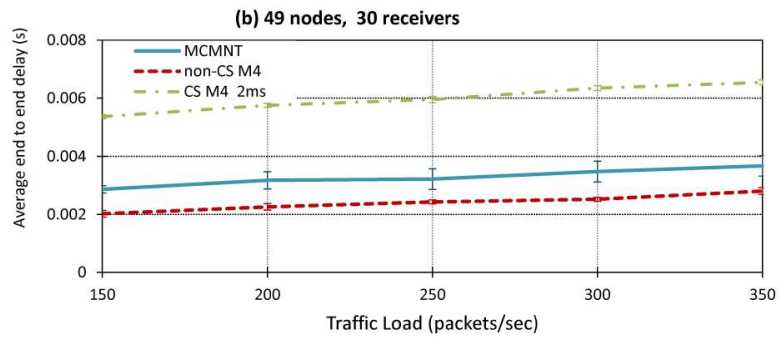
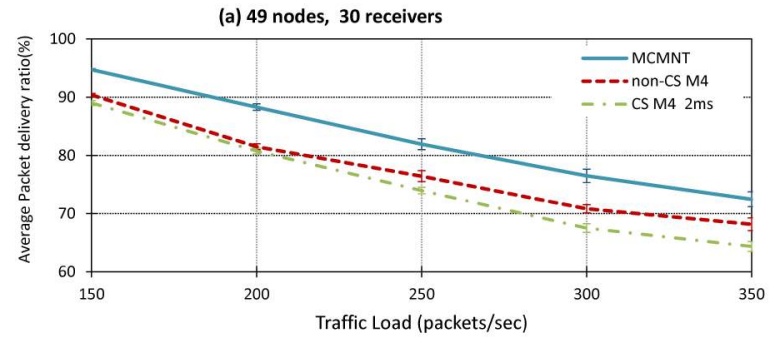


Figure 5.1: Functions of traffic load - 49-node network

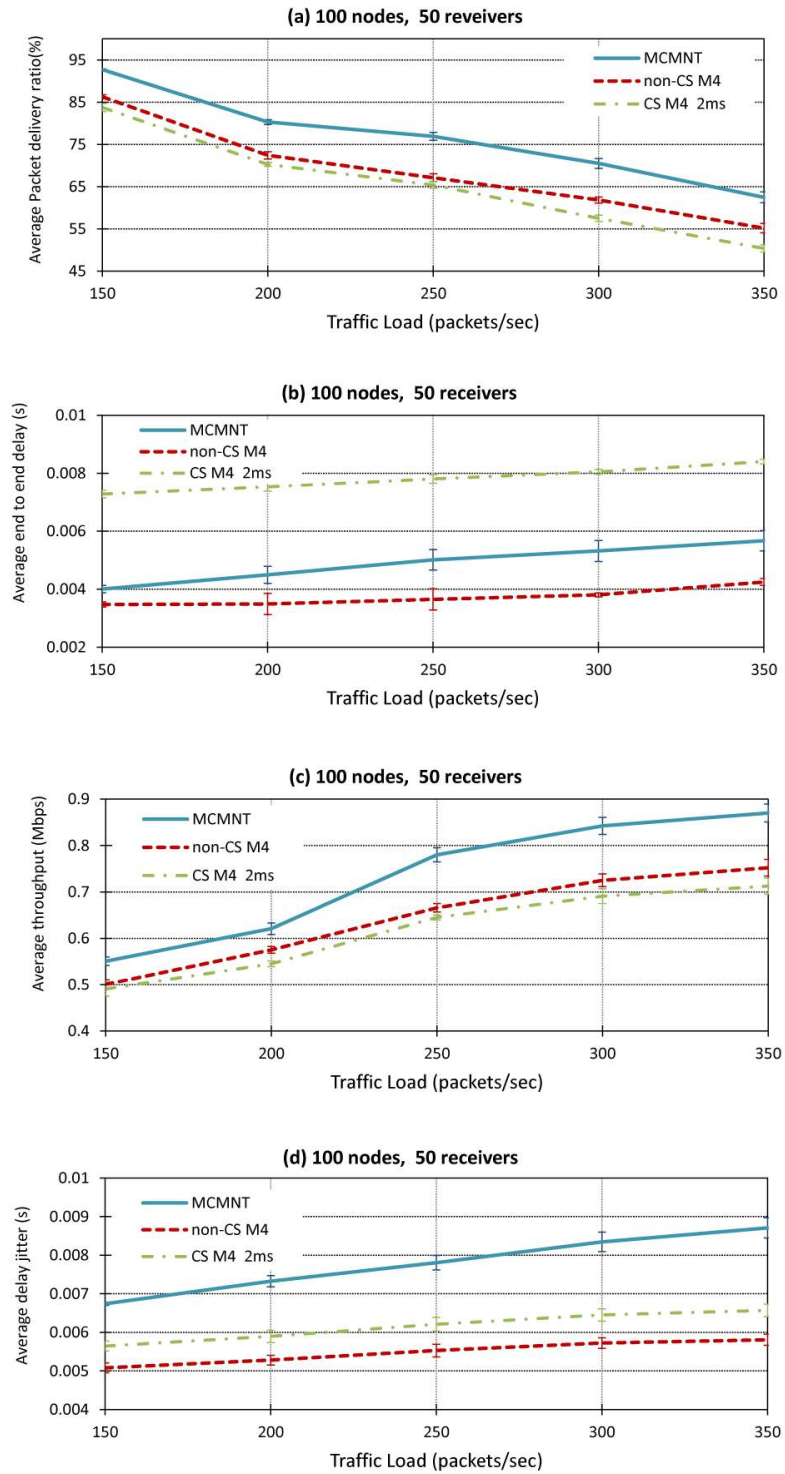


Figure 5.2: Functions of traffic load - 100-node network

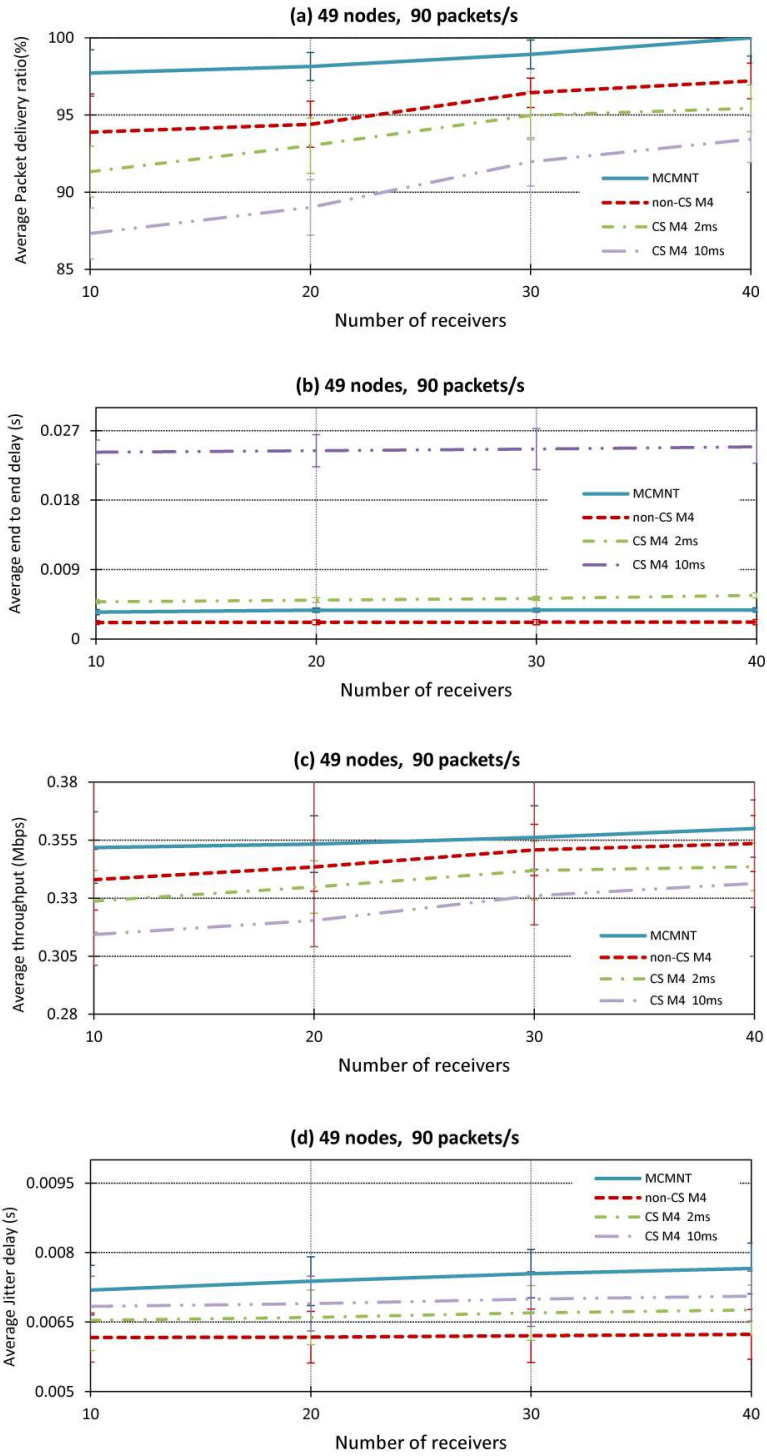


Figure 5.3: Functions of group size - 49-node network (90 packets/sec)

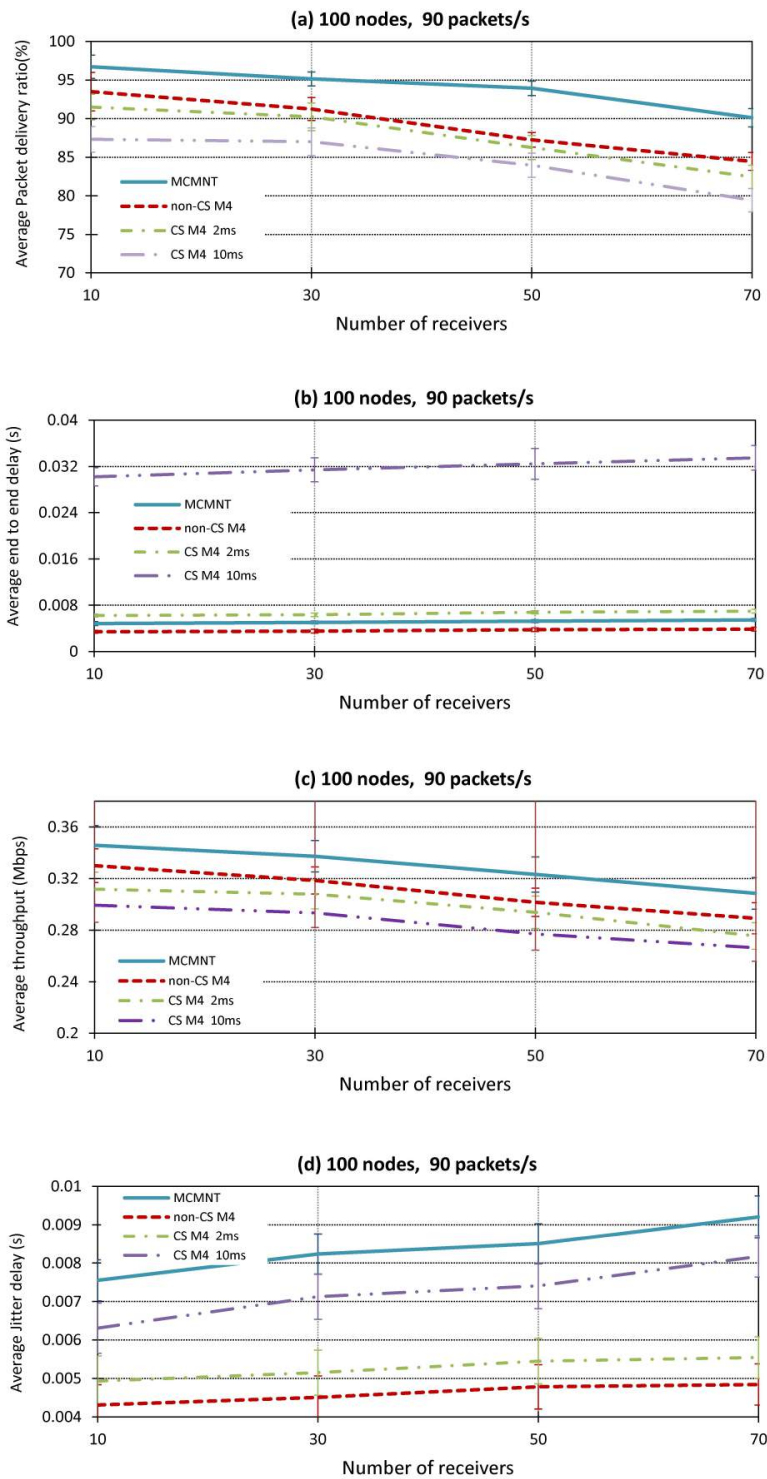


Figure 5.4: Functions of group size - 100-node network (90 packets/sec)

Chapter 6

Conclusion and Future Research Directions

In this thesis, we present simulation-based studies of the following problems:

1. The performance of multicast in MCMR WMNs with three orthogonal channels versus eleven overlapping channels defined in IEEE 802.11b.
2. The performance of the Minimum-interference Multi-channel Multi-radio Multicast (M4) algorithm with and without channel switching.
3. The performance of the Multi-Channel Minimum Number of Transmissions (MCMNT) algorithm (which does not do channel switching) in comparison with the M4 algorithm (which performs channel switching).

Performance of the M4 Algorithm: Orthogonal vs. Overlapping Channels

We studied the performance of networks that use three orthogonal channels versus those using eleven overlapping channels of IEEE 802.11b. In our work, we measured the average packet delivery ratio (PDR), end-to-end delay, throughput and delay jitter as functions of traffic load and multicast group size. The results obtained from our simulations show that in all cases, using eleven overlapping channels offers higher performance in terms of packet delivery ratio, end-to-end delay, throughput and delay jitter.

Impact of Channel-Switching on the Performance of Multicast in MCMR WMNs

We performed simulation-based study to measure the overhead of channel-switching on the performance of the M4 algorithm in MCMR-WMNs. We simulated different network scenarios and ran each simulation for two cases: with and without channel switching. In our simulations, we used eleven overlapping channels as specified in IEEE 802.11b. We measured the average PDR, throughput, end-to-end delay and delay jitter as functions of multicast group size, number of channels used in the network and traffic load. The results obtained from the simulations show that channel switching multicast performs worse than non-channel switching multicast in all scenarios due to channel switching delay. Moreover, the latency of channel switching has the most significant effect on the average end-to-end delay.

Comparison between the $c \leq r$ and $c > r$ Approaches

We compared the performance of multicast using two channel assignment approaches: $c \leq r$ and $c > r$. For the first approach, we used a random channel-assignment scheme and the MCMNT routing algorithm. For the second approach, where $c > r$, we used the M4 channel assignment algorithm and shortest path multicast routing trees. We measured the average PDR, end-to-end delay, throughput and jitter as functions of multicast group size, number of available channels and traffic load. The results obtained from the simulations show that in all cases, in terms of average PDR, end to end delay and throughput, the $c \leq r$ network offers better results. As for the average delay jitter, the $c > r$ network provides better results.

Open Issues and Directions for Future Research

In the following sections, we outline open issues and research directions for future work.

Theoretical analysis of channel switching overheads on multicast performance

In Chapter 4 and Chapter 5, we applied a simple channel switching algorithm to the simulations. In our future work, we will perform a theoretical analysis to evaluate the performance of multicast with and without channel switching.

More comprehensive simulations by using multiple multicast flows

When evaluating the performance of multicast, we used a single multicast source in our simulations. To have a more comprehensive evaluation of the performance of multicast with and without channel switching, we will further use multiple multicast sources in our simulation scenarios.

Channel assignment schemes for MCMNT

In our work in Chapter 5, we used random channel assignment scheme along with MCMNT multicast tree in our simulations. In our future work, we will evaluate the performance of multicast when applying more sophisticated channel assignment schemes in our simulations.

Appendix A

Implementation of Channel Switching in QualNet Simulator

We used QualNet network simulator for the simulations reported in this thesis. QualNet simulator is a scalable simulation engine which makes good use of computational resources and models large-scale networks with heavy traffic and mobility, in reasonable simulation time.

This simulator uses the layered architecture of the TCP/IP network protocol stack (see Figure A.1). Within that architecture, data moves between adjacent layers. QualNet's protocol stack consists of, from top to bottom, the application, transport, network, data link and physical layers.

Adjacent layers in the protocol stack communicate via well-defined APIs, and generally, layer communication occurs only between adjacent layers. For example, transport-layer protocols interact with application and network layers, but cannot do so with the

data link-layer protocols or the physical-layer protocols. This rule concerning communication only between adjacent layers may be circumvented by the programmer.

Although QualNet simulator comes with many built-in protocols, its functionality can be further extended by implementing and adding custom protocols to each of the layers of the QualNet protocol stack.

For this thesis, to be able to run the channel switching simulations, we modified the source code of the QualNet and added our channel switching algorithm to augment the functionalities of the simulator. The channel switching algorithm that we implemented and added to QualNet is described in Section 4.2. Table A.1 presents a list of source files that we modified and the number of lines of code added to each file.

Specifically, we modified files “networkip.cpp” and “network.cpp” to add the code of our channel switching algorithm into the simulator. In file “multicastrouting.cpp”, we modified the queue structure of the routers in QualNet in order to accommodate the Announcement Messages (ANC) generated by the channel switching algorithm as described in Section 4.2.

Table A.1: List of the source files modified in QualNet

File name	Layer in protocol stack	Lines of code added
networkip.cpp	Network layer	223
network.cpp	Network layer	114
multicastrouting.cpp	Network layer	87

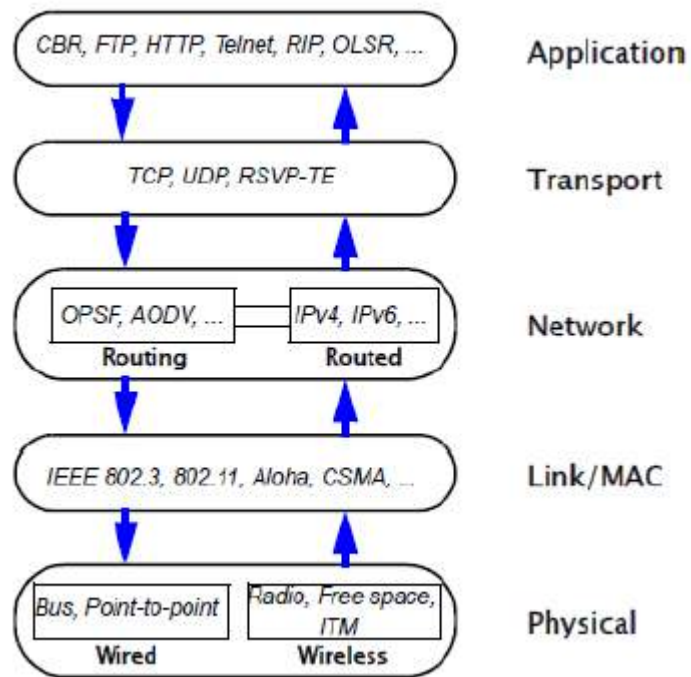


Figure A.1: QualNet protocol stack

Appendix B

Sample Network Topologies

Figures B.1 to B.8 illustrate sample network topologies used in our simulations. In these figures, nodes are indicated by numbers and are distributed randomly in a square area the dimension of which is specified on the axes. The multicast source node, node 1, is located in the centre of the area and the multicast receivers are illustrated in red. The blue line segments connecting the nodes represents the multicast routing tree connecting the multicast source to all multicast destinations.

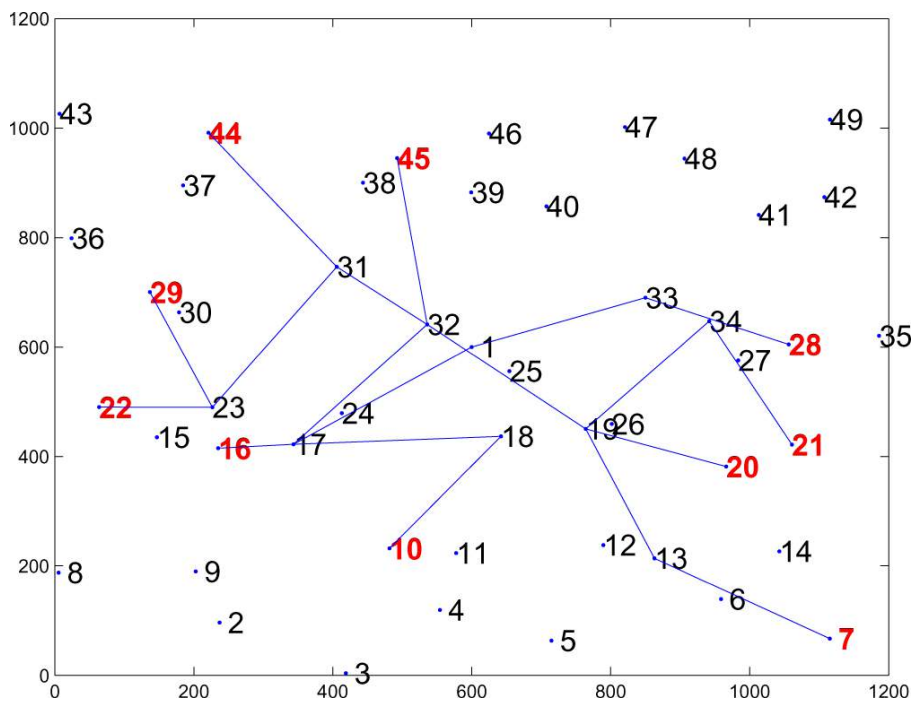


Figure B.1: 49-node network using MCMNT routing tree and 10 multicast receivers

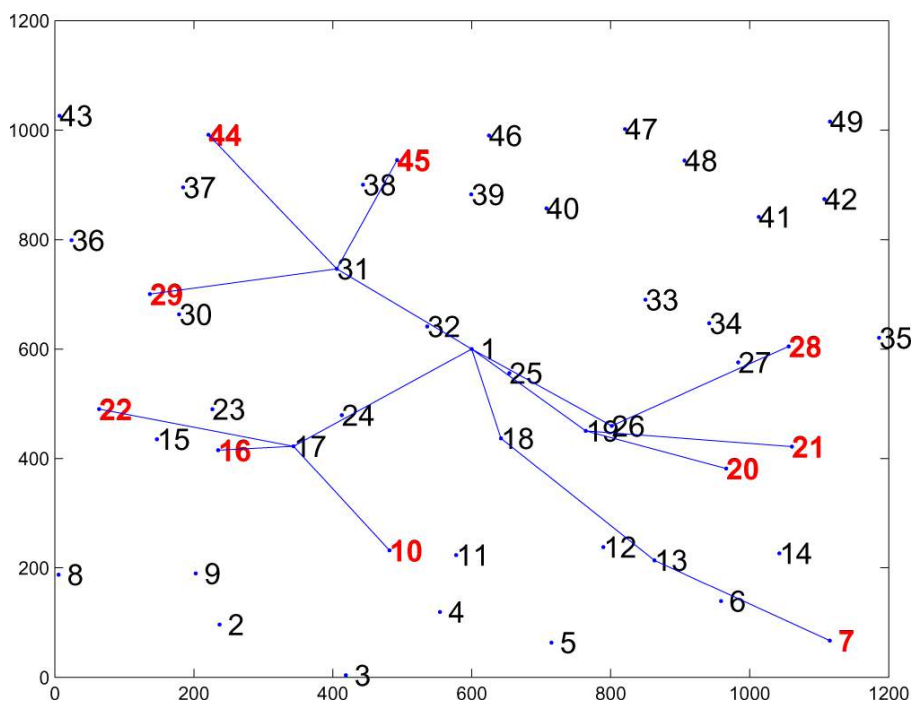


Figure B.2: 49-node network using SPT routing tree and 10 multicast receivers

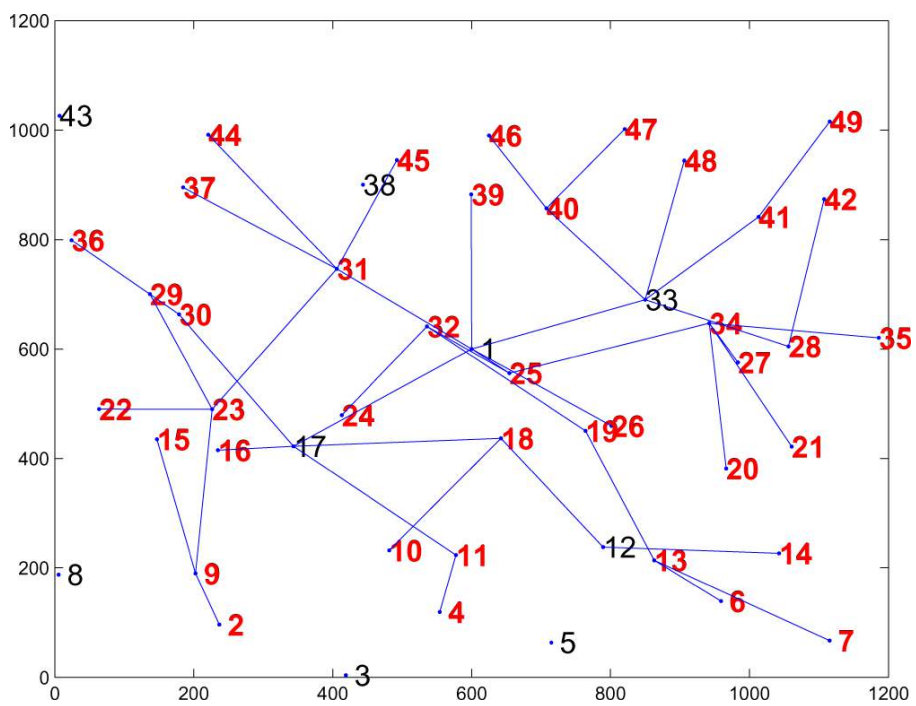


Figure B.3: 49-node network using MCMNT routing tree and 40 multicast receivers

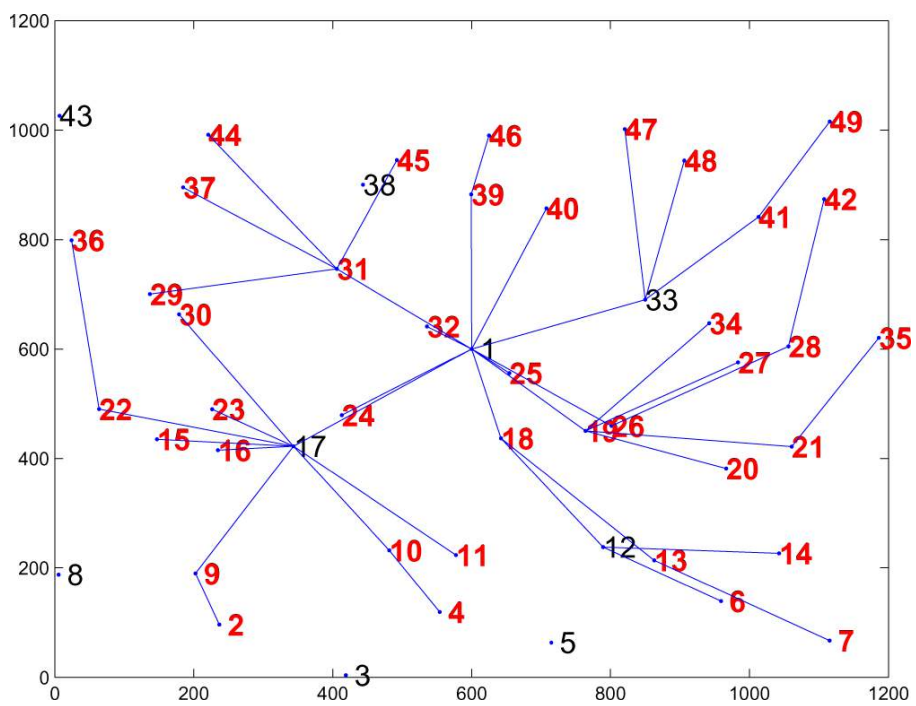


Figure B.4: 49-node network using SPT routing tree and 40 multicast receivers

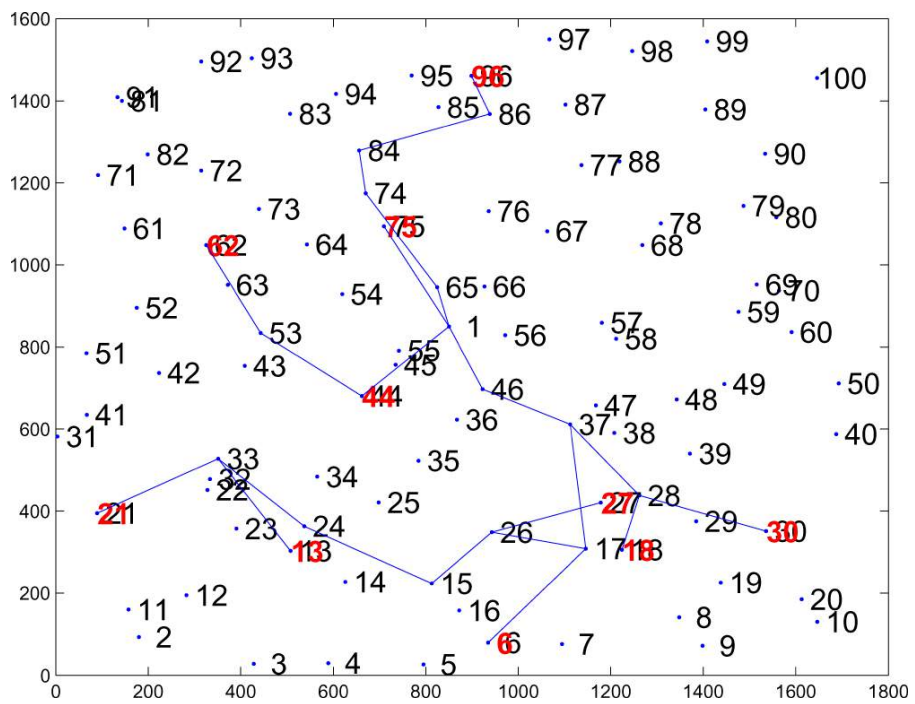


Figure B.5: 100-node network using MCMNT routing tree and 10 multicast receivers

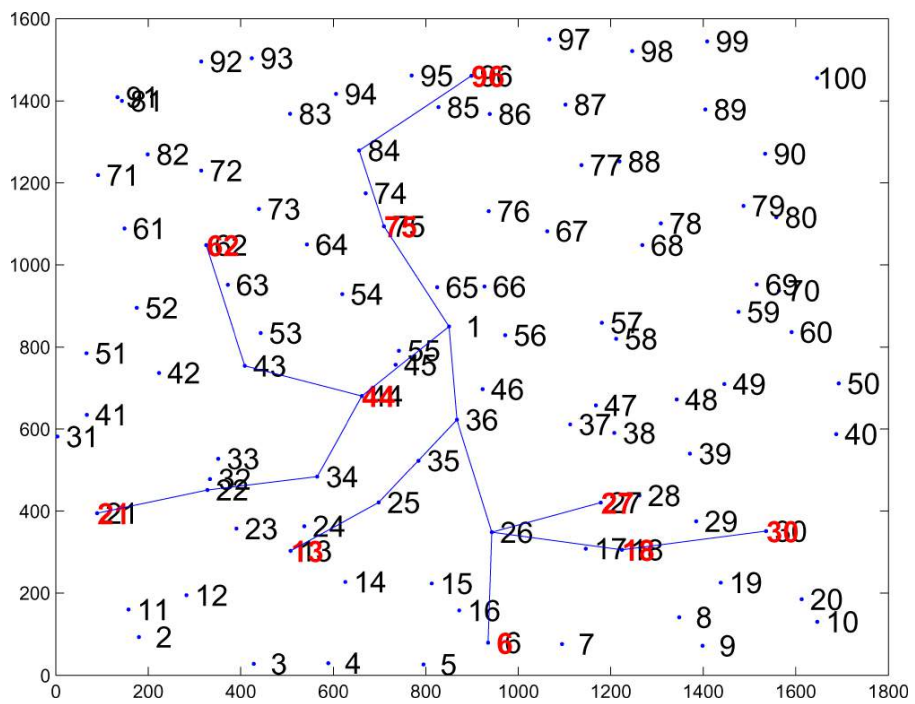


Figure B.6: 100-node network using SPT routing tree and 10 multicast receivers

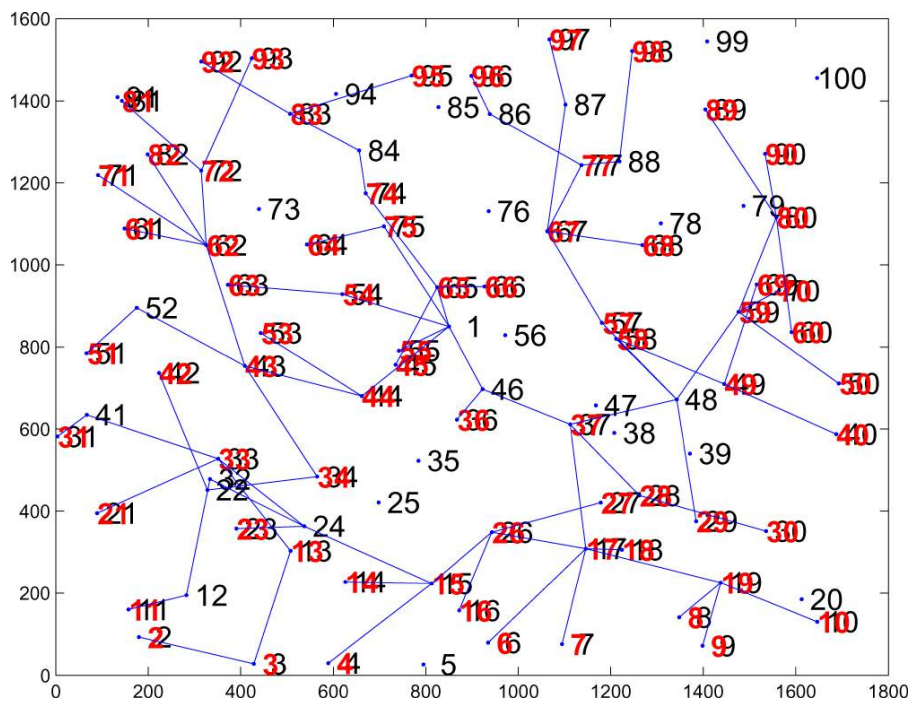


Figure B.7: 100-node network using MCMNT routing tree and 70 multicast receivers

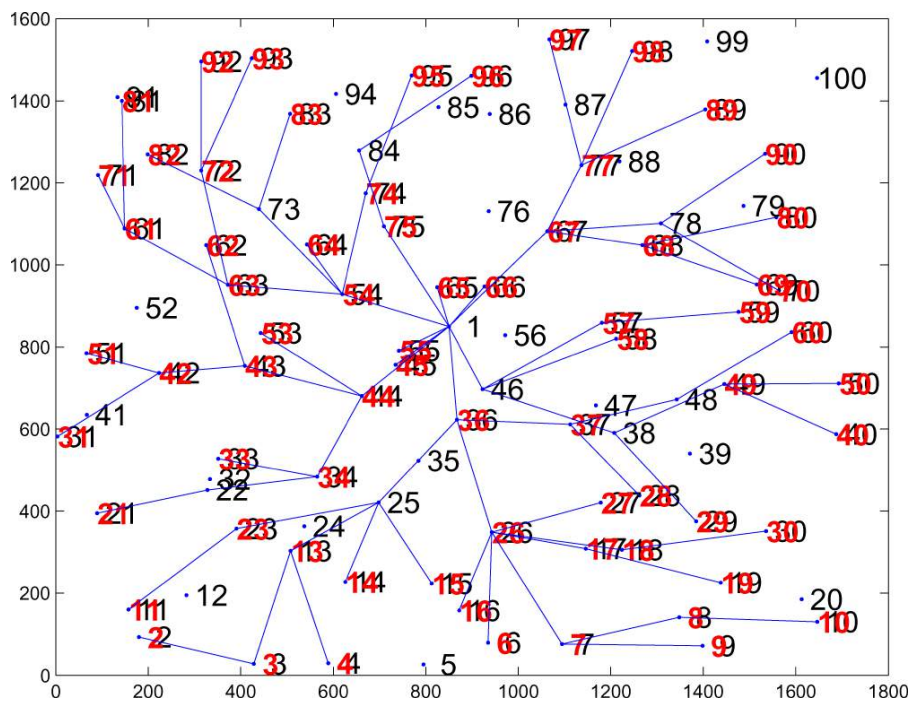


Figure B.8: 100-node network using SPT routing tree and 70 multicast receivers

Bibliography

- [1] M. L. Sichitiu, “Wireless mesh networks: opportunities and challenges,” in *Proceedings of World Wireless Congress*, vol. 2, 2005.
- [2] I. F. Akyildiz, X. Wang, and W. Wang, “Wireless mesh networks: a survey,” *Computer Networks*, vol. 47, no. 4, pp. 445 – 487, 2005.
- [3] P. Gupta and P. Kumar, “The capacity of wireless networks,” *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388–404, 2000.
- [4] S. Shakkottai, X. Liu, and R. Srikant, “The multicast capacity of large multi-hop wireless networks,” *IEEE/ACM Transactions on Networking*, vol. 18, no. 6, pp. 1691–1700, 2010.
- [5] V. Kapse and U. Shrawankar, “Interference-aware channel assignment for maximizing throughput in WMN,” *International Journal on Ad-hoc Networking Systems*, vol. 1, pp. 1–12, 2013.
- [6] K. Ramachandran, E. Belding, K. Almeroth, and M. Buddhikot, “Interference-aware channel assignment in multi-radio wireless mesh networks,” in *IEEE International Conference on Computer Communications (INFOCOM)*, pp. 1–12, 2006.
- [7] A. Singh and K. Singh, “Load balancing based channel assignment in multicast wireless mesh network,” in *IEEE International Conference on Computing for Sustainable Global Development*, pp. 865–869, 2014.
- [8] M. Yun, Y. Zhou, A. Arora, and H.-A. Choi, “Channel-assignment and scheduling in wireless mesh networks considering switching overhead,” in *IEEE International Conference on Communications*, pp. 1–6, 2009.
- [9] M. Harris and S. Harvey, “Channel switching overhead for 802.11b,” Technical Report, 2009.
- [10] P. N. Kyasanur, *Multi-Channel Wireless Networks: Capacity and Protocols*. PhD thesis, University of Illinois at Urbana-Champaign, 2006.

- [11] N. Jain, S. R. Das, and A. Nasipuri, "A multi-channel CSMA MAC protocol with receiver-based channel selection for multi-hop wireless networks," in *IEEE International Conference on Computer Communications and Networks*, pp. 432–439, 2001.
- [12] A. Nasipuri, J. Zhuang, and S. R. Das, "A multi-channel CSMA MAC protocol for multi-hop wireless networks," in *IEEE Conference on Wireless Communications and Networking*, pp. 1402–1406, 1999.
- [13] A. Nasipuri and S. R. Das, "Multichannel CSMA with signal power-based channel selection for multi-hop wireless networks," in *IEEE Vehicular Technology Conference*, vol. 1, pp. 211–218, 2000.
- [14] A. Raniwala and T.-c. Chiueh, "Architecture and algorithms for an ieee 802.11-based multi-channel wireless mesh network," in *Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 3, pp. 2223–2234, 2005.
- [15] M. Alicherry, R. Bhatia, and L. E. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," in *ACM International Conference on Mobile Computing and Networking*, pp. 58–72, 2005.
- [16] J. Tang, G. Xue, and W. Zhang, "Interference-aware topology control and QoS routing in multi-channel wireless mesh networks," in *ACM International Symposium on Mobile Ad-hoc Networking and Computing*, pp. 68–77, 2005.
- [17] A. K. Das, H. M. Alazemi, R. Vijayakumar, and S. Roy, "Optimization models for fixed channel assignment in wireless mesh networks with multiple radios," in *IEEE International Conference on Sensing, Communication and Networking*, pp. 463–474, 2005.
- [18] M. K. Marina, S. R. Das, and A. P. Subramanian, "A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks," *Computer Networks*, vol. 54, no. 2, pp. 241–256, 2010.
- [19] A. P. Subramanian, H. Gupta, S. R. Das, and J. Cao, "Minimum interference channel assignment in multi-radio wireless mesh networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 12, pp. 1459–1473, 2008.
- [20] V. W. Wong *et al.*, "Joint optimal channel assignment and congestion control for multi-channel wireless mesh networks," in *IEEE International Conference on Communications*, vol. 5, pp. 1984–1989, 2006.
- [21] P. Kyasanur and N. H. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," in *IEEE Conference on Wireless Communications and Networking*, vol. 4, pp. 2051–2056, 2005.

- [22] H. Wu, F. Yang, K. Tan, J. Chen, Q. Zhang, and Z. Zhang, "Distributed channel assignment and routing in multi-radio multi-channel multihop wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, pp. 1972–1983, 2006.
- [23] B.-J. Ko, V. Misra, J. Padhye, and D. Rubenstein, "Distributed channel assignment in multi-radio 802.11 mesh networks," in *IEEE Conference on Wireless Communications and Networking*, pp. 3978–3983, 2007.
- [24] K. Almeroth and B. Quinn, "IP multicast applications: challenges and solutions," Technical Report, 2001.
- [25] N. Jain, S. R. Das, and A. Nasipuri, "A multi-channel CSMA MAC protocol with receiver-based channel selection for multi-hop wireless networks," in *ACM International Conference on Computer Communications and Networks*, pp. 432–439, 2001.
- [26] Y. Liu and E. Knightly, "Opportunistic fair scheduling over multiple wireless channels," in *IEEE INFOCOM*, vol. 2, pp. 1106–1115, 2003.
- [27] J. So and N. H. Vaidya, "A routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver," *University of Illinois at Urbana-Champaign*, 2004.
- [28] J. So and N. H. Vaidya, "Multi-channel mac for ad-hoc networks: handling multi-channel hidden terminals using a single transceiver," in *ACM International Symposium on Mobile Ad-hoc Networking and Computing*, pp. 222–233, 2004.
- [29] Z. Yang and J. Garcia-Luna-Aceves, "Hop-reservation multiple access (HRMA) for ad-hoc networks," in *IEEE INFOCOM*, vol. 1, pp. 194–201, 1999.
- [30] P. Kyasanur and N. H. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," in *IEEE Conference on Wireless Communications and Networking*, vol. 4, pp. 2051–2056, IEEE, 2005.
- [31] A. Raniwala, K. Gopalan, and T.-c. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *ACM Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50–65, 2004.
- [32] "Wireless lan Medium Access Control (MAC) and Physical Layer (PHY) specifications," *IEEE Computer Society LAN MAN Standards Committee and others*, 1997.
- [33] K. Tang and M. Gerla, "Random access MAC for efficient broadcast support in ad-hoc networks," in *IEEE Wireless Communications and Networking Conference*, vol. 1, pp. 454–459, 2000.

- [34] M. Sun, L. Huang, S. Wang, A. Arora, and T.-H. Lai, “Reliable MAC layer multicast in ieee 802.11 wireless networks,” *Wireless Communications and Mobile Computing*, vol. 3, no. 4, pp. 439–453, 2003.
- [35] A. Chen, D. Lee, G. Chandrasekaran, and P. Sinha, “Himac: High throughput MAC layer multicasting in wireless networks,” in *IEEE International Conference on Mobile Ad-hoc and Sensor Systems*, pp. 41–50, 2006.
- [36] S.-H. Lee and J.-Y. Choi, “A medium access control scheme for providing reliability in wireless ad-hoc networks,” *WASA*, 2006.
- [37] J. Xie, A. Das, and S. Nandi, “An improvement to the reliability of ieee 802.11 broadcast scheme for multicasting in mobile ad-hoc networks,” in *IEEE Communications Society Conference on Sensor and Ad-hoc Communications and Networks*, pp. 359–366, 2004.
- [38] X. Wang, L. Wang, Y. Wang, Y. Zhang, and A. Yamada, “Supporting MAC layer multicast in ieee 802.11 n: Issues and solutions,” in *IEEE Conference on Wireless Communications and Networking*, pp. 1–6, 2009.
- [39] J. Li, C. Blake, D. S. De Couto, H. I. Lee, and R. Morris, “Capacity of ad-hoc wireless networks,” in *ACM International Conference on Mobile Computing and Networking*, pp. 61–69, 2001.
- [40] P. Kyasanur and N. H. Vaidya, “Capacity of multi-channel wireless networks: impact of number of channels and interfaces,” in *ACM International Conference on Mobile Computing and Networking*, pp. 43–57, 2005.
- [41] H. L. Nguyen, *High-performance Multicast in Multi-Channel Mlti-Radio Wireless Mesh Networks*. PhD thesis, York University, 2012.
- [42] M. Doraghinejad, H. Nezamabadi-Pour, and A. Mahani, “Channel assignment in multi-radio wireless mesh networks using an improved gravitational search algorithm,” *Journal of Network and Computer Applications*, vol. 38, pp. 163–171, 2014.
- [43] E. Rashedi, H. Nezamabadi-Pour, and S. Saryazdi, “Gsa: a gravitational search algorithm,” *Information Sciences*, vol. 179, no. 13, pp. 2232–2248, 2009.
- [44] S.-L. Tsao, J.-J. Su, K.-L. Huang, Y.-C. Shih, and C.-C. Tseng, “An end-to-end channel allocation scheme for a wireless mesh network,” *International Journal of Communication Systems*, vol. 27, no. 12, pp. 4407–4429, 2014.
- [45] A. Dhananjay, H. Zhang, J. Li, and L. Subramanian, “Practical, distributed channel assignment and routing in dual-radio mesh networks,” in *ACM SIGCOMM Computer Communication Review*, vol. 39, pp. 99–110, 2009.

- [46] D. Benyamina, A. Hafid, and M. Gendreau, "Wireless mesh networks design: a survey," *IEEE Communications Surveys and Tutorials*, vol. 14, no. 2, pp. 299–310, 2012.
- [47] K. Athota and A. Negi, "A topology preserving cluster-based channel assignment for wireless mesh networks," *International Journal of Communication Systems*, 2014.
- [48] H. Cheng, N. Xiong, L. T. Yang, G. Chen, X. Zhuang, and C. Lee, "Links organization for channel assignment in multi-radio wireless mesh networks," *Multimedia tools and Applications*, vol. 65, no. 2, pp. 239–258, 2013.
- [49] R. Poli, J. Kennedy, and T. Blackwell, "Particle swarm optimization," *Swarm Intelligence*, vol. 1, no. 1, pp. 33–57, 2007.
- [50] Y.-Y. Chen and C. Chen, "Simulated annealing for interface-constrained channel assignment in wireless mesh networks," *Ad-hoc Networks*, vol. 29, pp. 32–44, 2015.
- [51] S. Kirkpatrick, C. D. Gelatt, M. P. Vecchi, *et al.*, "Optimization by simulated annealing," *Science*, vol. 220, no. 4598, pp. 671–680, 1983.
- [52] G. Zeng, B. Wang, Y. Ding, L. Xiao, and M. Mutka, "Multicast algorithms for multi-channel wireless mesh networks," in *IEEE International Conference on Network Protocols*, pp. 1–10, 2007.
- [53] H. Skalli, S. Ghosh, S. K. Das, L. Lenzini, and M. Conti, "Channel assignment strategies for multi-radio wireless mesh networks: issues and solutions," *IEEE Communications Magazine*, vol. 45, no. 11, pp. 86–95, 2007.
- [54] W. Si, S. Selvakennedy, and A. Y. Zomaya, "An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks," *Journal of Parallel and Distributed Computing*, vol. 70, no. 5, pp. 505–524, 2010.
- [55] J. Yang, Y. Wang, K. Hua, and W. Wang, "Fairness based dynamic channel allocation in wireless mesh networks," in *International Conference on Computing, Networking and Communications*, pp. 556–560, 2014.
- [56] Y. Ding and L. Xiao, "Channel allocation in multi-channel wireless mesh networks," *Computer Communications*, vol. 34, no. 7, pp. 803–815, 2011.
- [57] H. Cheng, N. Xiong, A. V. Vasilakos, L. T. Yang, G. Chen, and X. Zhuang, "Nodes organization for channel assignment with topology preservation in multi-radio wireless mesh networks," *Ad Hoc Networks*, vol. 10, no. 5, pp. 760–773, 2012.
- [58] E. Ahmed, M. Shiraz, and A. Gani, "Spectrum-aware distributed channel assignment for cognitive radio wireless mesh networks," *Malaysian Journal of Computer Science*, vol. 26, no. 3, pp. 232–250, 2013.

- [59] R. Riggio, T. Rasheed, S. Testi, F. Granelli, and I. Chlamtac, "Interference and traffic aware channel assignment in wifi-based wireless mesh networks," *Ad-hoc Networks*, vol. 9, no. 5, pp. 864–875, 2011.
- [60] M. Shojafar, S. Abolfazli, H. Mostafaei, and M. Singhal, "Improving channel assignment in multi-radio wireless mesh networks with learning automata," *Wireless Personal Communications*, vol. 82, no. 1, pp. 61–80, 2015.
- [61] X. Deng, Q. Liu, X. Li, L. Cai, and Z. Chen, "A load balance link layer protocol for multi-channel multi-interface wireless mesh networks," in *IEEE International Conference on High Performance Computing and Communications*, pp. 1287–1293, 2013.
- [62] J. Wang, W. Shi, and F. Jin, "On channel assignment for multicast in multi-radio multi-channel wireless mesh networks: A survey," *Communications, China*, vol. 12, no. 1, pp. 122–135, 2015.
- [63] G. Zeng, B. Wang, Y. Ding, L. Xiao, and M. Mutka, "Multicast algorithms for multi-channel wireless mesh networks," in *IEEE International Conference on Network Protocols*, pp. 1–10, 2007.
- [64] P. Bahl, R. Chandra, and J. Dunagan, "Ssch: slotted seeded channel hopping for capacity improvement in ieee 802.11 ad-hoc wireless networks," in *ACM International Conference on Mobile Computing and Networking*, pp. 216–230, 2004.
- [65] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-P. Sheu, "A new multi-channel mac protocol with on-demand channel assignment for multi-hop mobile ad hoc networks," in *International Symposium on Parallel Architectures, Algorithms and Networks*, pp. 232–237, IEEE, 2000.
- [66] A. Raniwala and Chiueh, "Evaluation of a wireless enterprise backbone network architecture," in *IEEE Symposium on High Performance Interconnects*, pp. 98–104, 2004.
- [67] C. Zhao, F. Chen, Y. Wang, and X. Zheng, "Interference-aware QoS routing and dynamic channel assignment for multi-radio multi-channel wireless mesh network," *International Journal of Mobile Network Design and Innovation*, vol. 5, no. 4, pp. 238–248, 2014.
- [68] M. Parsapoor and U. Bilstrup, "A centralized channel assignment algorithm for clustered ad-hoc networks," in *IEEE Conference on Wireless Sensor (ICWISE)*, pp. 73–78, 2013.
- [69] V. Sarasvathi and N. C. S. Iyengar, "Centralized rank based channel assignment for Multi-Radio Multi-Channel wireless mesh networks," *Procedia Technology*, vol. 4, pp. 182–186, 2012.

- [70] M. Jahanshahi, M. Dehghan, and M. R. Meybodi, "On channel assignment and multicast routing in multi-channel multi-radio wireless mesh networks," *International Journal of Ad-hoc and Ubiquitous Computing*, vol. 12, no. 4, pp. 225–244, 2013.
- [71] C.-S. Chou, C. Chen, Y.-Y. Chen, R. Jan, and C.-C. Hsieh, "Multicast routing and channel assignment in wireless mesh networks," in *IEEE International Conference on Mobile Adhoc and Sensor Systems*, pp. 676–681, 2009.
- [72] H. S. Chiu, K. L. Yeung, and K.-S. Lui, "Bandwidth-guaranteed multicast in multi-channel multi-interface wireless mesh networks," in *IEEE International Conference on Communications*, pp. 1–5, 2009.
- [73] W.-L. Yang and W.-T. Huang, "The study of interference-free multicast using non-orthogonal channels for multi-radio and multi-channel wireless mesh networks," in *IEEE International Computer Symposium*, pp. 547–552, 2010.
- [74] A. Raniwala and Chiueh, "Evaluation of a wireless enterprise backbone network architecture," in *IEEE Annual Symposium on High Performance Interconnects*, pp. 98–104, 2004.
- [75] A. Raniwala and T.-c. Chiueh, "Architecture and algorithms for an ieee 802.11-based multi-channel wireless mesh network," in *Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 3, pp. 2223–2234, 2005.
- [76] A. Nargesi, M. Bag-Mohammadi, and A. T. Haghghat, "Efficient multicast and channel assignment in multi-channel wireless mesh networks," in *International Conference on ICT Convergence*, pp. 404–409, 2012.
- [77] Y. Wei-Guang, C. Zhi-Gang, and L. Wei, "The study on channel assignment in wireless mesh networks.," *International Journal of Advancements in Computing Technology*, vol. 3, no. 11, 2011.
- [78] J.-W. Lin and J.-Y. Zhuang, "A delay-constrained and priority-aware channel assignment algorithm for efficient multicast in wireless mesh networks," *Journal of Systems and Software*, vol. 86, no. 3, pp. 789–800, 2013.
- [79] F. Juraschek, Mesut, M. Philipp, B. Blywis, *et al.*, "State-of-the-art of distributed channel assignment," 2011.
- [80] P. Kyasanur and N. H. Vaidya, "Routing and link-layer protocols for multi-channel multi-interface ad hoc wireless networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 10, no. 1, pp. 31–43, 2006.
- [81] J. Crichigno, M.-Y. Wu, and W. Shu, "Protocols and architectures for channel assignment in wireless mesh networks," *Ad Hoc Networks*, vol. 6, no. 7, pp. 1051–1077, 2008.

- [82] X. Lin and S. Rasool, "A distributed joint channel-assignment, scheduling and routing algorithm for multi-channel ad-hoc wireless networks," in *IEEE International Conference on Computer Communications*, pp. 1118–1126, 2007.
- [83] Z. Yin, Z. Li, and M. Chen, "A novel channel assignment algorithm for multicast in multi-radio wireless mesh networks," in *IEEE Symposium on Computers and Communications*, pp. 283–288, 2007.
- [84] G. Zeng, B. Wang, Y. Ding, L. Xiao, and M. W. Mutka, "Efficient multicast algorithms for multichannel wireless mesh networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 21, no. 1, pp. 86–99, 2010.
- [85] Z. Yin, Z. Li, and M. Chen, "A novel channel assignment algorithm for multicast in multi-radio wireless mesh networks," in *IEEE Symposium on Computers and Communications*, pp. 283–288, 2007.
- [86] X. Li and C. Xu, "Joint channel assignment and routing in real time wireless mesh network," in *IEEE Conference on Wireless Communications and Networking*, pp. 1–6, 2009.
- [87] M. Kodialam and T. Nandagopal, "Characterizing the capacity region in multi-radio multi-channel wireless mesh networks," in *ACM International Conference on Mobile Computing and Networking*, pp. 73–87, 2005.
- [88] Y. Peng, Y. Yu, L. Guo, D. Jiang, and Q. Gai, "An efficient joint channel assignment and QoS routing protocol for IEEE 802.11 multi-radio multi-channel wireless mesh networks," *Journal of Network and Computer Applications*, vol. 36, no. 2, pp. 843–857, 2013.
- [89] J. Wellons and Y. Xue, "The robust joint solution for channel assignment and routing for wireless mesh networks with time partitioning," *Ad-hoc Networks*, vol. 13, pp. 210–221, 2014.
- [90] M. Jahanshahi, M. Dehghan, and M. R. Meybodi, "A mathematical formulation for joint channel assignment and multicast routing in multi-channel multi-radio wireless mesh networks," *Journal of Network and Computer Applications*, vol. 34, no. 6, pp. 1869–1882, 2011.
- [91] D. Wu, S.-H. Yang, L. Bao, and C. H. Liu, "Joint multi-radio multi-channel assignment, scheduling, and routing in wireless mesh networks," *Journal of Wireless Networks (Springer)*, vol. 20, no. 1, pp. 11–24, 2014.
- [92] M. Jahanshahi, M. Dehghan, and M. R. Meybodi, "Lamr: learning automata based multicast routing protocol for multi-channel multi-radio wireless mesh networks," *Applied Intelligence*, vol. 38, no. 1, pp. 58–77, 2013.

- [93] H. Cheng and S. Yang, “Joint multicast routing and channel assignment in multi-radio multi-channel wireless mesh networks using tabu search,” in *International Conference on Natural Computation*, vol. 4, pp. 325–330, 2009.
- [94] H. Cheng and S. Yang, “Joint multicast routing and channel assignment in multi-radio multi-channel wireless mesh networks using simulated annealing,” in *Simulated evolution and learning*, pp. 370–380, Springer, 2008.
- [95] H. Cheng and S. Yang, “Joint QoS multicast routing and channel assignment in multi-radio multi-channel wireless mesh networks using intelligent computational methods,” *Applied Soft Computing*, vol. 11, no. 2, pp. 1953–1964, 2011.
- [96] G. Zeng, B. Wang, Y. Ding, L. Xiao, and M. Mutka, “Multicast algorithms for multi-channel wireless mesh networks,” in *IEEE International Conference on Network Protocols*, pp. 1–10, 2007.
- [97] T. H. Cormen, *Introduction to Algorithms*. MIT press, 2009.
- [98] J. Moy, “Rfc 1584–multicast extensions to OSPF,” *SRI Network Information Center*, 1994.
- [99] T. Pusateri *et al.*, “Distance vector multicast routing protocol,” *Work in Progress. Authors Addresses J. Mark Pullen C3I Center/Computer Science Mail Stop 4A5 George Mason University Fairfax, VA*, vol. 22032, 2003.
- [100] Y. Yuan, C. Bian, T. Zhao, and W. Yan, “Gamll: Gateway assisted multicast algorithm towards low latency for wireless mesh networks,” in *IEEE Vehicular Technology Conference*, pp. 1–5, 2013.
- [101] S.-J. Lee, W. Su, and M. Gerla, “On-demand multicast routing protocol in multi-hop wireless mobile networks,” *Mobile networks and Applications*, vol. 7, no. 6, pp. 441–453, 2002.
- [102] J. Garcia-Luna-Aceves and E. L. Madruga, “The core-assisted mesh protocol,” *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 8, pp. 1380–1394, 1999.
- [103] E. M. Royer and C. E. Perkins, “Multicast operation of the ad-hoc on-demand distance vector routing protocol,” in *ACM International Conference on Mobile Computing and Networking*, pp. 207–218, 1999.
- [104] N. Kumar, N. Chilamkurti, and J.-H. Lee, “A novel minimum delay maximum flow multicast algorithm to construct a multicast tree in wireless mesh networks,” *Computers and Mathematics with Applications*, vol. 63, no. 2, pp. 481–491, 2012.

- [105] P. M. Ruiz and A. F. Gomez-Skarmeta, "Approximating optimal multicast trees in wireless multi-hop networks," in *IEEE Symposium on Computers and Communications*, pp. 686–691, 2005.
- [106] U. T. Nguyen, "On multicast routing in wireless mesh networks," *Computer Communications*, vol. 31, no. 7, pp. 1385–1399, 2008.
- [107] U. T. Nguyen and J. Xu, "Multicast routing in wireless mesh networks: Minimum cost trees or shortest path trees?," *Communications Magazine, IEEE*, vol. 45, no. 11, pp. 72–77, 2007.
- [108] S. Roy, D. Koutsonikolas, S. Das, and Y. C. Hu, "High-throughput multicast routing metrics in wireless mesh networks," *Ad-hoc Networks*, vol. 6, no. 6, pp. 878–899, 2008.
- [109] L. Kou, G. Markowsky, and L. Berman, "A fast algorithm for steiner trees," *Acta Informatica*, vol. 15, no. 2, pp. 141–145, 1981.
- [110] A. Z. Zelikovsky, "An 11/6-approximation algorithm for the network steiner problem," *Algorithmica*, vol. 9, no. 5, pp. 463–470, 1993.
- [111] S.-J. Lee, W. Su, and M. Gerla, "On-demand multicast routing protocol in multi-hop wireless mobile networks," *Mobile networks and applications*, vol. 7, no. 6, pp. 441–453, 2002.
- [112] R. Menchaca-Mendez and J. Garcia-Luna-Aceves, "Hydra: Efficient multicast routing in manets using sender-initiated multicast meshes," *Pervasive and Mobile Computing*, vol. 6, no. 1, pp. 144–157, 2010.
- [113] W.-L. Yang, "Optimal and heuristic algorithms for constructing interference-free multicast trees subject to delay and energy constraints on wireless mesh networks," Accepted in Inderscience, *International Journal of Ad Hoc and Ubiquitous Computing*.
- [114] C. Papageorgiou, K. Christodoulopoulos, N. Doulamis, and E. Varvarigos, "On least expected transmissions multicasting in wireless networks," in *International Conference on Computing, Networking and Communications*, pp. 836–841, 2014.
- [115] E. Zouaoui, L. Derdouri, and N. Zeghib, "Dynamic multicast membership algorithms for multi-channel multi-radio wireless mesh network," *International Journal of Computer Science Telecommunication*, vol. 3, p. 12, 2012.
- [116] A. Avokh and G. Mirjalily, "Load-balanced multicast tree routing in multi-channel multi-radio wireless mesh networks using a new cost function," *Wireless Personal Communications*, vol. 69, no. 1, pp. 75–106, 2013.

- [117] L. Farzinvas and M. Dehghan, “Minimum cost bandwidth guaranteed multicast routing in multi-channel multi-radio wireless mesh networks,” *Wireless Personal Communications*, vol. 80, no. 2, pp. 493–520, 2015.
- [118] O. Baghban Karimi, J. Liu, and Z. Li, “Multicast with cooperative gateways in multi-channel wireless mesh networks,” *Ad-hoc Networks*, vol. 13, pp. 170–180, 2014.
- [119] A. Avokh, G. Mirjalily, J. Abouei, and S. Valaee, “On the relationship between multicast/broadcast throughput and resource utilizations in wireless mesh networks,” *The Scientific World Journal*, vol. 3, 2013.
- [120] M. Jahanshahi and A. T. Barmi, “Multicast routing protocols in wireless mesh networks: a survey,” *Computing*, vol. 96, no. 11, pp. 1029–1057, 2014.
- [121] H. S. Chiu and K. L. Yeung, “Maximizing multicast call acceptance rate in multi-channel multi-interface wireless mesh networks,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 8, pp. 2622–2631, 2010.
- [122] A. Avokh and G. Mirjalily, “Interference-aware multicast and broadcast routing in wireless mesh networks using both rate and channel diversity,” *Computers and Electrical Engineering*, vol. 40, no. 2, pp. 624–640, 2014.
- [123] N. PISCATAWAY, “Wireless LAN medium access control (MAC) and physical layer (PHY) specifications,” *IEEE P802. 11 D3*, 1996.
- [124] A. Raniwala, K. Gopalan, and T.-c. Chiueh, “Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks,” *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50–65, 2004.
- [125] H. L. Nguyen and U. T. Nguyen, “High-performance multicast routing in multi-channel multi-radio wireless mesh networks,” in *IEEE Global Telecommunications Conference*, pp. 1–6, 2010.
- [126] ABB, “Wireless mesh router,” 2011.
- [127] W. Schäfer and E. Lutz, “Propagation characteristics of short-range radio links at 60 ghz for mobile inter-vehicle communication,” in *IEEE International Symposium on Telecommunications*, pp. 212–216, 1990.
- [128] S. N. Technologies, “Qualnet simulator,” 2011.
- [129] A. Sharma and E. M. Belding, “Freemac: framework for multi-channel MAC development on 802.11 hardware,” in *ACM Workshop on Programmable Routers for Extensible Services of Tomorrow*, pp. 69–74, 2008.

- [130] N. Hoang Lan and N. Uyen Trang, “Channel assignment for multicast in multi-channel multi-radio wireless mesh networks,” *Wireless Communications and Mobile Computing*, vol. 9, no. 4, pp. 557–571, 2009.
- [131] H. L. Nguyen and U. T. Nguyen, “Algorithms for bandwidth efficient multicast routing in multi-channel multi-radio wireless mesh networks,” in *IEEE Wireless Communications and Networking Conference*, pp. 1107–1112, 2011.
- [132] H. L. Nguyen and U. T. Nguyen, “Minimum interference channel assignment for multicast in multi-radio wireless mesh networks,” in *IEEE Conference on Wireless Communications and Mobile Computing Conference*, pp. 557–571, 2008.