**Channel Assignment using Topology Control based on
Power Control in Wireless Mesh Networks**

by

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Abstract

Single-radio mesh routers operating on a single channel suffer from low throughput due to collisions. Equipping mesh routers with multiple radios operating on non-overlapping channels can significantly improve the end-to-end throughput. However, the number of available non-overlapping channels is limited and the assignment of channels to radios is a challenging task.

The goal of the channel assignment algorithm proposed in this thesis, TICA (Topology-controlled Interference-aware Channel-assignment Algorithm), is to improve the network throughput in a multi-radio multi-channel wireless mesh network by minimizing interference within the mesh network by intelligently controlling the network topology based on power control as well as guaranteeing network connectivity before efficiently assigning channels to multi-radio mesh routers. In addition to channel assignment, TICA also performs routing. It is fault-tolerant and supports automatic and fast failure recovery.

The performance of TICA is compared with two commonly-used benchmark schemes and significant improvements are shown through simulations in both small and large networks. TICA has also been shown to achieve better performance than two well-known centralized channel assignment schemes.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACK	Acknowledgement
AND	Average Node Degree
AODV	Ad hoc On-Demand Distance Vector
AP	Access Point
AT	Average Throughput
BFS-CA	Breadth First Search – Channel Assignment
CA	Channel Assignment
CAA	Channel Assignment Algorithm
CARM	Channel Assignment and Routing Message
CBR	Constant Bit Rate
CCA	Common Channel Assignment
C-HYA	Centralized Hyacinth
CRT	Controlled Random Topology
CS	Carrier Sensing
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
DCF	Distributed Coordination Function
D-HYA	Distributed Hyacinth
DNT	Direct Neighbor Table
FNT	Final Neighbor Table
FRM	Failure Recovery Mechanism
FTP	File Transfer Protocol
GT	Grid Topology
GW	Gateway
HMCP	Hybrid Multi-Channel Protocol
IL	Interference Level
IR	Interference Range
ISM	Industrial, Scientific, and Medical Band
LAN	Local Area Network
LIC	Least Interfering Channel

MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MCG	Multi-Radio Conflict Graph
MesTiC	Mesh-based Traffic and interference-aware Channel-assignment
MMAC	Multi-channel Medium Access Control
MND	Maximum Node Degree
MPNT	Maximum Power Neighbor Table
MPSPT	Minimum Power-based Shortest Path Tree
MR	Mesh Router
MRMC	Multi-Radio Multi-Channel
NS2	Network Simulator Version 2
PCF	Point Coordination Function
PHY	Physical Layer
RT	Random Topology
RTS	Request to Send
SPT	Shortest Path Tree
SRSC	Single-Radio Single-Channel
STA	Station
TC	Topology Control
TCA	Topology Control Algorithm
TCP	Transmission Control Protocol
TICA	Topology-controlled Interference-aware Channel-assignment Algorithm
TIF	Throughput Improvement Factor
TP	Traffic Profile
TPC	Transmit Power Control
TR	Transmission Range
UDP	User Datagram Protocol
VCA	Varying Channel Assignment
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Network
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

In this chapter, an overview of Wireless Mesh Networks (WMNs) is presented, and some unique features which distinguish WMNs from Mobile Ad hoc Networks (MANETs) and Wireless Sensor Networks (WSNs) are listed. The main purpose of this thesis is discussed, and the thesis contribution is presented along with the main features of this work.

1.1. Overview

The use of Wireless Local Area Networks (WLANs) has grown tremendously in the past few years due to their ease of deployment and maintenance. However, the access points in these WLANs have to be connected to the backbone network through wired media. Wireless Mesh Networks offer an attractive alternative for providing broadband wireless Internet connectivity by using a wireless backhaul network and eliminating the need for extensive cabling.

Figure 1.1: A sample enterprise WMN [1]

In traditional WLANs, each Access Point (AP) is connected to the wired network while only a subset of APs is connected to the wired network in WMNs. An AP that is connected to the wired network is called Gateway (GW); APs without wired connections are called Mesh Routers (MRs), and they connect to the GW through multiple hops. Like routers in a wired network, MRs in a WMN forward each other's traffic to establish and

maintain their connectivity. MRs and GWs are similar in design, with the only difference that a GW is directly connected to the wired network, while a MR is not. Figure 1.1 shows a sample mesh network in a typical enterprise such as a university [1].

Distinguishing WMNs from MANETs and WSNs

The following are some unique features that distinguish WMNs from MANETs and WSNs [1]:

- **Mesh routers are static**

Mesh routers in a WMN are stationary; therefore, the route selection should focus on discovering links that interfere with as few nodes as possible to provide high end-to-end throughput.

- **Mesh routers have no power constraint**

In contrast to traditional wireless networks, such as MANETs and WSNs, where nodes are typically power-constrained, MRs have abundant power at their disposal.

- **Mesh routers have multiple radios**

With the reduced cost of radios, MRs can be equipped with multiple radios. Hence, simultaneous transmission and reception can be achieved using intelligent channel assignment to these radios.

- **The traffic model is different**

In MANETs, traffic can be from any peer Mobile Node (MN) to any other MN, while in WMNs, traffic is between MRs and the GW.

- **Traffic is concentrated along certain paths**

In MANETs, traffic distribution is generally assumed to be uniform, while in WMN, traffic is concentrated along the paths directed towards the GW.

- **Traffic volume is high**

MANETs have been designed essentially for enabling communication within a small group of people, while WMNs aim to provide high-bandwidth broadband connections to a large community, and thus should be able to accommodate a large number of users accessing the Internet. Due to high estimated traffic volume in WMNs, scalability and fault tolerance become important considerations in algorithm design.

1.2. Motivation

To the best of my knowledge, the proposed channel assignment algorithm is the first of its kind to use topology control based on power control for channel assignment in multi-radio multi-channel wireless mesh networks.

The main purpose of network topology control using power control is to minimize the interference between a MR and other MRs in the network by adjusting its transmission range using transmission power control. This leads to a better frequency reuse during channel assignment which results in achieving the objective of significant improvement in the overall network throughput.

1.3. Thesis Contribution

Specifically, the contribution of this thesis is as follows: “*A new Topology-controlled Interference-aware Channel-assignment Algorithm (TICA) which intelligently assigns the available non-overlapping 802.11a frequency channels to the mesh routers with the objective of minimizing interference and, thereby, improving network throughput.*” The main features of this work are as follows:

- A Topology Control Algorithm (TCA) named *Select x for less than x* ; that builds the network topology by selecting the nearest neighbors for each node in the network, with the objective of minimizing interference among MRs and enhancing frequency reuse
- A scheme that uses the minimum power as the link weight when building the Shortest Path Tree (SPT) with the required node degree with the objective of minimizing interference and enhancing frequency reuse
- A Channel Assignment Algorithm (CAA), TICA, which assigns the available non-overlapping 802.11a frequency channels to the mesh nodes with the objective of improving the overall network throughput by minimizing interference between mesh nodes as well as ensuring connectivity between them
- A concept of assigning the Least Interfering Channel (LIC) to a link if all the available frequency channels have already been assigned within the interference range of that link (LIC is the channel with the minimum interference level, which means that assigning this channel to the link would result in minimum interference in the network.)

- A scheme that builds the Interference Level (IL) for all the frequency channels if all the available frequency channels have already been assigned within the interference range of a link
- A centralized Failure Recovery Mechanism (FRM) for TICA which provides automatic and fast failure recovery by reorganizing the network in order to bypass the failed node and to restore connectivity

1.4. Thesis Organization

The rest of the thesis is organized as follows. Chapter 2 gives an overview of IEEE 802.11 standard, including a brief description of its physical layer and medium access mechanism. Different IEEE 802.11 standards including 802.11 a, b and g, are briefly discussed, along with their respective transmission technologies. The chapter also includes a brief overview of the IEEE 802.11s standard for wireless mesh networks. The related work on topology control and CAAs is presented in this chapter.

Chapter 3 presents the medium access issues encountered by IEEE 802.11 single-radio single-channel nodes. It discusses the connectivity and interference trade-off, which is an important issue in WMNs. Finally, the channel assignment problem is presented with respect to multi-radio multi-channel wireless mesh network.

Chapter 4 presents the network architecture for the proposed model and the proposed topology control algorithm and CAA, along with the details of their respective phases. The FRM of the proposed CAA is also presented in this chapter.

Chapter 5 provides a performance evaluation of the proposed CAA. The network topologies used for performance evaluation are presented, and details on the working of different phases and FRM of TICA are presented with examples.

Chapter 6 contains the results for the different phases of the proposed CAA including topology control, connectivity graph, minimum power based SPT with the required maximum node degree, link ranking and channel assignment. The results of simulations for performance evaluation based on throughput analysis of a 36-node network and a 144-node network are presented in this chapter. The chapter also presents the results for the performance comparison of TICA with two well-known centralized channel assignment schemes.

Chapter 7 presents the conclusions, along with some directions for future work.

CHAPTER 2

BACKGROUND

In this chapter, an overview of the IEEE 802.11 standard for WLANs is given by highlighting some important details of the Physical (PHY) and Medium Access Control (MAC) layers defined by this standard. Various IEEE 802.11 standards including a, b and g, are discussed, along with IEEE 802.11s, which is being developed for multihop wireless mesh networks. The chapter discusses the effects of topology control on the operation of a network, gives the taxonomy of the topology control schemes for multihop wireless networks, and presents some related well-known topology control algorithms. The chapter also contains a taxonomical classification of the channel assignment schemes for wireless mesh networks, and discusses some related well-known channel assignment algorithms for each class.

2.1. IEEE 802.11 Standard

The IEEE 802.11 family of standards is currently the most successful wireless networking standards for WLANs. The initial specification was completed in 1999 (IEEE 802.11a/b) [2] and later extended in 2003 (IEEE 802.11g). It defines the PHY and MAC layer for the devices used in WLAN. The physical layer of the IEEE 802.11 protocol architecture describes the frequency band, data rate, and transmission technology, as shown in Table 2.1.

Table 2.1: IEEE 802.11 Physical Layer Standards

IEEE Standard	Spectrum	Max. Physical Rate	Transmission Technology	Compatible with	Major Disadvantages	Major Advantages
802.11	2.4 GHz	2 Mbps	FHSS/DSSS	None	Limited bit rate	Higher range
802.11a	5.0 GHz	54 Mbps	OFDM	None	Smallest range of all 802.11 standards	Higher bit rate in less-crowded spectrum
802.11b	2.4 GHz	11 Mbps	DSSS	802.11	Bit rate too low for many emerging applications	Widely deployed; higher range
802.11g	2.4 GHz	54 Mbps	OFDM	802.11 and 802.11b	Limited no. of co-located WLANs due to narrow spectrum	Higher bit rate in 2.4 GHz band; higher range than 802.11a

2.1.1. Physical Layer Transmission Technologies

The original IEEE 802.11 standard defines the MAC layer and three different PHY layers. The transmission technologies that the original standard defined are as follows [3]:

- Frequency-Hopping Spread Spectrum (FHSS)
- Direct-Sequence Spread Spectrum (DSSS)
- Infrared (IR)

A fourth physical layer transmission technology, Orthogonal Frequency Division Multiplexing (OFDM), was introduced later.

DSSS operates in the 2.4 GHz ISM band, at data rates of 1 Mbps and 2 Mbps. The available number of channels ranges from 13 in most countries to just one in Japan. The DSSS PHY operates in the frequency range of 2.4 GHz to 2.4835 GHz in North America and 2.471 GHz to 2.497 GHz in Japan. Out of 13 available channels in North America, only channels 1, 6 and 11 are not overlapping, as shown in Figure 2.1 [4].

Figure 2.1: Available channels for DSSS in the 2.4 GHz ISM band [4]

OFDM, also called multicarrier modulation, uses multiple carrier signals at different frequencies, sending bits on each carrier. This is similar to FDM (Frequency Division Multiplexing), which uses each subchannel for a separate data source. OFDM, however, dedicates all of the subchannels to a single data source. The possible data rates per channel range from 6 to 54 Mbps. The support of transmitting and receiving at data rates of 6, 12, and 24 Mbps is mandatory for 20 MHz channel spacing. The system uses 52 subcarriers, of which only 12 are non-overlapping [5].

2.1.2. Medium Access Control Layer

The IEEE 802.11 MAC layer has two main sublayers. The lower one, Distributed Coordination Function (DCF), uses an Ethernet-style contention algorithm that provides access to all traffic. The upper MAC sublayer, Point Coordination Function (PCF), is a centralized MAC algorithm that provides contention-free service by polling STAs in turn [3].

DCF is the basic medium access protocol of the IEEE 802.11 MAC that allows distributed medium sharing between compatible physical layers through the use of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and a random backoff time following a busy medium condition [5].

Carrier Sensing (CS) is performed both through physical and virtual mechanisms. A physical CS mechanism is provided by the physical layer, while a virtual CS mechanism is provided by the MAC layer.

A. Physical CS using CSMA/CA

In physical CS, a STA senses the medium before it transmits, in order to determine if another STA is transmitting. If the medium is not busy, the transmission may proceed. The CSMA/CA-distributed algorithm requires that a gap of a minimum specified duration exist between frame sequences. A transmitting STA ensures that the medium is idle for this required duration before attempting to transmit. If the medium is determined to be busy, the STA defers until the end of the current transmission. After deferral, or prior to attempting to transmit again immediately after a successful transmission, the STA selects a random backoff interval and decrements the backoff interval counter while the medium is idle. A transmission is successful when an ACK frame is received from the addressed STA [5].

B. Virtual CS using Request to Send and Clear to Send

The virtual CS mechanism is achieved by distributing reservation information announcing the impending use of the medium. The exchange of Request to Send (RTS) and Clear to Send (CTS) frames prior to the actual data frame is used for the distribution of the medium reservation information. The RTS and CTS frames contain a duration field that defines the period of time the medium is to be reserved in order to transmit the actual

data frame and the returning ACK frame. All STAs within the reception range of either the originating STA (which transmits the RTS) or the destination STA (which transmits the CTS) can learn of the medium reservation [5].

2.1.2. IEEE 802.11a

The IEEE 802.11a specification uses the 5-GHz band and was established so that the users could take advantage of a newly allocated unlicensed radio band, the Unlicensed National Information Infrastructure (UNII) band. The FCC (Federal Communications Commission, a United States government agency) created UNII to support the development of high-speed wireless networks. To meet the increasing bandwidth demand, FCC established the band at 5 GHz, making it incompatible with 2.4-GHz equipment.

2.1.3. IEEE 802.11b

IEEE 802.11b is an extension of the IEEE 802.11 DSSS scheme, providing data rates of up to 11 Mbps. Like an IEEE 802.11 DSSS channel, each IEEE 802.11b channel requires the same bandwidth. To achieve a higher data rate in the same bandwidth, the standard employs a modulation scheme called Complementary Code Keying (CCK) [5]. IEEE 802.11b is currently the most commonly used IEEE 802.11 standard in commercial products.

2.1.4. IEEE 802.11g

IEEE 802.11g extends IEEE 802.11b to data rates of up to 54 Mbps per channel. IEEE 802.11g is compatible with IEEE 802.11b because they both operate in the 2.4 GHz range. The key difference between IEEE 802.11b and IEEE 802.11g is that the latter uses OFDM and DSSS rather than DSSS only. With this standard, IEEE 802.11b devices will work when connected to an IEEE 802.11g access point and vice versa, in both cases using the lower IEEE 802.11b data rate.

2.2. IEEE 802.11s for Wireless Mesh Networks

The IEEE 802.11s [6] mesh networking standard aims at applying multihop routing techniques to extend the range of WLAN. Hence, the WLAN mesh can be

considered as a set of access points interconnected with each other via wireless links, resulting in a “mesh of connectivity.”

The IEEE 802.11s Task Group, formed in 2004, is in the process of developing specifications of a new protocol suite for the installation, configuration, and operation of WLAN mesh. It will be implemented on top of the existing PHY layer of IEEE 802.11a/b/g operating in the unlicensed spectrum of 2.4 and 5 GHz frequency bands [7].

2.2.1. Network Architecture

In IEEE 802.11s, a meshed wireless LAN is formed where access points do not need to be connected by wired LANs and are connected by wireless mesh networking, with multiple hops in between. Portals, which are also called Gateways (GWs), are used to connect access points with the Internet. Typical network architecture of IEEE 802.11s is shown in Figure 2.2 [8].

Figure 2.2: IEEE 802.11s Mesh Network Architecture [8]

There are three types of nodes in this architecture.

A. Mesh Point (MP)

Any node that supports the mesh services, including neighbor discovery, channel selection, and forming an association with neighbors, is a Mesh Point [9]. MPs can directly communicate with their neighbors and forward traffic on behalf of other MPs.

B. Mesh Access Point (MAP)

In addition to being a MP, if a mesh node acts as an access point by supporting access to client stations; it is called a Mesh Access Point (MAP).

C. Mesh Portal (MPP)

A Mesh Portal (MPP) is a MP that has a non-802.11 wired connection to the Internet and serves as a logical point for MAC Service Data Units (MSDUs) to enter or exit the mesh network. A MPP and a MAP may be co-located on a single device.

2.2.2. Protocol Stack

The protocol stacks of the three types of nodes described above are illustrated in Figure 2.3 [8].

Figure 2.3: IEEE 802.11s Protocol Stack [8]

The IEEE 802.11s MAC is based on the existing IEEE 802.11 MAC, and the mesh routing protocol resides in the MAC layer. In a MPP, a layer-3 routing protocol is also needed for path selection from the mesh network to external network or vice versa [8].

2.3. Topology Control Schemes

The importance of Topology Control (TC) lies in the fact that it affects network spatial reuse and hence the traffic carrying capacity. Choosing a large transmit power results in excessive interference, while choosing a small transmit power results in a disconnected network [10]. Using TC through transmission power control, the network connectivity and hence the network topology is affected, interference levels are

mitigated, which reduces the co-channel interference, and the opportunity of spatial channel re-use is enhanced [11].

2.3.1. Topology Control in Multi-radio WMNs

One method for reducing the co-channel interference is to appropriately select the channels for the wireless interfaces. The channel assignment problem in multi-radio wireless mesh networks involves assigning a channel to each wireless interface. In addition to reducing the level of interference, channel assignment also affects the connectivity of wireless mesh networks, since two interfaces within the transmission range of each other can communicate only if they operate on the same channel. There is a trade-off between maximizing the connectivity and reducing the level of interference.

The connectivity graph in a multi-radio WMN is determined through topology control. So, the problem of TC in multi-radio WMNs involves the selection of transmission power for each radio interface of each mesh node in the network, so as to maintain the network connectivity with the use of minimum power.

2.3.2. Effect of Topology Control

The problem of TC is complex, since the choice of the transmit power fundamentally affects many aspects of the operation of the network [12].

- The transmit power level determines the quality of the signal received at the receiver.
- It determines the transmission range.
- It determines the interference range, i.e. the magnitude of the interference created for the other receivers.

A. Effect of TC on the OSI layers

Due to the following factors, Topology Control (TC) via Transmit Power Control (TPC) affects the following layers of the OSI protocol stack:

- It affects the physical layer as the transmit power level affects the Received Signal Strength (RSS).
- It affects the MAC layer because the interference range affects the spatial channel reuse.

- It affects the network layer because the transmission range affects routing.
- It affects the transport layer because interference causes congestion.

B. Effect of TC on the Performance of the Network

TC via TPC has a multi-dimensional effect on the performance of the whole network:

- The transmit power levels determine the performance of medium access control, since the spatial channel reuse depends on the number of other nodes within the interference range.
- The choices of power levels affect the connectivity of the network, and consequently the ability to deliver a packet to its destination [13].
- The power level affects the throughput capacity of the network [14].
- Power control affects the network topology which affects the number of hops, and thus the end-to-end delay.

C. Effect of TC on the Performance of the MAC and Routing Protocols

In addition, the assumption of fixed power levels is so ingrained into the design of many protocols in the OSI stack that changing the power levels results in their malfunctioning.

- Changing power levels can create uni-directional links, which can happen when a node i 's power level is high enough for a node j to hear it, but not vice versa.
- Bi-directionality of links is implicitly assumed in many routing protocols.
- Medium access control protocols in IEEE 802.11 implicitly rely on bi-directionality assumption of links.

2.3.3. Guidelines for an Effective Topology Control Algorithm

The following guidelines are essential to an effective Topology Control Algorithm (TCA) [10]:

- The network connectivity should be preserved with the use of minimum possible power. This is the most important objective of topology control algorithms, as less transmit power translates to less interference.
- The algorithm should be distributed and should depend only on the information collected locally, e.g. information collected within one hop. Algorithms that

depend only on local information incur less message-overhead in the process of collecting information.

- It is desirable that all links be bi-directional. As mentioned earlier, bi-directional links are required to facilitate link level acknowledgment and ensure the existence of reverse paths.
- It is also desirable that the node degree in the topology derived under the algorithm is small. A small node degree helps to mitigate co-channel interference and enhance spatial channel reuse.

2.3.4. Taxonomy of Topology Control Schemes

These schemes are mainly divided into two types [15].

A. Homogeneous

This is the basic type of TC, as all the nodes are assumed to use the same transmitting range. So, the topology control problem reduces to determining the minimum value of transmission range that ensures network connectivity. This minimum transmission range is also called the Critical Transmitting Range (CTR).

B. Non-homogeneous

In this type of TC, nodes are allowed to choose different transmitting ranges, provided they do not exceed the maximum range. Depending on the type of information that is used to compute the topology, non-homogeneous topology control is further classified into three categories.

i) Location-based schemes

In such schemes, exact node positions are known. If this information is used by a centralized authority to compute a set of transmitting range assignments which optimizes a certain measure such as the energy cost, this is the case of the Range Assignment Problem and its variants. If, however, this information is exchanged between nodes and used to compute an “almost optimal” topology in a fully distributed manner, this is the case for protocols used for building energy-efficient topologies for unicast or broadcast communication.

ii) Direction-based schemes

In such schemes, it is assumed that nodes do not know their position, but they can estimate the relative direction of each of their neighbors.

iii) Neighbor-based schemes

In such schemes, nodes are assumed to know only the ID of the neighbors, and are able to order them according to some criterion such as link quality.

2.3.5. Related Topology Control Algorithms

The goal of the TCA for multi-radio WMNs, *Select x for less than x* , proposed in this thesis, is to minimize the interference among the MRs. To achieve this goal, the proposed TCA controls the network topology by selecting the nearest neighbors for each node in the network. Some related TCAs are discussed below.

A. Local Minimum Spanning Tree Algorithm

In this algorithm, each node builds its local minimum spanning tree independently and only keeps as its neighbors those on-tree nodes that are one hop away in the final topology. It is a location-based scheme as it assumes that each node is equipped with the ability to gather its location information. Some important properties of the Local Minimum Spanning Tree (LMST) algorithm [10] include:

- The topology constructed under LMST preserves the network connectivity
- The degree of any node in the resulting topology is bounded by 6
- The resulting topology can be converted into one with bi-directional links after the removal of uni-directional links.

The feature of small node degree is desirable as it reduces interference. LMST is composed of the following three phases: information exchange, topology construction, and determination of transmission power. The phase of topology construction with bidirectional links is an optional phase.

B. Enhanced Local Minimum Shortest Path Tree Algorithm

The objective of this topology control algorithm is to find a topology that preserves certain network requirements, namely, decrease in average node degree, an averagely low power consumption which results in a longer network lifetime, and a

maintenance of connectivity in the resultant network topology. The Enhanced Local Minimum Shortest-Path Tree (ELMST) algorithm [11] is a location-based topology control scheme and consists of two main phases:

- Construction of Local Minimum Shortest Path Tree (LMSPT)
- Removal of Unidirectional links

Each node gathers its neighbor information and constructs LMSPT, as shown in Figure 2.4.

Figure 2.4: ELMST (a) before topology control (b) after topology control [11]

C. Maximum Minimum Power Algorithm

A drawback of WMNs is that multihop communication consumes a multiple of radio resources required to transmit a frame, thereby reducing capacity. As the wireless channel is shared by the ongoing transmissions at various hops, mutual interference either requires sequential transmissions at high data rate or spatial reuse with simultaneous transmissions at low data rates by using a robust Modulation and Coding Scheme (MCS) [14]. The objective of the Maximum Minimum Power (MMP) algorithm [16] is to maintain the best possible MCS for each link while decreasing the transmission power as much as possible.

D. Local Mean Algorithm

To model the behavior of the Local Mean Algorithm (LMA) [17] in WMNs, the following procedure is used in [16].

All nodes start with same initial transmission power. Every node periodically broadcasts a “Life”-Message. Upon the reception of a “Life”-Message, each node responds with a “Live-Acknowledgement”-Message. The number of responses is counted and if it is greater than a pre-set threshold “NodeMaxThres,” the node decreases transmission power and repeats the algorithm. However, if the number of responses is less than or equal to the pre-set threshold “NodeMaxThres,” the node does not change the transmission power and repeats the algorithm after some delay. LMA is a typical power

control algorithm, putting emphasis on the power conservation while keeping the connectivity of the network. To ensure connectivity of the WMN, “NodeMaxThres” is set to either 4 or 5 for all nodes.

2.4. Channel Assignment Schemes

Channel Assignment (CA) in a multi-radio WMN environment consists of assigning channels to the radios in order to achieve efficient channel utilization (i.e. minimize co-channel interference) and, simultaneously, to guarantee an adequate level of connectivity. The problem of optimally assigning channels in an arbitrary mesh topology has been proven to be NP-hard, based on its mapping to a graph-coloring problem [18]. Therefore, channel assignment schemes employ heuristic techniques to assign channels to radios belonging to mesh nodes. A taxonomical classification of various CA schemes for wireless mesh networks is as follows [19].

2.4.1. Fixed Channel Assignment Schemes

Fixed assignment schemes assign channels to radios either permanently, or for intervals that are long with respect to the radio switching time. Such schemes can be further subdivided into two types.

A. Common Channel Assignment (CCA)

In CCA [20], the radios of each node are all assigned the same set of channels. For example, if each node has two radios, then the same two channels are used at every node. The main benefit is that the connectivity of the network is the same as that of a single channel approach, while the use of multiple channels increases network throughput. However, it does not take into account the effect of interference on the channel assignment in a WMN.

B. Varying Channel Assignment (VCA)

In the VCA scheme, the radios of different nodes are assigned different sets of channels. However, the assignment of channels may lead to network partitions and/or topology changes, which may increase the length of routes between mesh nodes. Therefore, in such a scheme, channel assignment needs to be carried out carefully. The VCA approach is discussed in more detail by presenting algorithms that belong to this category.

i) Centralized Hyacinth (C-HYA)

C-HYA, a centralized channel assignment algorithm for multi-radio multi-channel WMNs, was proposed in [18]. Assuming that the offered traffic load is known, this algorithm assigns channels ensuring network connectivity and satisfying the bandwidth limitations of each link. It first estimates the total expected load on each virtual link by summing the load due to each offered traffic flow. Then, the channel assignment algorithm visits each virtual link in decreasing order of expected traffic load and assigns it a channel.

ii) Mesh-based Traffic and interference-aware Channel-assignment (MesTiC)

MesTiC, a fixed algorithm for centralized CA, was proposed in [21], and visits nodes once in the decreasing order of their rank. The rank of each node is computed on the basis of its link-traffic characteristics, topological properties and number of radios on a node.

Figure 2.5: An example of MesTiC [21]

The working principle of MesTiC is illustrated in Figure 2.5 where the input connectivity graph and estimated link traffic are shown in Figure 2.5a. The network is configured with three channels and two radios per node. Assuming that node b is the gateway node, the rank of the remaining nodes, in decreasing order, is d, a, and c. The algorithm starts by visiting node b first, assigning channel C1 to the link between (b, a) (which carries the highest traffic of 120), and then moves on to assign channel C2 to the link (b, d). Now, when assigning a channel to link (b, c), the algorithm has to choose between C1 and C2. However, as C1 carries more traffic than C2, it assigns C2 to link (b, c). Likewise, at node d, it assigns a previously unassigned channel C3 to the link (d, c)

and, as C3 carries less traffic than C2 ($90 + 80 = 170$) or C1 (120), it assigns C3 to the link (d, a). The algorithm proceeds until all links and radios have been assigned channels, as shown in Figure 2.5b.

2.4.2. Dynamic Channel Assignment Schemes

In dynamic CA schemes, any radio can be assigned any channel but additionally, radios can frequently switch from one channel to another. Therefore, when nodes need to communicate with each other in such a scheme, a coordination mechanism is required to ensure that they are on a common channel.

The key challenge with the dynamic switching approach is how to coordinate decisions in terms of when to switch radios, as well as what channel to switch radios to.

A. Multi-channel Medium Access Control (MMAC)

MMAC [22] [23] is a link-layer multi-channel protocol for nodes with a single network interface. A node equipped with a single interface can only listen to one channel at a time. Therefore, in order to use multiple channels, the interface has to be switched between channels.

As mentioned above, when nodes are allowed to switch channels, a pair of nodes need to listen on the same channel at the time of communication and a channel coordination method is necessary which is not required in TICA.

B. Distributed Hyacinth (D-HYA)

D-HYA, a dynamic and distributed channel assignment algorithm proposed in [24], can adapt to traffic load dynamically. The algorithm builds on a spanning tree network topology. The gateway node is the root of a spanning tree, and every mesh node belongs to that tree. The channel assignment problem consists of the following two steps.

1. *Neighbor-to-interface binding* determines the interface that a node uses to communicate with each of its neighbors with whom it intends to establish a link
2. *Interface-to-channel binding* determines which radio channel a network interface should use.

Based on per-channel total load information, a WMN node determines the set of channels that are least used in its vicinity. As nodes higher up in the spanning trees need

more relay bandwidth, they are given a higher priority in channel assignment. More specifically, the priority of a WMN node is equal to its hop distance from the gateway.

The CA schemes, such as C-HYA, MesTiC and D-HYA, require the traffic load to be known before assigning channels, whereas TICA requires no such knowledge for channel assignment.

2.4.3. Hybrid Channel Assignment Schemes

Hybrid channel assignment schemes combine both static and dynamic assignment properties by applying a fixed assignment for some radios and a dynamic assignment for other radios. The fixed radios can be assigned dedicated channels while the other radios can be switched dynamically among channels.

A. Hybrid Multi-Channel Protocol (HMCP)

HMCP [25] [26] is a link-layer multi-channel protocol for nodes with multiple radio interfaces. Out of the available interfaces at each node, X interfaces are assigned statically to X channels, and these interfaces are designated as “fixed interfaces.” The fixed interfaces stay on the specified channels for long durations of time. The remaining interfaces can frequently switch between any of the remaining channels, based on the data traffic, and are designated as “switchable interfaces.” Different nodes assign their “fixed interfaces” to different channels, thereby ensuring that all available channels are occupied, while switching the remaining interfaces (based on traffic requirements) ensures that communication between any pair of nodes is possible.

However, a co-ordination protocol is required to decide what channel to assign to the fixed interface, and also for enabling neighbors of a node X to know about the channels used by fixed interface of node X . Time synchronization and coordination between mesh nodes which is required in HMCP is not needed in TICA.

B. Breadth First Search - Channel Assignment (BFS-CA)

BFS-CA [27] is a centralized, interference-aware algorithm aimed at improving the capacity of the WMN backbone and at minimizing interference. This algorithm is based on an extension to the conflict graph concept called the Multi-radio Conflict Graph (MCG) where the vertices in the MCG represent edges between radios instead of edges between mesh routers.

To compensate for the drawbacks of a dynamic network topology, the proposed solution assigns one radio on each node to operate on a default common channel throughout the network. This strategy ensures a common network connectivity graph, provides alternate fallback routes and avoids flow disruption by traffic redirection over a default channel.

This scheme computes interference and bandwidth estimates based on the number of interfering radios, where an interfering radio is a simultaneously operating radio that is visible to a mesh router, but is external to its network. Each mesh router then derives two separate channel rankings. The first ranking depends on the increasing number of interfering radios. The second depends on the increasing channel utilization. The mesh router then merges the two rankings by taking the average of the individual ranks. The resulting ranking is used by the CA scheme. This scheme, called the Breadth First Search Channel Assignment (BFS-CA) algorithm, uses a breadth first search to assign channels to the radios. The search begins with links emanating from the gateway node, while links fanning outwards towards the edge of the network are given lower priority. To adapt to the changing interference characteristics, the algorithm periodically re-assigns channels.

BFS-CA requires certain number of MRs with certain number of radio interfaces to be placed at certain hops from the gateway, whereas TICA simply requires all MRs to have four data radios, does not require any careful router placement strategy, and works with any placement of routers as verified by a comprehensive performance evaluation.

The most significant difference between TICA and existing CA schemes is that TICA uses topology control based on power control to build the topology for CA with the objective of minimizing the interference between the MRs, whereas no other CA scheme has used topology control based on power control for CA.

CHAPTER 3

CHANNEL ASSIGNMENT PROBLEM

In this chapter, the medium access issues encountered by IEEE 802.11-based Single-Radio Single-Channel (SRSC) WMNs are presented, and a multiple-channel approach using multiple radios to overcome these problems is discussed. The connectivity and interference trade-off in a multi-radio WMN scenario are given, and the key issue of channel assignment in multi-radio multi-channel WMNs is presented, along with its objectives and constraints.

3.1. IEEE 802.11 Medium Access Issues

Since the WMN has to provide access to broadband Internet, it is expected to have higher bandwidth. Even though the physical layer can support very high bit rate, current MAC protocols are not able to utilize the entire bandwidth provided by the physical layer. The main reason for this poor performance is the suboptimal media access protocols, which were primarily designed for single-hop networks [1].

Figure 3.1: Hidden and exposed terminal problems [1]

3.1.1. Hidden and Exposed Terminal Problems

IEEE 802.11 DCF is one such widely accepted MAC protocol but, when used in a multihop network scenario, it results in poor performance and is therefore unacceptable.

The reason is that some nodes remain starved due to hidden and exposed terminals in a multihop environment. Figure 3.1 illustrates these problems [1].

Node 2, which is outside the interference range of Node 3 and unaware of the ongoing transmission at Node 3, continues to send RTS to Node 1 causing collision. This is a case of the hidden terminal problem.

Node 4 is prevented from transmitting because of the neighboring transmission at Node 3. This is a case of the exposed terminal problem.

3.1.2. Single-radio Single-channel Mesh Network

A Single-Radio Single-Channel (SRSC) mesh architecture, shown in Figure 3.2a [1], suffers from hidden and exposed terminal problems. Assigning orthogonal channels to the MRs within the interference range can help alleviate the hidden and exposed terminal problems, and assist in improving the overall capacity of the network. However, considering the traffic characteristics in a WMN, frequent channel switching may be required to communicate with neighboring nodes. In such scenarios, single-radio multi-channel MAC may not provide any significant performance gains due to high channel switching delay.

3.1.3. Dual-radio Single-channel Mesh Network

The decreasing cost of wireless radios has opened up new avenues for designing MRs using multiple radios. MRs can now use multiple radios tuned to orthogonal channels for simultaneously communicating with their neighbors. Figure 3.2b shows the use of a dual-radio WMN [1]. One radio provides service to its mesh clients (using channel 6 in 2.4 GHz 802.11 b), and the other radio forms the backhaul link connecting all the MRs to the gateway (using channel 1 in 5 GHz 802.11a). However, it suffers from the disadvantage of sharing the channel with the neighboring MRs at each hop along the backhaul path to the gateway.

3.1.4. Multi-radio Multi-channel Mesh Network

Figure 3.2c shows the use of a multi-channel approach using multiple radios that successfully overcomes all the problems encountered in the previous architectures [1]. Two radios are employed for the backhaul link and one for servicing the mesh clients.

The uplink and downlink backhaul radios and the service radio operate at non-overlapping channels which eliminates the co-channel interference.

Figure 3.2: Different mesh network architectures [1]

As each mesh router can be equipped with multiple radios, fixed channel assignment to these radios is a more viable solution. Efficient and intelligent channel assignment schemes have to be designed, as the number of channels is limited.

3.2. Connectivity and Interference Trade-off

Equipping each node with multiple radios is emerging as a promising approach for improving the capacity of WMNs. The IEEE 802.11a standard provides 12 non-overlapping frequency channels, which can be used simultaneously within the interference range neighborhood by assigning non-overlapping channels to radios. This leads to efficient spectrum utilization and increases the actual bandwidth available to the network [21].

Although multi-radio mesh nodes have the potential to significantly improve the performance of mesh networks, efficient channel assignment is a key issue in guaranteeing network connectivity while still mitigating the adverse effects of interference from the limited number of channels available to the network. A WMN node needs to share a common channel with each of its communication-range neighbors with which it needs to set up a link. However, to reduce interference, a node should minimize the number of neighbors with which it shares a common channel. Therefore, there is a trade-off between maximizing connectivity and minimizing interference, as illustrated in Figure 3.3 [19].

3.2.1. Maximum Connectivity in a Single-radio Single-channel Scenario

Fig. 3.3a shows the connectivity of the network when a single radio is operating on a single channel. In this scenario, a link is placed between two nodes if they are within their respective transmission ranges. This is the maximum achievable network connectivity since a single common channel is shared between all the nodes.

Figure 3.3: Trade-off between connectivity and interference [19]

3.2.2. Maximum Connectivity in a Multi-radio Multi-channel Scenario

Fig. 3.3b shows the maximum network connectivity achieved by the assignment of different channels to the radios. Although, there is a direct communication link between every pair of neighbors, not all the links can be active simultaneously because of possible interference.

3.2.3. Minimum Interference in a Multi-radio Multi-channel Scenario

On the other hand, Fig. 3.3c shows how interference could be completely eliminated and all links can be simultaneously active. The compromise here is that there is no common channel and hence no link between neighbors b and d.

The above example clearly illustrates that the goal of channel assignment is to achieve a balance between “minimizing interference and maximizing connectivity.”

3.3. Channel Assignment Problem

In a typical WMN, the total number of radios is much higher than the number of available channels. Thus, many links between the mesh routers operate on the same set of channels and interference among transmissions on these channels decreases their utilization. Therefore, minimizing the effect of interference is required for the efficient reuse of the scarce radio spectrum. So, the key issue in a Multi-Radio Multi-Channel

(MRMC) WMN architecture is the channel assignment problem, which involves assigning a channel to each radio of a MR in a way that minimizes interference on any given channel and guarantees connectivity between the mesh nodes [19].

3.3.1. Objectives

The CAA should satisfy the following two main goals:

1. Minimize co-channel interference between mesh routers
2. Ensure network connectivity

3.3.2. Constraints

Given the connectivity graph, the main challenge for CAA is to assign a channel to each radio in a way that minimizes interference between MRs and ensures connectivity between them. In order to achieve these goals, the CAA should satisfy the following requirements:

1. In order to communicate, a pair of nodes within transmission range of each other needs to have a common channel assigned to their end-point radios.
2. Links in direct interference range of each other should be assigned non-overlapping channels.
3. The number of distinct channels that can be assigned to a mesh router is bounded by the number of radios it has.
4. The total number of non-overlapping channels is fixed.
5. Since the traffic in a WMN is directed to and from the gateway, the traffic flows aggregate at routers close to the gateway. Links that are expected to support heavy traffic should be given more bandwidth than others. In other words, these links should use a radio channel that is shared by fewer nodes. Therefore, priority in channel assignment should be given to links starting from the gateway based on the number of nodes that use a link to reach the gateway.

At first glance, the problem of assigning channels to links in a mesh network appears to be a graph-coloring problem. However, standard graph-coloring algorithms cannot satisfy all of its constraints, and it is NP-hard to find an optimal channel assignment to maximize the overall network throughput [18]. Also, the channel assignment problem for mesh networks is similar to the list coloring problem, which is NP-complete [28].

CHAPTER 4

TOPOLOGY CONTROL AND CHANNEL ASSIGNMENT ALGORITHMS

In this chapter, the graph theory representation of interference modeling in multi-radio WMNs is discussed, and the network architecture of the proposed model is presented. The chapter presents the topology control and channel assignment algorithms for MRMC WMNs proposed in this thesis with details of their respective phases. The procedure of fault recovery with the proposed channel assignment algorithm is also presented in this chapter.

4.1. Interference Modeling

4.1.1. Graph Theory Representation of a WMN

At any point in time, the elements of a WMN can be represented as a graph [4]. A graph, G , is defined as a set of vertices V and a set of edges E and can be denoted as $G = (V, E)$. The sets V and E have to be nonempty and finite. An edge is a link between two vertices, that joins the vertices i and j , and is denoted by (i, j) . The vertices i and j are the end-vertices of this edge. If an edge exists between two vertices, then these two vertices are called adjacent or neighboring vertices of G . An example of such a graph is depicted in Figure 4.1.

Figure 4.1: Graph representation of a WMN [4]

In a graphical representation of Multi-Radio-Wireless Mesh Network (MR-WMN), each vertex in the graph represents a router in a MR-WMN, and each edge between two vertices represents a radio link between a pair of peer radio interfaces of two

routers. A radio link is said to be operational between a pair of radio interfaces of two nodes if (a) these two radio interfaces operate on the same frequency channel and (b) the signals transmitted from one node can be received above a minimum required power threshold by the peer node, and vice versa. Two nodes are connected if there is a link between them.

4.1.2. Connectivity Graph

For modeling purposes, a WMN is generally considered in which the mesh routers are distributed on a plane, as shown in Figure 4.2. Each mesh router is equipped with one or multiple radios with omni-directional antennas. It is assumed that all radios are characterized by an identical transmission range (R) and also by the same interference range (R').

Figure 4.2: A connectivity graph [19]

A. Transmission Range

The Transmission Range (TR) is defined as the distance at which a neighbor can receive packet transmissions successfully. When a receiver is within the TR of two transmitters that are transmitting simultaneously, the packets are assumed to interfere with each other. This then leads to a collision at the receiver, and thus no packet is received successfully.

B. Interference Range

The Interference Range (IR) is defined as the distance at which packet transmission cannot be decoded successfully at the receiver. However, any new

transmission from a router within IR from the receiver interferes with the packet reception. TR is smaller than IR ($R < R'$) and IR is generally assumed to be twice the TR.

According to the above assumptions, connectivity between mesh routers can be modeled using an undirected graph referred to as a connectivity graph, G. As illustrated in Figure 4.2, two nodes in the connectivity graph are linked if they are located within TR of each other [19].

4.2. Network Architecture

In our proposed model, each mesh router is equipped with five radios which operate on IEEE 802.11a channels (5 GHz band). One of these radios is used for control purpose while other radios are used for data traffic.

The control radios of all mesh nodes operate on the same non-overlapping IEEE 802.11a channel. Out of the 12 available non-overlapping 802.11a channels, channel 12 is used as the common control channel. Each mesh router is equipped with 4 data radios in order to utilize the remaining 11 non-overlapping channels available in IEEE 802.11a frequency band. Each MR communicates with its transmission range neighbors using these data radios for data transmission. So, each MR can have a maximum of 4 TR neighbors with whom it can communicate for data transmission which implies that the Maximum Node Degree (MND) per node is four.

The MND of 4 is selected in order to fully utilize the 11 available non-overlapping 802.11a frequency channels. Results have shown that with 12 available non-overlapping channels, the network throughput increases until a MND of four per node but saturates after that [18].

4.3. Topology Control Algorithm

The proposed Topology Control Algorithm (TCA) controls the network topology by selecting the nearest neighbors for each node in the network. The objective of the proposed TCA is to build a connectivity graph with a small node degree to mitigate the co-channel interference and enhance spatial channel reuse as well as preserve network connectivity with the use of minimal power, as less transmit power translates to less interference.

4.3.1. Gateway Advertisement Process

Initially, the gateway broadcasts a “Hello” message, using its control radio on the control channel, announcing itself as the gateway. Each mesh node that receives this Hello message over its control radio broadcasts it again and in this way, this Hello message is flooded throughout the mesh network. The Hello message contains a hop-count field that is incremented at each hop during its broadcast. So, a mesh node may receive multiple copies of the Hello message over its control radio. However, distance of a mesh node from the gateway is the shortest path length (shortest hop count) of the Hello message received by a mesh node through its control radio over different paths. In this way, each mesh node knows the next hop to reach the gateway using its control radio.

4.3.2. Assumptions

The proposed TCA assumes the following:

- Each node knows its location.
- Each node uses an omni-directional antenna for both transmission and reception.
- Each node is able to adjust its own transmission power.
- The maximum transmission power is the same for all nodes and hence, the maximum TR for any pair of nodes to communicate directly is also the same.

Note that all nodes start with the maximum transmission power, and that the initial topology graph created, when every node transmits with full power, is strongly connected.

4.3.3. Phases of TCA

The proposed TCA consists of the following five phases:

A. Exchange of Information Between Nodes

In the first exchange, each node broadcasts a HELLO message at maximum transmission power containing its node ID and the node position.

B. Building the Maximum Power Neighbor Table (MPNT)

From the information in the received HELLO messages, each node arranges its neighboring nodes in the ascending order of their distance. The result is the Maximum Power Neighbor Table (MPNT). Then, each node sends its MPNT along with its position and node ID to the gateway node using its control radio over the control channel.

C. Building the Direct Neighbor Table (DNT)

For each node in the network, the gateway builds a Direct Neighbor Table (DNT). Based on information in the MPNT of node v and the MPNTs of its neighbors, if

(a) node w is in the MPNT of node v , and

(b) node w is closer to any other node y in the MPNT of node w than to node v , then gateway eliminates node w from the MPNT of node v .

If, after removing nodes from the MPNT of node v , the remaining number of nodes in the MPNT of node v is less than “ x ,” then the gateway selects “ x ” nearest nodes as neighbors of node v which results in the DNT. However, if after removing nodes from the MPNT of node v , the remaining number of nodes is greater than or equal to “ x ,” then the result is the DNT.

This algorithm is called *Select x for less than x TCA* where x is a positive integer. The *Select x for less than x TCA* ensures that each node has at least x neighbors, as shown in Figure 4.3.

D. Converting into Bi-directional Links

For each node in the network, the gateway converts the uni-directional links in the DNT of a node into bi-directional links. For each uni-directional link, this is done by adding a reverse link in the DNT of the neighboring node. This converts the DNT into Bi-directional DNT. This results in the Final Neighbor Table (FNT).

E. Calculating the Minimum Power Required

For each node in the network, the gateway calculates the minimum power, $P_{\min}$, required to reach each of the nodes in the FNT of a node, using the appropriate propagation model formulas.

4.3.4. Propagation Models

The free space model is used for short distances and the two ray ground reflection model is used for longer distances, depending on the value of the Euclidean distance in relation to the cross-over distance. The cross-over distance is calculated by [29]

$$Cross_over_dist = \frac{4\pi h_t h_r}{\lambda}, \quad (1)$$

where h_t and h_r are the antenna heights of the transmitter and receiver, respectively. If the distance between two nodes is less than the cross over distance, i.e. $d(u,v) <$

$Cross_over_dist$, Free Space propagation model is used, whereas if $d(u,v) > Cross_over_dist$, Two-ray propagation model is used. The minimum power for the free-space propagation model is calculated by [29]

$$P_{\min} = \frac{RxThresh(4\pi d)^2}{G_t G_r \lambda^2}. \quad (2)$$

The minimum power for the two-ray propagation model is calculated by [29]

$$P_{\min} = \frac{RxThresh(d)^4}{G_t G_r h_t^2 h_r^2}, \quad (3)$$

where G_t and G_r are transmitter and receiver antenna gain respectively, and $RxThresh$ is power threshold required by radio interface of receiving node to correctly understand the message.

4.4. Channel Assignment Algorithm

4.4.1. Interference-range Edge Coloring

If K be the number of available colors (channels), then for $K \geq 4$, the distance-2 edge coloring problem, also known as strong edge coloring problem, is NP-complete [30]. A distance-2 edge coloring of a graph G is an assignment of colors to edges so that any two edges within distance 2 of each other have distinct colors. Two edges of G are within distance 2 of each other if either they are adjacent, as shown in Figure 4.4a or there is some other edge that is adjacent to both of them, as shown in Figure 4.4b. The distance-2 edge coloring has been used in [31] for channel assignment, where the authors have described the interference model as two-hop interference model. In this model, two edges interfere with each other if they are within two-hop distance. In other words, two edges e_1 and e_2 cannot transmit simultaneously on the same channel if they are sharing a node or adjacent to a common edge.

To minimize co-channel interference in a wireless mesh network, it is necessary to assign channels to links such that links within interference range of each other are assigned different channels (colors). This problem can be termed as *interference-range edge coloring*, and the corresponding interference model can be called *interference-range interference model*. In a grid topology where links are of equal length, the interference-range edge coloring is similar to distance-2 edge coloring, as shown in Figure 4.5a. The

channel assigned to link l_1 cannot be assigned to links l_2 and l_3 as they are within the interference range of link l_1 . Note that l_2 and l_3 are also within two-hop distance of l_1 .

Figure 4.3: Select x for less than x TCA

However, in a random topology where links are of different lengths due to the random nature of the topology, the interference-range edge coloring can be harder than distance-2 edge coloring as shown in Figure 4.5b. In this case, the channel assigned to

link l_1 cannot be assigned to links l_2 , l_3 and l_4 as they are within the interference range of link l_1 . Note that l_2 , l_3 and l_4 are within three-hop distance of l_1 .

Figure 4.4: Two edges at distance-2 of each other [30]

Figure 4.5: Interference-range edge coloring

In the network model proposed in this thesis, the number of available channels (colors) is 11 which means that $K = 11$. Based on its similarity to distance-2 edge coloring problem which is NP-complete for $K \geq 4$, the interference-range edge coloring problem is, therefore, also NP-complete.

Therefore, I propose an approximate algorithm for channel assignment. The proposed channel assignment algorithm, TICA, is shown in Figure 4.6 and has the following phases.

4.4.2. Phases of TICA

A. Topology Control

In order to create the network connectivity graph with the aim of reducing the interference between MRs, network topology is controlled using the topology control algorithm.

All nodes send their MPNTs to the gateway using their control radio. Note that in order to send its MPNT to the gateway, each mesh node knows the next hop to reach the gateway using its control radio via the “gateway advertisement process.” The gateway starts with the *Select 1 for less than 1* TCA and builds the FNTs of all nodes.

B. Connectivity Graph

Based on the FNTs of all nodes, the gateway builds the connectivity graph and checks the resulting network for connectivity. A topology is said to be connected if the gateway can reach any node in the connectivity graph directly or through intermediate hops.

If the resulting network is not connected, the gateway moves to the next higher TCA by incrementing x in the *Select x for less than x* TCA, builds the connectivity graph and checks the resulting network for connectivity. The gateway keeps on moving to a higher TCA until it finds that the network resulting from the connectivity graph is connected.

C. Minimum Power-based Shortest Path Tree with a MND of Four

After ensuring that the connectivity graph is connected, the gateway builds the Shortest Path Tree (SPT), using Dijkstra’s algorithm [32], based on the connectivity graph. The metric for path selection is minimum power.

The node degree is defined as the number of TR neighbors of a node. The number of TR neighbors of a mesh router is bounded by the number of its radios and each node has four data radios. So, if any node in the shortest path tree has more than four links, the gateway selects those four links for that node which have the minimum weight and sets the weight of all other links to infinity. In other words, the gateway ensures that each node can have a maximum of four TR neighbors and builds a Minimum Power-based SPT (MPSPT) with a MND of 4 per node. The gateway checks the resulting MPSPT graph for connectivity. If the resulting MPSPT graph is not connected, the gateway moves to a higher TCA.

Once the MPSPT graph is determined, the gateway has to assign channels to links of the MPSPT. Now, the objective is to assign channels to the links of the MPSPT such that the interference between simultaneous transmissions on links operating on the same channel is minimized and the overall network throughput is maximized.

Figure 4.6: Topology-controlled Interference-aware Channel-assignment Algorithm (TICA)

D. Link Ranking

In order to assign channels to the links of the MPSPT graph, each link is assigned a ranking by the gateway. The ranking associated with each link is derived from the number of nodes that use a link to reach the gateway node. If l is link and n is node using link l to reach the gateway, then rank of link l , i.e. r_l , is given by

$$r_l = \sum_{n=1}^N I_{n,l}, \quad (4)$$

where N is the total number of nodes in the network. $I_{n,l}$ is 1 if node n is using link l and 0 otherwise.

In the case of two or more links that have the same rank, the link whose power of the farthest node to the gateway is smaller is given priority in channel assignment. If there are some links that still have the same rank, the link with smaller node IDs is given priority in channel assignment.

E. Channel Assignment

The gateway assigns a channel to each link in the order of its rank, and it begins with assigning the 11 available non-overlapping channels to the 11 highest-ranked links such that Channel 1 is assigned to the highest-ranked link. For the 12th-ranked link and onwards, the gateway checks the channel assignment of all links within the interference range of both nodes that constitute that link.

i) Non-conflicting Channel

Out of the 11 available channels, channels which are not assigned to any link within the interference range of both nodes that constitute the 12th-ranked link are termed as non-conflicting channels. If the gateway finds one or more non-conflicting channels, it assigns that channel from the unassigned non-conflicting channels to the 12th-ranked link which has the highest channel number.

ii) Least Interfering Channel

If the gateway cannot find any channel among the 11 available channels that is not assigned to any link within the interference range of both nodes that constitute the 12th-ranked link, it selects the least interfering channel and assigns it to that link. A Least

Interfering Channel (LIC) is a channel which causes minimum interference within the interference range of both nodes that constitute the 12th-ranked link.

iii) Interference Level

In order to find out the LIC, the gateway builds the interference level for all the 11 channels. The LIC is the channel with the minimum interference level, which means that assigning this channel to the 12th-ranked link would result in minimum interference in the network.

In order to build the IL for Channel One, the gateway finds all links within the interference range of each of the two nodes that constitute the 12th-ranked link that use Channel One, and calculates IL of each link based on its rank and distance from a node of the 12th-ranked link. It sums up individual ILs of all links that use Channel One within the interference range of each of the two nodes that constitute the 12th-ranked link, to find out total IL for Channel One. This is done by

$$(IL)_i = \sum_m \left(\frac{r_m}{R} \right) \left(\frac{1}{d_m^\alpha} \right), \quad (5)$$

where i is the channel that has value between 1 and 11,

$(IL)_i$ is interference level of channel i ,

m is a link using channel i that is within the interference range of a node of the 12th-ranked link,

r is the rank of link m ,

R is the maximum rank assigned to a link,

d is distance from a node of link m to a node of the 12th-ranked link, and

α is the path loss exponent and is 2 or 4, depending on cross over distance.

If a link is emanating from either of the two nodes that constitute the 12th-ranked link and a channel has been assigned to that link, then the IL for this channel is set to infinity.

The LIC is the channel with the minimum interference level and is selected by

$$(IL)_{LIC} = \min[(IL)_1, (IL)_2, \dots, (IL)_{11}]. \quad (6)$$

Similarly, the gateway assigns channels to all the links of the MPSPT.

iv) Channel Assignment and Routing Message

Using its control radio, the gateway then sends each mesh node the Channel Assignment and Routing Message (CARM). For each channel assigned to a mesh router, CARM contains the channel number and the neighbor node to communicate with, using this channel. The CARM also contains the next hop to reach the gateway for data traffic. Based on the channel assigned to a mesh router to communicate with a neighbor and its distance to that neighbor, the mesh router applies power control and adjusts its transmission power accordingly by using either the free space propagation model given by (2) or the two-ray propagation model given by (3), depending on the cross-over distance which is calculated using (1).

4.5. Failure Recovery Mechanism of TICA

When a node fails, nodes in its sub-tree lose their connectivity to the gateway and hence the Internet through the wired world. TICA supports automatic and fast failure recovery and reorganizes the network to bypass the failed node and to restore the connectivity.

In case of node failure, the FRM of TICA which is initiated by the gateway has following phases, as shown in Figure 4.7.

A. Periodic Keep-Alive Messages

All nodes send periodic "keep-alive" messages to the gateway on the control channel using their control radios. The keep-alive message from a node tells the gateway that the node is active.

B. Topology Control

If a gateway does not receive three consecutive keep-alives from a node z , then it concludes that node z has failed and is no longer active. The gateway then deletes the MPNT for this node and deletes node z from the MPNT of all its neighboring nodes. Note that the gateway has MPNTs of all nodes, as all nodes sent their MPNTs to the gateway during the setup phase. The gateway builds the FNTs for all nodes using the *Select x for less than x TCA*.

C. Connectivity Graph

Based on the FNTs of all nodes, the gateway builds the connectivity graph and checks the resulting network for connectivity. If the resulting network is not connected, the gateway moves to a higher TCA.

D. Minimum Power-based SPT with a MND of Four

After ensuring that the connectivity graph is connected, the gateway builds the MPSPT with a MND of four. Again, the gateway checks the resulting MPSPT graph for connectivity. If the resulting MPSPT is not connected, the gateway moves to a higher TCA.

E. Link Ranking

After ensuring that the MPSPT is connected, the gateway builds the link ranking for all links of the MPSPT.

F. Channel Assignment

Based on the link ranking, the gateway assigns the channels to all links of the MPSPT.

The gateway then sends the new CARM to all nodes in the network on the control channel. Each MR receives the CARM on the control channel over its control radio and compares the existing CA with the updated CA. It switches its radios to new channels in case the new CA is different from the old one. Based on the channel assigned to a MR to communicate with a neighbor and its distance to that neighbor, the MR applies power control and adjusts its transmission power accordingly. This is done by calculating the required controlled transmission power by using either the free space propagation model using (2) or the two-ray propagation model using (3), depending on the cross-over distance, which is calculated using (1). Each MR also updates its next hop required to reach the gateway for data traffic.

Figure 4.7: Failure Recovery Mechanism of TICA

CHAPTER 5

PERFORMANCE EVALUATION

In this chapter, the performance evaluation of the proposed channel assignment algorithm is provided. Different topologies used for performance evaluation are presented, and details on the working of different phases of TICA and FRM of TICA are discussed, with examples. The objective of the simulation-based evaluation is to understand the behavior of TICA in small-scale and large-scale networks.

The performance of the proposed algorithm for MRMC WMNs, TICA, is compared against a “Single-Radio Single-Channel” (SRSC) scheme and a “Common Channel Assignment” (CCA) scheme for multi-radio mesh nodes. In the CCA scheme [20], all mesh routers have four radio interfaces. The first radio on all nodes is tuned to the first non-overlapping channel; the second radio is tuned to the second non-overlapping channel, and so on.

5.1. Simulation Environment

For the performance evaluation via throughput analysis, NS2 (version 2.30) [33] simulation tool is used. However, MATLAB [34] is used to generate the power controlled topology, the MPSPT graph, the link ranking of the MPSPT and the channel assignment for the links of the MPSPT.

Multi-interface wireless mesh nodes are created in NS2 by modifying the built-in IEEE 802.11 node model in NS2, using the procedure given in [35]. Based on the channel assignment by the gateway, the radio interfaces are configured for each node and the transmission power for each radio of each mesh node is set accordingly. All the mesh nodes at the periphery of the network send traffic to the gateway. Each of these nodes generates an 8 Mbps Constant Bit Rate (CBR) traffic stream consisting of 1024 byte packets, and sends data to the gateway node at the same time. They do not stop transmitting until the end of the simulation. So, this is a scenario in which multiple flows within the mesh network interfere with each other.

All radios are IEEE 802.11a radios and support 12 channels. The first 11 non-overlapping channels are used by the data radios, whereas the 12th channel is used by the

control radio on each node. If the distance between the nodes is less than the cross-over distance, free space propagation model is used; if the distance between the nodes is greater than the cross-over distance, two-ray propagation model is used. As shown in Tables 5.1 and 5.2 [5], the minimum receiver sensitivity ($RxThresh$) is set to -65 dBm (3.16227×10^{-10} Watts) in order to achieve a maximum data rate of 54 Mbps supported by IEEE 802.11a.

Table 5.1: IEEE 802.11a Receiver Requirements [5]

Modulation	Coding rate (R)	Adjacent channel rejection (dB)	Alternate adjacent channel rejection (dB)	Minimum sensitivity (dBm) (20 MHz channel spacing)	Minimum sensitivity (dBm) (10 MHz channel spacing)	Minimum sensitivity (dBm) (5 MHz channel spacing)
BPSK	1/2	16	32	-82	-85	-88
BPSK	3/4	15	31	-81	-84	-87
QPSK	1/2	13	29	-79	-82	-85
QPSK	3/4	11	27	-77	-80	-83
16-QAM	1/2	8	24	-74	-77	-80
16-QAM	3/4	4	20	-70	-73	-76
64-QAM	2/3	0	16	-66	-69	-72
64-QAM	3/4	-1	15	-65	-68	-71

Table 5.2: IEEE 802.11a Modulation Parameters [5]

Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSK})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})	Data rate (Mb/s) (20 MHz channel spacing)	Data rate (Mb/s) (10 MHz channel spacing)	Data rate (Mb/s) (5 MHz channel spacing)
BPSK	1/2	1	48	24	6	3	1.5
BPSK	3/4	1	48	36	9	4.5	2.25
QPSK	1/2	2	96	48	12	6	3
QPSK	3/4	2	96	72	18	9	4.5
16-QAM	1/2	4	192	96	24	12	6
16-QAM	3/4	4	192	144	36	18	9
64-QAM	2/3	6	288	192	48	24	12
64-QAM	3/4	6	288	216	54	27	13.5

In order to achieve a strongly connected topology, the maximum transmission power for all the radios is set to 27 dBm. The maximum power transmission range is 164 meters and the maximum power interference range is 328 meters. RTS/CTS is disabled.

Note that in the CCA and SRSC schemes, the mesh nodes do not control their power, transmit with the same maximum power (27 dBm) and use AODV (Ad hoc On-Demand Distance Vector) [36] routing protocol as their routing agent.

5.2. Network Topologies

Three topologies are used in the evaluation. Each topology consists of 36 mesh nodes distributed in an area of 500x500 meters.

Topology 1 is a grid topology; Topology 2 is a randomly generated topology while in Topology 3, called controlled random, the physical terrain is divided into a number of cells and a mesh node is placed randomly within each cell.

Grid Topology (GT), as shown in Figure 5.1, is used to evaluate TICA in a densely populated topology.

Figure 5.1: Grid Topology

Random Topology (RT), as shown in Figure 5.2, is used to evaluate TICA in an unplanned deployment of randomly and uniformly distributed mesh nodes.

Controlled Random Topology (CRT), as shown in Figure 5.3, is used to reflect real-world deployments where mesh routers are uniformly distributed for maximum coverage.

Figure 5.2: Random Topology

Figure 5.3: Controlled Random Topology

5.3. Working of TICA

The working of different phases of TICA is explained below, with examples. The random topology shown in Figure 5.2 is considered for this purpose.

5.3.1. Topology Control Phase

A. Exchanging Hello Messages

Each node broadcasts a HELLO message at maximum transmission power containing its node ID and node position. As shown in Figure 5.4, Node 1 receives Hello messages from all nodes in its maximum power transmission range.

Figure 5.4: Maximum Power Transmission Range neighbors of Node 1

Table 5.3 shows the node ID and node location of the maximum power transmission range neighbors obtained, from the received Hello messages, by Node 1.

Similarly, from the received hello messages, each node in the network obtains the node ID and node location of its maximum power transmission range neighbors.

Table 5.3: Neighbor information received by Node 1

Neighbor Node ID	X coordinate	Y coordinate
3	96	185
5	79	428
7	96	215
25	35	160
30	53	306
32	46	134
33	77	141

B. Building the MPNT

In order to build its MPNT, Node 1 calculates its distance to each of its maximum power transmission range neighbors. For example, Node 1 calculates its distance to Node 3 using the distance formula as follows:

$$distance_{1-3} = \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} = \sqrt{(17 - 96)^2 + (281 - 185)^2} = 124 \text{ m}$$

Note that the x and y coordinates of Node 1 are 17 and 281 respectively.

Then Node 1 arranges its neighboring nodes in the ascending order of their distance, which results in the MPNT of Node 1, as shown in Table 5.4.

Table 5.4: MPNT of Node 1

Node ID	Neighbor Node ID	Distance (m)
1	30	44
1	7	103
1	25	122
1	3	124
1	32	150
1	33	152
1	5	160

Similarly, each node builds its MPNT, and sends it along with its position and node ID to the gateway node using its control radio over the control channel.

C. Building the DNT

For each node in the network, the gateway builds the DNT based on the MPNT of that node and its neighboring nodes. Based on information in the MPNT of Node 1 and the MPNT of its neighboring Node 3, shown in Table 5.5, the gateway does not select

Node 3 as the neighbor of Node 1 as distance between Node 1 and Node 3 ($\text{distance}_{1,3} = 124 \text{ m}$) is more than the distance between Node 3 and Node 7 ($\text{distance}_{3,7} = 30 \text{ m}$). Node 3 is closer to Node 7 than to Node 1.

Table 5.5: MPNT of Node 3

Node ID	Neighbor Node ID	Distance (m)
3	7	30
3	33	48
3	11	49
3	25	66
3	32	71
3	20	96
3	19	120
3	1	124
3	30	128
3	10	144
3	34	148

Similarly, the gateway removes all such nodes from the MPNT of Node 1 which are closer to any node in their MPNTs than to Node 1. After removing all such nodes from the MPNT of Node 1, the remaining number of nodes in the MPNT of Node 1 is shown in Table 5.6.

Table 5.6: Remaining nodes in MPNT of Node 1

Node ID	Neighbor Node ID	Distance (m)
1	30	44

i) DNT for Select 1 for less than 1 TCA

For *Select 1 for less than 1 TCA*, since after removing nodes from the MPNT of Node 1, the remaining number of nodes in MPNT of Node 1 is equal to 1, the result is the DNT of Node 1, as shown in Table 5.7.

Table 5.7: DNT of Node 1 for Select 1 for less than 1 TCA

Node ID	Neighbor Node ID	Distance (m)
1	30	44

ii) DNT for Select 2 for less than 2 TCA

For *Select 2 for less than 2 TCA*, since after removing nodes from the MPNT of Node 1, the remaining number of nodes in the MPNT of Node 1 is less than 2, the

gateway selects 2 nearest nodes as neighbors of Node 1, which results in the DNT of Node 1 as shown in Table 5.8.

Table 5.8: DNT of Node 1 for Select 2 for less than 2 TCA

Node ID	Neighbor Node ID	Distance (m)
1	30	44
1	7	103

iii) DNT for Select 3 for less than 3 TCA

For *Select 3 for less than 3 TCA*, since after removing nodes from the MPNT of Node 1, the remaining number of nodes in the MPNT of Node 1 is less than 3, the gateway selects 3 nearest nodes as neighbors of Node 1, which results in the DNT of Node 1 as shown in Table 5.9.

Table 5.9: DNT of Node 1 for Select 3 for less than 3 TCA

Node ID	Neighbor Node ID	Distance (m)
1	30	44
1	7	103
1	25	122

D. Converting into Bi-directional Links

For each node in the network, the gateway converts the uni-directional links in the DNT of a node into bi-directional links. For each uni-directional link, this is done by adding a reverse link in the DNT of the neighboring node. The DNT of Node 7 for Select 3 for less than 3 TCA is shown in Table 5.10.

Table 5.10: DNT of Node 7 for Select 3 for less than 3 TCA

Node ID	Neighbor Node ID	Distance (m)
7	3	30
7	11	75
7	33	76

As shown in DNT of Node 1 in Table 5.9, there is a link from Node 1 to Node 7. However, there is no reverse link from Node 7 to Node 1 as shown in the DNT of Node 7 in Table 5.10. So, the gateway adds the link from Node 7 to Node 1 in the DNT of Node 7. This converts the DNT into Bi-directional DNT, which results in the FNT. The FNT of Node 7 for Select 3 for less than 3 TCA is shown in Table 5.11.

Table 5.11: FNT of Node 7 for Select 3 for less than 3 TCA

Node ID	Neighbor Node ID	Distance (m)
7	3	30
7	11	75
7	33	76
7	30	101
7	1	103

The FNT of Node 1 for Select 3 for less than 3 TCA is shown in Table 5.12.

Table 5.12: FNT of Node 1 for Select 3 for less than 3 TCA

Node ID	Neighbor Node ID	Distance (m)
1	30	44
1	7	103
1	25	122

E. Calculating the Minimum Power Required

For each node in the network, the gateway calculates the minimum power, required to reach each of the nodes in the FNT of a node, using the appropriate propagation model formulas. For example, the cross over distance is calculated by using equation (1) as follows:

$$Cross_over_dist = \frac{4\pi h_t h_r}{\lambda} = \frac{4\pi \times 3 \times 3}{\left(\frac{3 \times 10^8}{5.805 \times 10^9} \right)} = 2189 \text{ m}$$

As shown in Table 5.12, since the distance₁₋₃₀ < cross-over distance, so the gateway uses the free-space propagation model, given by Equation (2), to calculate the power required to reach Node 30 from Node 1 as follows:

$$P_{min,1-30} = \frac{RxThresh(4\pi d_{1-30})^2}{G_t G_r \lambda^2} = \frac{3.16227 \times 10^{-7} \times (4\pi \times 44)^2}{1 \times 1 \times \left(\frac{3 \times 10^8}{5.805 \times 10^9} \right)^2} = 37 \text{ mW}$$

Similarly, the gateway calculates the minimum power required to reach each of the nodes in the FNT of Node 1, as shown in Table 5.13.

Table 5.13: FNT of Node 1 with power required to reach its neighbors

Node ID	Neighbor Node ID	Distance (m)	Power (mW)
1	30	44	37
1	7	103	199
1	25	122	279

5.3.2. Connectivity Graph

Based on the information of the FNTs of all nodes, the gateway builds the connectivity graph and checks the resulting network for connectivity. Note that Node 15 is the gateway node.

A. Connectivity Graph for Select 1 for Less Than 1 TCA

The FNTs of all nodes resulting from Select 1 for less than 1 TCA are shown in the Appendix in Table A.1. Based on these FNTs, the gateway builds the connectivity graph as shown in Figure 5.5.

Note that the connectivity graph resulting from Select 1 for less than 1 TCA is not connected.

B. Connectivity Graph for Select 2 for Less Than 2 TCA

Since the connectivity graph resulting from Select 1 for less than 1 is not connected, the gateway moves to the next higher TCA. The FNTs of all nodes resulting from Select 2 for less than 2 TCA are shown in the Appendix in Table A.2. Based on these FNTs, the gateway builds the connectivity graph as shown in Figure 5.6.

Note that the connectivity graph resulting from Select 2 for less than 2 TCA is not connected.

C. Connectivity Graph for Select 3 for Less Than 3 TCA

Since the connectivity graph resulting from Select 2 for less than 2 TCA is not connected, the gateway moves to the next higher TCA. The FNTs of all nodes resulting from Select 3 for less than 3 TCA are shown in the Appendix in Table A.3. Based on these FNTs, the gateway builds the connectivity graph as shown in Figure 5.7.

Note that the connectivity graph resulting from Select 3 for less than 3 TCA is connected.

5.3.3. MPSPT with a MND of Four

Since the network resulting from Select 3 for less than 3 TCA is connected, the gateway proceeds to build the SPT with a MND of four based on the connectivity graph. The metric for path selection is minimum power to reach the gateway and the tree is rooted at the gateway. The resulting MPSPT with a MND of four is shown in Figure 5.8.

Figure 5.5: Connectivity Graph for Select 1 for less than 1 TCA

Figure 5.6: Connectivity Graph for Select 2 for less than 2 TCA

Figure 5.7: Connectivity Graph for Select 3 for less than 3 TCA

Figure 5.8: MPSPT with a MND of four for Select 3 for less than 3 TCA

For each node in the MPSPT, if the gateway finds more than 4 links, it selects four links with minimum weight and sets the weight for all other links to infinity. For example, when the gateway starts to build the MPSPT, it has the following five links, as shown in Table 5.14.

Table 5.14: Possible Links for the gateway

Node ID	Neighbor ID	Distance (m)	Power (mW)
15	18	42	33
15	24	46	40
15	8	51	49
15	9	60	68
15	21	81	123

Out of the five available links, the gateway selects those four links which have the minimum power and sets the weight of the fifth link to Node 21 to infinity, as shown in Table 5.15.

Table 5.15: Links selected by the gateway

Node ID	Neighbor ID	Distance (m)	Power (mW)
15	18	42	33
15	24	46	40
15	8	51	49
15	9	60	68
15	21	81	INF

Similarly, the gateway checks each node for a maximum of four links and builds a MPSPT with a MND of four per node.

5.3.4. Link Ranking

Since the resulting MPSPT is connected, the gateway proceeds to assign a ranking to each link of the MPSPT. The ranking associated with each link is derived from the number of nodes that use a link to reach the gateway. For example, the rank of link between Node 15 and Node 9 is calculated, using equation (4), as follows:

$$r_{15-9} = \sum_{n=1}^N I_{n,l} = \sum_{n=1}^{36} I_{n,15-9} = I_{1,15-9} + I_{2,15-9} + \dots + I_{36,15-9} = 31$$

Similarly, the gateway calculates the rank of all links in the MPSPT. If two or more links have the same rank, then the link whose power of the farthest node to the gateway is smallest is given priority. If there are still some links with the same rank, then

the link with the smallest node IDs is given priority. The resulting link ranking for the MPSPT is shown in Table 5.16.

Table 5.16: Link Ranking of MPSPT

Link		Distance (m)	Power (mW)	RANK	Power from the farthest node of the link to the gateway (mW)
15	9	60	68	31	68
9	12	24	11	18	79
12	6	58	63	17	142
9	29	57	61	12	129
29	19	53	53	11	182
6	22	52	51	10	193
19	11	88	145	10	327
22	34	84	132	8	325
6	14	46	40	6	182
34	10	40	30	6	355
11	3	49	45	5	372
10	27	119	265	5	620
14	31	47	42	4	224
11	33	49	45	4	372
3	7	30	17	4	389
27	35	38	27	4	647
31	2	133	331	3	555
15	8	51	49	2	49
33	32	32	20	2	392
7	30	101	191	2	580
35	36	46	40	2	687
2	16	106	211	2	766
15	18	42	33	1	33
15	24	46	40	1	40
8	21	33	21	1	70
14	17	59	66	1	248
32	25	28	15	1	407
33	20	51	49	1	421
34	26	78	114	1	439
22	23	124	288	1	481
7	1	103	199	1	588
35	4	53	53	1	700
16	13	66	82	1	848
30	5	125	293	1	873
36	28	101	191	1	878

As shown in Table 5.16, the link between Node 6 and Node 22 and link between Node 19 and Node 11 have the same rank. In this case, the link between 6 and 22 is given

priority on the link between 19 and 11 as the power from Node 22 to the gateway is 193mW which is smaller than the power from Node 11 to the gateway which is 327mW.

5.3.5. Channel Assignment

The gateway assigns a channel to each link in the order of its rank, first assigning the 11 available non-overlapping channels to the 11 highest-ranked links as shown in Table 5.17.

Table 5.17: Channel Assignment of the 11 highest-ranked links

Link		Channel
15	9	1
9	12	2
12	6	3
9	29	4
29	19	5
6	22	6
19	11	7
22	34	8
6	14	9
34	10	10
11	3	11

For the 12th-ranked link and onwards, the gateway checks the channel assignment of all links within the interference range of both nodes that constitute that link. For example, for the 12th-ranked link between Node 10 and Node 27, the gateway finds all the channel-assigned links within the interference range of Node 10 and Node 27, as shown in Table 5.18 and Figures 5.9 and 5.10 respectively.

Since the gateway cannot find any channel among the 11 available channels that are not assigned to any link within the IR of both nodes that constitute the 12th-ranked link, it computes a LIC and assigns it to the link between Node 10 and Node 27.

Figure 5.9: Channel-assigned links within IR of Node 10

Figure 5.10: Channel-assigned links within IR of Node 27

Table 5.18: Channel Assignment of links within IR of 12th-ranked link

Node ID	Link		Channel	Distance	RANK
10	10	34	10	0	6
10	3	11	11	144	5
10	6	12	3	166	17
10	6	22	6	166	10
10	6	14	9	166	6
10	9	15	1	205	31
10	9	12	2	205	18
10	9	29	4	205	12
10	11	19	7	161	10
10	11	3	11	161	5
10	12	9	2	197	18
10	12	6	3	197	17
10	14	6	9	211	6
10	19	29	5	136	11
10	19	11	7	136	10
10	22	6	6	121	10
10	22	34	8	121	8
10	29	9	4	148	12
10	29	19	5	148	11
10	34	22	8	40	8
10	34	10	10	40	6
27	10	34	10	119	6
27	22	6	6	199	10
27	22	34	8	199	8
27	34	22	8	147	8
27	34	10	10	147	6

A. Interference Level

In order to find out the LIC, the gateway calculates the interference level for all the 11 channels. For example, the gateway calculates the IL for channel nine, using equation (5) as follows:

$$(IL)_9 = \sum_m \left(\frac{r_m}{R} \right) \left(\frac{1}{d_m^\alpha} \right) = \left(\frac{6}{31} \right) \left(\frac{1}{166^2} \right) + \left(\frac{6}{31} \right) \left(\frac{1}{211^2} \right) = 1.137117 \times 10^{-5}$$

Similarly, the gateway calculates the IL for all the 11 channels as shown in Table 5.19. Note that since another link is emanating from Node 10, i.e. link between Node 10 and Node 34, and channel 10 has been assigned to this link, therefore, the IL for channel 10 is set to infinity.

Table 5.19: Interference Level for all 11 channels

Channel	IL
1	2.379536e-05
2	2.877827e-05
3	3.403123e-05
4	2.688353e-05
5	3.538434e-05
6	4.188483e-05
7	2.988532e-05
8	1.973755e-04
9	1.137117e-05
10	INF
11	1.400066e-05

B. Least Interfering Channel

As shown in Table 5.19, channel 9 is the channel with the minimum IL. So, using equation (6) as follows, the gateway selects channel 9 as the LIC and assigns it to the 12th-ranked link.

$$\begin{aligned}
 (IL)_{LIC} &= \min[(IL)_1, (IL)_2, \dots, (IL)_{11}] \\
 (IL)_{LIC} &= (IL)_9 \\
 \Rightarrow LIC &= 9
 \end{aligned}$$

C. Non-conflicting Channel

For the 13th-ranked link between Nodes 14 and 31, the gateway finds Channels 5, 7, 10, and 11, which are non-conflicting channels as they are not assigned to any links within IR range of both nodes that constitute the 13th-ranked link, as shown in Table 5.20.

From the available non-conflicting channels, the gateway selects the channel with the highest channel number, i.e. Channel 11 and assigns it to the 13th-ranked link. Similarly, the gateway assigns channels to all links in the MPSPT, as shown in Table 5.21.

Table 5.20: Channel Assignment of links within IR of 13th-ranked link

Node ID	Link		Channel	Distance	RANK
14	14	6	9	0	6
14	6	12	3	46	17
14	6	22	6	46	10
14	6	14	9	46	6
14	9	15	1	92	31
14	9	12	2	92	18
14	9	29	4	92	12
14	12	9	2	69	18
14	12	6	3	69	17
14	22	6	6	92	10
14	22	34	8	92	8
31	6	12	3	71	17
31	6	22	6	71	10
31	6	14	9	71	6
31	14	6	9	47	6
31	22	6	6	93	10
31	22	34	8	93	8

Table 5.21: Channel Assignment for links of MPSPT

Link		Channel	Link		Channel
15	9	1	33	32	8
9	12	2	7	30	6
12	6	3	35	36	10
9	29	4	2	16	5
29	19	5	15	18	10
6	22	6	15	24	9
19	11	7	8	21	8
22	34	8	14	17	10
6	14	9	32	25	11
34	10	10	33	20	5
11	3	11	34	26	2
10	27	9	22	23	7
14	31	11	7	1	3
11	33	10	35	4	8
3	7	9	16	13	11
27	35	11	30	5	4
31	2	7	36	28	6
15	8	11			

D. Channel Assignment and Routing Message

The gateway then sends each mesh node the CARM, via the control radio on the control channel, which contains the channel number and the neighbor node to

communicate with using this channel. The channel assignment message also contains the next hop to reach the gateway for data traffic. Based on channel assigned to a mesh router to communicate with a neighbor and its distance to that neighbor, the mesh router applies power control and adjusts its transmission power by using the appropriate propagation model based on equation (1).

5.4. Failure Recovery Mechanism of TICA

All nodes send periodic "keep-alive" messages to the gateway. If the gateway does not receive three consecutive keep-alives from any node, it concludes that that node has failed and is no longer active. After deleting the MPNT for this node and deleting it from the MPNT of all its neighboring nodes, the gateway builds the FNTs for all nodes. The gateway then proceeds with all the phases required to calculate the channel assignment.

After calculating the new channel assignment, the gateway sends the new CARM to all nodes in the network on the control channel.

In order to understand the different phases of FRM of TICA, the random topology shown in Figure 5.2 is considered and four different scenarios of failure recovery with TICA are discussed.

5.4.1. Scenario 1 - Node 9 Fails

In this scenario, I suppose that Node 9 has failed. After missing three consecutive keep-alives from Node 9, the gateway concludes that Node 9 is not active. The gateway then deletes the MPNT of Node 9 and deletes Node 9 from the MPNT of its neighbors. The gateway runs the Select 3 for less than 3 TCA, builds the FNTs for all nodes and builds the connectivity graph as shown in Figure 5.11. The gateway starts with Select 3 for less than 3 TCA, as it resulted in a connected network when Node 9 was alive. Note that the network resulting from Select 3 for less than 3 TCA is not connected.

Since the connectivity graph resulting from Select 3 for less than 3 TCA is not connected, the gateway moves to Select 4 for less than 4 TCA and builds the connectivity graph as shown in Figure 5.12. Note that the network resulting from Select 4 for less than 4 TCA is connected.

Since the connectivity graph resulting from Select 4 for less than 4 TCA is connected, the gateway builds the MPSPT with a MND of 4, as shown in Figure 5.13.

Figure 5.11: Connectivity Graph with Select 3 for less than 3 TCA after Node 9 fails

Figure 5.12: Connectivity Graph with Select 4 for less than 4 TCA after Node 9 fails

Figure 5.13: MPSPT with a MND of 4 after Node 9 fails

Since the resulting MPSPT is connected, the gateway builds the link ranking for each link of the MPSPT, as shown in Table 5.22.

Based on the link ranking, the gateway assigns a channel to each link in the MPSPT, as shown in Table 5.23.

Node 9 was part of the highest ranked link before its failure. So, after its failure, the link rankings and in turn, the channel assignment of all links in the MPSPT changes.

Note that the other three scenarios for failure recovery with TICA are presented in the appendix B.

During failure recovery with TICA, after deleting the MPNT of the failed node and deleting the failed node from the MPNTs of its neighbors, the gateway runs the TCA and builds the MPSPT. Based on the new MPSPT, the link rankings and hence, the channel assignments of links change.

Table 5.22: Link Ranking of MPSPT after Node 9 fails

Link		Distance (m)	Power (mW)	RANK	Power from the farthest node of the link to the gateway (mW)
15	12	81	123	30	123
12	6	58	63	12	186
12	29	52	51	11	174
6	22	52	51	11	237
29	19	53	53	10	227
19	11	88	145	9	372
12	14	69	90	6	213
22	26	98	180	6	417
26	27	103	199	5	616
14	31	47	42	4	255
11	3	49	45	4	417
11	33	49	45	4	417
3	7	30	17	3	434
31	2	133	331	3	586
27	35	38	27	3	643
15	8	51	49	2	49
22	34	84	132	2	369
33	32	32	20	2	437
22	23	124	288	2	525
2	16	106	211	2	797
15	18	42	33	1	33
15	24	46	40	1	40
8	21	33	21	1	70
14	17	59	66	1	279
34	10	40	30	1	399
32	25	28	15	1	452
33	20	51	49	1	466
7	30	101	191	1	625
7	1	103	199	1	633
35	36	46	40	1	683
35	4	53	53	1	696
23	28	136	346	1	871
16	13	66	82	1	879
27	5	126	297	1	913

Table 5.23: Channel Assignment for links of MPSPT after Node 9 fails

Node	Neighbor	Channel
15	12	1
12	6	2
12	29	3
6	22	4
29	19	5
19	11	6
12	14	7
22	26	8
26	27	9
14	31	10
11	3	11
11	33	10
3	7	9
31	2	11
27	35	11
15	8	11
22	34	11
33	32	8
22	23	6
2	16	5
15	18	10
15	24	9
8	21	8
14	17	9
34	10	10
32	25	11
33	20	7
7	30	4
7	1	2
35	36	10
35	4	8
23	28	7
16	13	10
27	5	3

5.5. Node Degree

The node degree is defined as the number of transmission range neighbors of a node.

5.5.1. Average Node Degree

The Average Node Degree (AND) for the entire network can be calculated by equation (7):

$$AND = \frac{\sum_{j=1}^N q_j}{N} \quad (7)$$

where q is the number of TR neighbors of a node, and N is the total number of nodes in the network.

5.5.2. Maximum Power Average Node Degree

A. Maximum Power TR Average Node Degree

It is defined as the average number of TR neighbors when all nodes transmit with the same maximum power.

B. Maximum Power IR Average Node Degree

It is defined as the average number of IR neighbors when all nodes transmit with the same maximum power.

5.5.3. Minimum Power Average Node Degree

A. Minimum Power TR Average Node Degree

It is defined as the average number of TR neighbors resulting from the *Select x for less than x* TCA.

B. Minimum Power IR Average Node Degree

It is defined as the average number of IR neighbors resulting from the *Select x for less than x* TCA.

A high average node degree indicates a stronger connectivity but results in a higher interference in the network. On the other hand, interference will be less in the case of a lower node degree but it will also affect the connectivity of the network and may result in a disconnected network.

CHAPTER 6

RESULTS

In this chapter, the results for the proposed TCA, *Select x for less than x*, and different phases of the proposed CAA, TICA, which include topology control, connectivity graph, MPSPT with the required maximum node degree, link ranking and channel assignment, are presented. The detailed results of simulations for performance evaluation of TICA based on throughput analysis of a 36-node network and a 144-node network are given, and analyzed. The chapter also presents the results for the performance comparison of TICA with well known centralized channel assignment schemes. The features' comparison of TICA with related well known channel assignment schemes is discussed.

6.1. Topology Control

6.1.1. Maximum Power Average Node Degree

The maximum power transmission range average node degrees for a 36-node network for the three topologies (random, controlled random and grid) are shown in Table 6.1.

Table 6.1: Max. Power TR Average Node Degree

TOPOLOGY		
Random	Controlled Random	Grid
9.33	7.5	6.11

Table 6.2 shows the maximum power interference range average node degrees for the three topologies.

Table 6.2: Max. Power IR Average Node Degree

TOPOLOGY		
Random	Controlled Random	Grid
17.7	16.4	17.9

6.1.2. Minimum Power Average Node Degree

A comparison of the different topology control algorithms based on the minimum power TR average node degrees for a network of 36 nodes is shown in Table 6.3.

Table 6.3: Min. Power TR Average Node Degree

Topology Control Algorithm	TOPOLOGY		
	R	CR	G
Select 1 for less than 1	1.44	1.61	3.33
Select 2 for less than 2	2.56	2.42	3.33
Select 3 for less than 3	3.67	3.58	3.56
Select 4 for less than 4	5.06	4.75	4.39

Figure 8.1 shows a graphical comparison of the different topology control algorithms for the three topologies (random, controlled random and grid) based on the minimum power TR average node degrees for a network of 36 nodes.

Figure 6.1: Minimum Power TR Average Node Degree

Figure 6.1 shows that as the number of selected neighbors increases from *Select 1 for less than 1* TCA to *Select 4 for less than 4* TCA, the minimum power TR average node degree increases, which means that the network connectivity increases.

Table 6.4 shows a comparison of the different topology control algorithms based on the minimum power IR average node degrees.

Table 6.4: Min. Power IR Average Node Degree

Topology Control Algorithm	TOPOLOGY		
	R	CR	G
Select 1 for less than 1	3.58	4.86	2.78
Select 2 for less than 2	6.42	6.06	2.78
Select 3 for less than 3	9.28	7.78	3.56
Select 4 for less than 4	10.7	9.47	7.56

Figure 6.2 shows a graphical comparison of the different topology control algorithms for the three topologies (random, controlled random and grid) based on the minimum power IR average node degrees for a network of 36 nodes.

Figure 6.2: Minimum Power IR Average Node Degree

Figure 6.2 shows that as the number of selected neighbors increases from *Select 1 for less than 1* TCA to *Select 4 for less than 4* TCA, the minimum power IR average node degree increases, which means that the interference in the network increases.

6.1.3. Connectivity and Interference

Table 6.5 indicates whether the connectivity graph resulting from a certain TCA is connected. Note that after receiving the FNTs from the nodes, the gateway builds the connectivity graph.

Table 6.5: Check for connected topology

Topology Control Algorithm	Connected Topology		
	R	CR	G
Select 1 for less than 1	No	No	Yes
Select 2 for less than 2	No	No	Yes
Select 3 for less than 3	Yes	Yes	Yes
Select 4 for less than 4	Yes	Yes	Yes

Table 6.6 shows the number of disconnected nodes (nodes not reachable by the gateway) in the connectivity graph resulting from a certain TCA.

Table 6.6: Number of disconnected nodes

Topology Control Algorithm	TOPOLOGY		
	R	CR	G
Select 1 for less than 1	33	32	0
Select 2 for less than 2	31	8	0
Select 3 for less than 3	0	0	0
Select 4 for less than 4	0	0	0

For random and controlled random topologies, a high minimum power average node degree, in case of *Select 3 for less than 3* and *Select 4 for less than 4* TCAs, indicates a stronger connectivity and leads to a connected network but results in a higher interference in the network. On the other hand, a lower minimum power average node degree translates to less interference with *Select 1 for less than 1* and *Select 2 for less than 2* TCAs, but it also affects the connectivity of the network and results in a disconnected network.

6.2. Connectivity Graph

Note that Node 15 is taken as the gateway node for all topologies.

A. Random Topology

Figure 5.7 shows the connectivity graph for random topology resulting from “Select 3 for less than 3” TCA for a 36-node network. Note that the resulting topology is connected.

B. Controlled Random Topology

Figure 6.3 shows the connectivity graph for controlled random topology resulting from “Select 3 for less than 3” TCA for a 36-node network. Note that the resulting topology is connected.

C. Grid Topology

Figure 6.4 shows the connectivity graph for grid topology resulting from “Select 1 for less than 1” TCA for a 36-node network. Note that the resulting topology is connected.

6.3. Minimum Power-based Shortest Path Tree

A. Random Topology

Figure 5.8 shows the MPSPT graph for random topology resulting from “Select 3 for less than 3” TCA for a 36-node network with a MND of 4.

B. Controlled Random Topology

Figure 6.5 shows the MPSPT graph for controlled random topology resulting from “Select 3 for less than 3” TCA for a 36-node network with a MND of 4.

C. Grid Topology

Figure 6.6 shows the MPSPT graph for grid topology resulting from “Select 1 for less than 1” TCA for a 36-node network with a maximum node degree of 4.

Figure 6.3: Connectivity Graph (CRT)

Figure 6.4: Connectivity Graph (GT)

Figure 6.5: MPSPT Graph (CRT)

Figure 6.6: MPSPT Graph (GT)

6.4. Link Ranking

A. Random Topology

Table 5.16 shows link ranking of MPSPT graph for random topology.

B. Controlled Random Topology

Table 6.7 shows link ranking of MPSPT graph for controlled random topology.

Table 6.7: Link Ranking of MPSPT (CRT)

Link		Distance (m)	Power (mW)	RANK	Power from the farthest node of the link to the gateway (mW)
15	21	88	145	12	145
15	9	93	162	12	162
15	14	80	120	11	120
21	16	86	139	11	284
14	20	62	72	8	192
16	22	47	42	8	326
20	25	92	159	7	351
22	23	54	55	7	381
9	2	46	40	6	202
9	10	88	145	5	307
25	26	77	111	5	462
23	30	102	195	5	576
10	11	94	166	4	473
2	8	55	57	3	259
26	32	67	84	3	546
30	29	96	173	3	749
14	13	49	45	2	165
2	3	65	79	2	281
8	7	42	33	2	292
16	17	59	66	2	350
11	12	78	114	2	587
32	33	58	63	2	609
13	19	101	191	1	356
3	4	73	100	1	381
7	1	92	159	1	451
23	24	66	82	1	463
25	31	110	227	1	578
26	27	80	120	1	582
11	5	79	117	1	590
17	18	114	243	1	593
12	6	47	42	1	629
33	34	56	59	1	668
29	28	42	33	1	782
29	35	57	61	1	810
30	36	121	274	1	850

C. Grid Topology

Table 6.8 shows link ranking of MPSPT graph for grid topology.

Table 6.8: Link Ranking of MPSPT (GT)

Link		Distance (m)	Power (mW)	RANK	Power from the farthest node of the link to the gateway (mW)
15	9	83	129	12	129
15	16	83	129	12	129
15	14	83	129	8	129
16	17	83	129	8	258
9	3	83	129	6	258
14	13	83	129	4	258
17	18	83	129	4	387
15	21	83	129	3	129
9	10	83	129	3	258
14	20	83	129	3	258
16	22	83	129	3	258
3	4	83	129	3	387
13	19	83	129	3	387
17	23	83	129	3	387
18	24	83	129	3	516
9	8	83	129	2	258
21	27	83	129	2	258
3	2	83	129	2	387
10	11	83	129	2	387
20	26	83	129	2	387
22	28	83	129	2	387
4	5	83	129	2	516
19	25	83	129	2	516
23	29	83	129	2	516
24	30	83	129	2	645
8	7	83	129	1	387
27	33	83	129	1	387
2	1	83	129	1	516
11	12	83	129	1	516
26	32	83	129	1	516
28	34	83	129	1	516
5	6	83	129	1	645
25	31	83	129	1	645
29	35	83	129	1	645
30	36	83	129	1	774

6.5. Channel Assignment

A. Random Topology

Table 5.21 shows CA for links of MPSPT graph for random topology.

B. Controlled Random Topology

Table 6.9 shows CA for links of MPSPT graph for controlled random topology.

Table 6.9: Channel Assignment for links of MPSPT (CRT)

Link		Channel
15	21	1
15	9	2
15	14	3
21	16	4
14	20	5
16	22	6
20	25	7
22	23	8
9	2	9
9	10	10
25	26	11
23	30	11
10	11	7
2	8	11
26	32	10
30	29	10
14	13	11
2	3	8
8	7	7
16	17	10
11	12	11
32	33	9
13	19	6
3	4	6
7	1	4
23	24	9
25	31	8
26	27	3
11	5	9
17	18	5
12	6	10
33	34	8
29	28	11
29	35	7
30	36	3

C. Grid Topology

Table 6.10 shows CA for links of MPSPT graph for grid topology.

Table 6.10: Channel Assignment for links of MPSPT (GT)

Link		Channel
15	9	1
15	16	2
15	14	3
16	17	4
9	3	5
14	13	6
17	18	7
15	21	8
9	10	9
14	20	10
16	22	11
3	4	11
13	19	11
17	23	10
18	24	11
9	8	7
21	27	9
3	2	10
10	11	6
20	26	7
22	28	6
4	5	8
19	25	9
23	29	9
24	30	8
8	7	4
27	33	5
2	1	8
11	12	5
26	32	6
28	34	7
5	6	10
25	31	8
29	35	5
30	36	7

6.6. Simulation Results in NS2 based on Throughput Analysis

6.6.1. Simulation Parameters

Based on the channel assignment done by the gateway node, IEEE 802.11a channels are assigned to the links between the mesh nodes and transmission power for each radio of each mesh node is set accordingly.

The node settings in NS2 which are used during the simulation are shown in Table 6.11. The propagation model used is free space model or two-ray model depending upon the distance between the mesh nodes.

Table 6.11: Node Configuration in NS2

Node Parameter	Setting
Channel Type	Wireless Channel
Propagation Model	Free Space / Two Ray Ground
Network Interface Type	Wireless
Mac Type	802.11
Interface Queue Type	Priority Queue
Link Layer Type	LL
Interface Queue Length (packets)	50

The physical layer settings of the node which are used during the simulation are shown in Table 6.12. Note that out of the 12 available non-overlapping 802.11a channels, 11 channels are used for data traffic and channel 12 is used for control.

As mentioned earlier, the maximum transmission power for all the radios is 27 dBm. In the CCA and SRSC schemes, MRs do not control their power, transmit with the same maximum power (27 dBm), and use AODV (Ad hoc On-Demand Distance Vector) routing protocol as their routing agent.

The value of the carrier sense threshold is set such that the carrier sensing range (interference range) is twice the packet reception range (transmission range). In NS2, packet transmissions in the carrier sensing range of a receiver are considered as potential sources of interference that can lead to packet collisions.

The packet capture threshold represents the Signal-to-Interference Ratio (SIR) such that if the power of the incoming packet is smaller than the power of the packet currently being received by at least the capture threshold, then the new packet is ignored.

Table 6.12: Physical Layer Node Configuration in NS2

Physical Layer Parameter	Setting
Antenna Type	Omni Antenna
TX Antenna Height (meters)	3
RX Antenna Height (meters)	3
Gain of TX Antenna (dB)	1
Gain of RX Antenna (dB)	1
Packet Capture Threshold (SIR) (dB)	10
Packet Reception Threshold (watts)	3.16227e-10
Carrier Sense Threshold (watts)	7.90569e-11
System Loss Factor	1
Transmit Power (W)	calculated for each radio interface of each mesh node depending upon the channel assigned by the gateway and the distance to the neighbor
Channel Settings	5 GHz channels Channel 1 - 5.18 GHz Channel 2 - 5.20 GHz Channel 3 - 5.22 GHz Channel 4 - 5.24 GHz Channel 5 - 5.26 GHz Channel 6 - 5.28 GHz Channel 7 - 5.30 GHz Channel 8 - 5.32 GHz Channel 9 - 5.745 GHz Channel 10 - 5.765 GHz Channel 11 - 5.785 GHz set for each radio interface of each mesh node according to the channel assigned by the gateway

The 802.11a MAC layer settings of the node which are used during the simulation are shown in Table 6.13.

Table 6.13: MAC Layer Node Configuration in NS2

MAC Layer Parameter	Setting
Minimum Contention Window	15
Maximum Contention Window	1023
Slot Time (micro seconds)	9
SIFS period (micro seconds)	16
Preamble Length (bits)	96
PLCP Header Length (bits)	24
PLCP Data Rate (Mbps)	6
Basic Rate (Mbps)	6
Data Rate (Mbps)	54
RTS/CTS Threshold (bytes)	10192 (disabled)

All the mesh nodes at the periphery of the network send traffic to the gateway. Each of these nodes generates an 8 Mbps Constant Bit Rate (CBR) traffic stream consisting of 1024 byte packets and sends data to the gateway node at the same time. They do not stop transmitting until the end of the simulation which is 600 seconds (10 minutes). The related traffic generation parameters used during the simulation are shown in Table 6.14.

Table 6.14: Traffic Generation Parameters in NS2

Traffic Generation Parameter	Setting
Traffic Type	Constant Bit Rate (CBR)
Transport Agent	User Datagram Protocol (UDP)
Start Time (seconds)	1
Stop Time (seconds)	600
Packet Size (bytes)	1024
Packet Inter-arrival time (seconds)	0.001

6.6.2. Simulation Results for a 36-node Network

The Average Throughput (AT) in Mega bits per second at the gateway node is calculated using the following formula:

$$AT = \frac{TPR \times 8 \times 1024}{(TrafficStopTime - TrafficStartTime) \times 1 \times 10^6} \quad (8)$$

Note that TPR is the Total Packets Received in (8).

A. Random Topology

i) Ten Different Random Topologies

Table 6.15 shows the average throughput of all schemes for ten random topologies for a network of 36 nodes. Note that AT is the Average Throughput in Mbps and x indicates that the resulting topology is not connected.

Table 6.15: AT (Mbps) for ten random topologies – 36-node network

AT \ Scheme	TICA		CCA	SRSC
AT SEED 1	Select 2 for less than 2 TCA	x	27.96	15.44
	Select 3 for less than 3 TCA	49.33		
AT SEED 2	Select 2 for less than 2 TCA	x	22.95	13.06
	Select 3 for less than 3 TCA	34.97		
AT SEED 3	Select 2 for less than 2 TCA	x	6.33	0.86
	Select 3 for less than 3 TCA	75.12		
AT SEED 4	Select 2 for less than 2 TCA	25.52	17.36	2.60
	Select 3 for less than 3 TCA	53.31		
AT SEED 5	Select 2 for less than 2 TCA	x	14.79	3.20
	Select 3 for less than 3 TCA	43.82		
AT SEED 6	Select 2 for less than 2 TCA	x	19.36	3.72
	Select 3 for less than 3 TCA	41.13		
AT SEED 7	Select 2 for less than 2 TCA	49.48	5.42	0.62
	Select 3 for less than 3 TCA	49.50		
AT SEED 8	Select 2 for less than 2 TCA	x	20.51	8.98
	Select 3 for less than 3 TCA	39.29		
AT SEED 9	Select 2 for less than 2 TCA	x	19.28	6.37
	Select 3 for less than 3 TCA	57.32		
AT SEED 10	Select 2 for less than 2 TCA	x	5.64	1.24
	Select 3 for less than 3 TCA	38.52		

Figure 6.7 shows a graphical comparison of the average throughput of all schemes for ten random topologies.

Figure 6.7: AT for Ten Random Topologies – 36-node network

The results in Figure 6.7 clearly indicate that the proposed algorithm TICA significantly outperforms other schemes for all different random topologies.

ii) Throughput Analysis for Different Random Topologies

For a topology, the maximum traffic that can reach the gateway depends on the number of links emanating from the gateway and the number of traffic sources using those links. The maximum traffic that can reach the gateway over a link emanating from the gateway is 8.192 Mbps if one traffic source is using that link, 16.384 Mbps in case of two sources, 24.576 Mbps in case of three sources and 24.8 Mbps in case of four or more sources.

The MPSPTs, for the different random and controlled random topologies for a 36-node network, showing the number of links emanating from the gateway and the number of sources using these links, are shown in Appendices C.1 and C.2. The maximum traffic

that can reach the gateway limits the actual throughput achieved by TICA. Table 6.16 shows the maximum traffic that can reach the gateway and the actual throughput achieved by TICA for different random topologies.

Table 6.16: Throughput Analysis for different RTs – 36-node network

RT Seed	GW links	Traffic sources using each GW link	Max. traffic on each GW link (Mbps)	Max. traffic at GW (Mbps)	Actual Throughput at GW with TICA (Mbps)
1	4	1,1,1,10	8.192, 8.192, 8.192, 24.8	49.376	49.33
2	2	3,11	24.576, 24.8	49.376	34.97
3	4	1,3,5,5	8.192, 24.576, 24.8, 24.8	82.368	75.12
4	3	2,4,5	16.384, 24.8, 24.8	65.984	53.31
5	2	3,8	24.576, 24.8	49.376	43.82
6	3	1,1,9	8.192, 8.192, 24.8	41.184	41.13
7	2	7,4	24.8, 24.8	49.60	49.50
8	4	1,3,1,7	8.192, 24.576, 8.192, 24.8	65.76	39.29
9	3	1,4,7	8.192, 24.8, 24.8	57.792	57.32
10	2	4,10	24.8, 24.8	49.60	38.52

The actual throughput, achieved by CCA and SRSC schemes, depends on the location of the gateway and the number of traffic sources located close to the gateway as compared to other traffic sources. Therefore, in seeds of the random topology where the gateway is located such that some traffic sources are located close to the gateway as compared to other traffic sources as shown in Appendix C.1, the CCA and SRSC schemes result in a relatively high throughput. In such cases, since some traffic sources are located close to the gateway and outside the interference range of other traffic sources, so their traffic experiences less interference which leads to a relatively high throughput at the gateway.

The placement of the nodes and the length of links in the MPSPT of a topology affects the interference range and hence the channel assignment. In random and controlled random topologies, the random placement of nodes results in variation in the length of links in the MPSPT. This results in LICs which may cause significant interference in the network and degrade the overall throughput.

In case of second, eight and tenth seeds of the random topology, the resulting LICs cause significant interference and result in a relatively lower throughput with TICA as shown in Table 6.16.

iii) Throughput Improvement Factor

The average Throughput Improvement Factor (TIF), over ten different random topologies, showing the throughput improvement with TICA as compared to CCA and SRSC schemes is shown in Table 6.17.

Table 6.17: TIF (RT) – 36-node network

Scheme	Average Throughput (Mbps)	TIF
TICA	48.23	-
CCA	15.96	3.021
SRSC	5.61	8.597

B. Controlled Random Topology

i) Ten Different Controlled Random Topologies

Table 6.18 shows the average throughput of all schemes for ten controlled random topologies for a network of 36 nodes. Note that AT is the Average Throughput in Mbps and x indicates that the resulting topology is not connected.

The “Select 1 for less than 1” TCA leads to a connected network in case of grid topology which is due to the symmetric nature of the grid topology. The “Select 1 for less than 1” TCA leads to a disconnected network in case of random and controlled random topologies which is due to the random nature of these topologies. The “Select 2 for less than 2” TCA leads to a disconnected network in case of random and controlled random topologies in most cases. However, in cases where it leads to a connected network for these topologies, the results show that the average throughput with “Select 2 for less than 2” TCA is less than that with “Select 3 for less than 3” TCA for TICA. This is due to the fact that the “Select 2 for less than 2” TCA results in a connectivity graph with low average node degree in TICA which leads to low throughput. Therefore, if the “Select 1 for less than 1” TCA leads to a disconnected network, this means that the topology is either random or controlled random. In this case, I have concluded that the next higher TCA for the gateway should be “Select 3 for less than 3.”

Table 6.18: AT (Mbps) for ten controlled random topologies – 36-node network

AT \ Scheme	TICA		CCA	SRSC
AT SEED1	Select 2 for less than 2 TCA	x	5.76	0.66
	Select 3 for less than 3 TCA	71.70		
AT SEED 2	Select 2 for less than 2 TCA	32.78	5.82	0.64
	Select 3 for less than 3 TCA	47.43		
AT SEED 3	Select 2 for less than 2 TCA	54.69	4.04	0.47
	Select 3 for less than 3 TCA	63.54		
AT SEED 4	Select 2 for less than 2 TCA	x	3.71	0.33
	Select 3 for less than 3 TCA	77.43		
AT SEED 5	Select 2 for less than 2 TCA	57.20	5.66	1.00
	Select 3 for less than 3 TCA	69.81		
AT SEED 6	Select 2 for less than 2 TCA	x	6.42	0.57
	Select 3 for less than 3 TCA	75.49		
AT SEED 7	Select 2 for less than 2 TCA	x	4.54	0.62
	Select 3 for less than 3 TCA	62.90		
AT SEED 8	Select 2 for less than 2 TCA	x	6.91	0.54
	Select 3 for less than 3 TCA	49.50		
AT SEED 9	Select 2 for less than 2 TCA	x	6.53	0.84
	Select 3 for less than 3 TCA	51.33		
AT SEED 10	Select 2 for less than 2 TCA	x	4.61	0.77
	Select 3 for less than 3 TCA	44.67		

Figure 6.8 shows a graphical comparison of average throughput of all schemes for ten controlled random topologies. The results in Figure 6.8 clearly indicate that the proposed algorithm TICA significantly outperforms other schemes for all different controlled random topologies.

ii) Throughput Analysis for Different Controlled Random Topologies

The maximum traffic that can reach the gateway and the actual throughput achieved by TICA for different controlled random topologies is shown in Table 6.19.

Figure 6.8: AT for Ten Controlled Random Topologies – 36-node network

Table 6.19: Throughput Analysis for different CRTs – 36-node network

CRT Seed	GW links	Traffic sources using each GW link	Max. traffic on each GW link (Mbps)	Max. traffic at GW (Mbps)	Actual Throughput at GW with TICA (Mbps)
1	3	4,5,4	24.8, 24.8, 24.8	74.40	71.70
2	3	4, 4, 7	24.8, 24.8, 24.8	74.40	47.43
3	3	4, 3, 7	24.8, 24.576, 24.8	74.176	63.54
4	4	4,1,4,6	24.8, 8.192, 24.8, 24.8	82.592	77.43
5	4	1,2,6,4	8.192, 16.384, 24.8, 24.8	74.176	69.81
6	4	4,6,2,3	24.8, 24.8, 16.384, 24.576	90.56	75.49
7	3	2,6,5	16.384, 24.8, 24.8	65.984	62.90
8	2	5,7	24.8, 24.8	49.60	49.50
9	3	3,3,6	24.576, 24.576, 24.8	73.952	51.33
10	2	4,9	24.8, 24.8	49.60	44.67

In all seeds of the controlled random topology as shown in Appendix C.2, the gateway is located such that no traffic sources are located close to the gateway and outside the interference range of other traffic sources. Therefore, in CCA and SRSC schemes, traffic from all traffic sources experiences interference which leads to a relatively low throughput for these schemes.

In the second and ninth seeds of the controlled random topology, the resulting LICs cause significant interference in the network and result in a relatively low throughput with TICA as shown in Table 6.19.

iii) Throughput Improvement Factor

The average TIF, over ten different controlled random topologies, showing the throughput improvement with TICA as compared to CCA and SRSC schemes is shown in Table 6.20.

Table 6.20: TIF (CRT) – 36-node network

Scheme	Average Throughput (Mbps)	TIF
TICA	61.38	-
CCA	5.40	11.366
SRSC	0.64	95.906

C. Grid Topology

i) Throughput Improvement Factor

The TIF showing the throughput improvement by TICA as compared to CCA and SRSC schemes is shown in Table 6.21.

Table 6.21: TIF (GT) – 36-node network

Scheme	Average Throughput (Mbps)	TIF
TICA	70.89	-
CCA	5.51	12.865
SRSC	0.53	133.754

ii) Throughput Analysis for Grid Topology

The maximum traffic that can reach the gateway and the actual throughput achieved by TICA for grid topology is shown in Table 6.22.

Table 6.22: Throughput Analysis for GT – 36-node network

GT	GW links	Traffic sources using each GW link	Max. traffic on each GW link (Mbps)	Max. traffic at GW (Mbps)	Actual Throughput at GW with TICA (Mbps)
1	4	4,3,1,2	24.8, 24.576, 8.192, 16.384	73.952	70.89

As shown in the MPSPT for the grid topology in Figure 6.6, there are no traffic sources which are located close to the gateway and outside the interference range of other traffic sources. Therefore, in CCA and SRSC schemes, traffic from all traffic sources experiences interference which leads to a relatively low throughput for these schemes.

Since all links in the grid topology have equal length due to the symmetric nature of this topology, so the resulting LICs succeed in minimizing the interference and lead to a high throughput with TICA, as shown in Table 6.22.

D. Throughput Comparison of All Schemes

Figure 6.9 shows the comparison of average throughput of all schemes for the three topologies (random, controlled random and grid) for a network of 36 nodes.

Figure 6.9: AT for all schemes – 36-node network

Note that for random and controlled random topologies in Figure 6.9, the average throughput is the average over ten different random and controlled random topologies, respectively. Figure 6.9 shows that as compared to the CCA scheme, the throughput improvement with TICA is 3 times for random topology, 11 times for controlled random topology and 12 times for grid topology. In comparison to the SRSC scheme, the throughput improvement with TICA is 8 times for random topology, 95 times for controlled random topology and 133 times for grid topology.

The results in Figure 6.9 clearly indicate that the proposed algorithm TICA significantly outperforms other schemes for the three topologies.

6.6.3. Simulation Results for a 144-node Network

In this case, 144 mesh nodes are distributed in an area of 500x500 meters for the three topologies (random, controlled random and grid). Node 66 is taken as the gateway and the remaining simulation parameters are the same.

A. Random Topology

The throughput improvement by TICA as compared to CCA and SRSC schemes is shown in Table 6.23. Note that Select 4 for less than 4 TCA results in a connected network for this topology.

Table 6.23: TIF (RT) – 144-node network

Scheme	Average Throughput (Mbps)	TIF
TICA	42.54	-
CCA	2.43	17.506
SRSC	0.82	51.878

B. Controlled Random Topology

The throughput improvement by TICA as compared to CCA and SRSC schemes is shown in Table 6.24. Note that Select 3 for less than 3 TCA results in a connected network for this topology.

Table 6.24: TIF (CRT) – 144-node network

Scheme	Average Throughput (Mbps)	TIF
TICA	67.79	-
CCA	0.07	968.428
SRSC	0.06	1129.833

C. Grid Topology

The throughput improvement by TICA as compared to CCA and SRSC schemes is shown in Table 6.25. Note that Select 1 for less than 1 TCA results in a connected network for this topology.

Table 6.25: TIF (GT) – 144-node network

Scheme	Average Throughput (Mbps)	TIF
TICA	82.42	-
CCA	0.23	358.347
SRSC	0.08	1030.250

D. Throughput Comparison of All Schemes

Figure 6.10 shows a graphical comparison of average throughput of all schemes for the three different topologies (random, controlled random and grid) for a network of 144 nodes.

Figure 6.10: AT for all schemes – 144-node network

The results in Figure 6.10 show that TICA significantly outperforms the other schemes for the three topologies in a 144-node network. These results show that the

throughput improvement with TICA in a large-scale network of 144 nodes, in comparison to CCA and SRSC schemes, is significantly higher than the throughput improvement with TICA in a small-scale network of 36 nodes.

The CCA and SRSC schemes perform poorly in 144-node network due to the large number of traffic sources. More traffic sources means more nodes competing for medium access. Increased contention for medium access combined with lack of power control in these schemes leads to more collisions and reduced throughput for these schemes.

E. Throughput Analysis for the Three Topologies

The maximum traffic that can reach the gateway and the actual throughput achieved by TICA for the three topologies for 144-node network is shown in Table 6.26.

Table 6.26: Throughput Analysis – 144-node network

Topology	GW links	Traffic sources using each GW link	Max. traffic on each GW link (Mbps)	Max. traffic at GW (Mbps)	Actual Throughput at GW with TICA (Mbps)
R	3	1, 10, 31	8.192, 24.8, 24.8	57.792	42.54
CR	3	6, 12, 26	24.8, 24.8, 24.8	74.4	67.79
G	4	10, 5, 1, 6	24.8, 24.8, 8.192, 24.8	82.592	82.42

As shown in the MPSPT for the random topology for 144-node network in Appendix C.3, there are some traffic sources which are located close to the gateway and outside the interference range of other traffic sources. Therefore, in CCA and SRSC schemes, traffic from such sources experience less interference and this leads to a relatively high throughput for these schemes in random topology.

Due to high degree of randomness in the random topology, the resulting LICs cause significant interference and result in low throughput with TICA, as shown in Table 6.26.

Since the degree of randomness in the controlled random topology is relatively low, so the resulting LICs cause relatively less interference and result in a relatively better throughput with TICA, as shown in Table 6.26.

In the grid topology, there is no variation in the length of links in MPSPT which results in LICs with minimum interference and a high throughput with TICA, as shown in Table 6.26.

6.6.4. Performance Comparison of TICA with Centralized CA Schemes

The proposed scheme, TICA, is a centralized and fixed channel assignment scheme. Therefore, it is being compared with the following two well-known centralized CA schemes.

A. TICA and C-HYA

i) Simulation Scenario

Similar to the scenario in C-HYA, the following simulation scenario is created.

- 100 mesh nodes are distributed in an area of 500x500 meters in a grid topology.
- Each mesh node can communicate with up to four neighbors.
- Twenty randomly selected mesh nodes generate CBR traffic streams consisting of UDP packets.
- The traffic sources send data to the sink (gateway) at the same time.
- The traffic sources do not stop transmitting until the end of the simulation.
- The amount of traffic generated by each source is chosen at random between 0 and 3 Mbps.
- The data rate is 54 Mbps.
- RTS/CTS is enabled.
- The ratio between interference range (carrier sense threshold) and transmission range (packet reception threshold) is fixed at two.

ii) Simulation Assumptions

The following simulation parameters are assumed.

- The inter router distance is 50 meters.
- The maximum transmission range for all mesh nodes is set to 50 meters and the maximum transmission power is set accordingly.
- The minimum receiver sensitivity ($RxThresh$) is set to -65 dBm (3.16227×10^{-10} Watts) in order to achieve a maximum data rate of 54 Mbps supported by IEEE 802.11a at a maximum transmission range of 50 meters.
- Node 45 is selected as the gateway due to its central location, as shown in the MPSPT in Appendix C.4.

- The mesh nodes use AODV routing protocol as their routing agent in CCA and SRSC schemes.
- The simulation duration is 600 seconds (10 minutes).
- The packet size is set to 1024 bytes.

iii) Simulation Parameters

The simulation parameters for this scenario are shown in Table 6.27.

Table 6.27: Simulation parameters

Parameter	Setting
Packet Reception Threshold (watts)	3.16227e-10
Carrier Sense Threshold (watts)	7.90569e-11
Maximum Transmit Power (watts)	0.0457
Maximum Transmission Range (meters)	50
Basic Rate (Mbps)	6
Data Rate (Mbps)	54
RTS/CTS Threshold (bytes)	512 (enabled)
Traffic Type	Constant Bit Rate (CBR)
Transport Agent	User Datagram Protocol (UDP)
Start Time (seconds)	1
Stop Time (seconds)	600
Packet Size (bytes)	1024
Packet Inter-arrival time (seconds)	Random

iv) Simulation Results

The throughput improvement by TICA as compared to CCA and SRSC schemes for ten different Traffic Profile (TP) seeds is shown in Table 6.28. In each TP seed, twenty mesh nodes are selected randomly as traffic sources and the amount of traffic generated by each source is chosen at random between 0 and 3 Mbps.

Table 6.28: AT (Mbps) with ten different TPs

AT \ Scheme	TICA	CCA	SRSC
AT for TP seed 1	31.33	14.39	3.52
AT for TP seed 2	28.64	16.22	4.95
AT for TP seed 3	32.23	14.32	3.77
AT for TP seed 4	27.37	14.89	4.59
AT for TP seed 5	31.36	14.72	3.83
AT for TP seed 6	30.59	16.34	4.00
AT for TP seed 7	24.34	14.84	3.47
AT for TP seed 8	27.34	15.29	3.62
AT for TP seed 9	34.11	14.21	3.63
AT for TP seed 10	28.69	15.58	4.48

v) Comparison of Results

The normalized throughput of TICA and SRSC schemes is shown in Figure 6.11. The normalized throughput is obtained after normalizing the results with the throughput obtained from the SRSC scheme.

Figure 6.11: Normalized Throughput with ten different TPs

For a 10x10 grid network of 100 nodes where UDP-based CBR traffic flows from 20 pairs of randomly chosen ingress-egress nodes interfere with each other, the throughput improvement with C-HYA is as high as 8 times in comparison with the SRSC scheme [18]. The throughput improvement with TICA for a similar scenario, where twenty randomly selected mesh nodes send UDP-based CBR traffic to the gateway at the same time, is as high as 9 times in comparison with the SRSC scheme, as shown in Figure 6.11. Hence, TICA has shown a better performance as compared to C-HYA for the same scenario where the transmission range of mesh nodes in CCA and SRSC schemes is controlled by controlling their transmission power.

B. TICA and BFS-CA

i) Simulation Scenario

Similar to the scenario in BFS-CA, the following simulation scenario is created.

- 30 mesh nodes are distributed in an area of 500x500 meters in a grid topology.
- The inter router distance is 75 meters.
- The maximum transmission power of all mesh nodes is 18 dBm.
- Ten randomly selected mesh nodes at the periphery of the network send FTP traffic to the gateway.
- Each of these sources generates an FTP traffic stream consisting of TCP packets and send data to the gateway at the same time.
- The source nodes do not stop transmitting until the end of the simulation.
- Since in BFS-CA, the mesh router which is approximately in the center of the topology is selected as the gateway, so mesh Node 13 is selected as the gateway due to its central location, as shown in the MPSPT in Appendix C.5.
- RTS/CTS is disabled.

ii) Simulation Assumptions

The following simulation parameters are assumed.

- The maximum transmission range for all mesh nodes is 75 meters.
- The maximum data rate is set to 36Mbps based on the maximum transmission power and the inter router distance.

- The minimum receiver sensitivity (*RxThresh*) is set to -67.2 dBm (1.90546×10^{-10} Watts) in order to achieve a maximum data rate of 36 Mbps supported by IEEE 802.11a at a maximum transmission range of 75 meters.
- The mesh nodes use AODV routing protocol as their routing agent in CCA and SRSC schemes.
- The packet size is set to 1024 bytes.
- The interference range is set as twice the transmission range.
- The simulation duration is 600 seconds (10 minutes).

iii) Simulation Parameters

The simulation parameters for this scenario are given in Table 6.29.

Table 6.29: Simulation parameters

Parameter	Setting
Packet Reception Threshold (watts)	1.90546e-10
Carrier Sense Threshold (watts)	4.76365e-11
Maximum Transmit Power (watts)	0.0631
Maximum Transmission Range (meters)	75
Basic Rate (Mbps)	6
Data Rate (Mbps)	36
RTS/CTS Threshold (bytes)	10192 (disabled)
Traffic Type	File Transfer Protocol (FTP)
Transport Agent	Transmission Control Protocol (TCP)
Start Time (seconds)	1
Stop Time (seconds)	600
Packet Size (bytes)	1024

iv) Simulation Results

The throughput improvement by TICA as compared to CCA and SRSC schemes for ten different TP seeds is shown in Table 6.30. In each TP seed, ten mesh nodes at the periphery of the network are selected randomly as FTP traffic sources.

Table 6.30: AT (Mbps) with ten different TPs

AT \ Scheme	TICA	CCA	SRSC
AT for TP seed 1	12.80	7.79	2.29
AT for TP seed 2	12.80	7.07	2.37
AT for TP seed 3	12.60	5.78	1.82
AT for TP seed 4	12.75	6.61	2.25
AT for TP seed 5	12.96	7.41	4.56
AT for TP seed 6	12.96	8.08	4.58
AT for TP seed 7	12.64	8.05	1.88
AT for TP seed 8	12.76	7.37	2.23
AT for TP seed 9	12.91	9.09	4.01
AT for TP seed 10	12.76	5.93	2.19

v) Comparison of Results

The normalized throughput of TICA and CCA schemes is shown in Figure 6.12. The normalized throughput is obtained after normalizing the results with the throughput obtained from the CCA scheme.

Figure 6.12: Normalized Throughput with ten different TPs

For a grid network of 30 mesh nodes where 10 randomly selected traffic sources at the periphery send TCP-based FTP traffic to the gateway at the same time, the throughput improvement with BFS-CA is 60% in comparison with the CCA scheme [27]. The average throughput improvement with TICA for a similar scenario for ten different TP seeds is 77% in comparison with the CCA scheme, as shown in Figure 6.12. Hence, TICA has shown a better performance as compared to BFS-CA for the same scenario where the transmission range of mesh nodes in CCA and SRSC schemes is controlled by controlling their receiver sensitivity.

6.7. Features' Comparison of Related CA Schemes

The important features of the related CA schemes are summarized in Table 6.31. They include channel switching, topology control, power control, knowledge of traffic load, connectivity, fault tolerance and CA control.

The CA schemes, such as C-HYA [18], MesTiC [21] and D-HYA [24], require the traffic load to be known before assigning channels, whereas TICA requires no such knowledge for channel assignment.

HMCP scheme [25] [26] requires radios to switch between channels on a per-packet basis. In such cases, time synchronization and coordination between mesh nodes is required which is not needed in TICA.

BFS-CA scheme [27] requires certain number of MRs with certain number of radio interfaces to be placed at certain hops from gateway whereas TICA simply requires all MRs to have four data radios, does not require any careful router placement strategy and works with any placement of routers as verified by a comprehensive performance evaluation. In TICA, the mesh nodes do not use an 802.11b channel for their control radios as in BFS-CA and hence, they are not affected by interference from other co-located IEEE 802.11b wireless networks. If all the available frequency channels have already been assigned within the interference range of a link and a non-conflicting channel is not available, the BFS-CA scheme randomly selects a channel and assigns it to that link whereas TICA selects a LIC and assigns it to the link.

The most significant difference between TICA and existing CA schemes is that TICA uses topology control based on power control to build the topology for CA with the

objective of minimizing the interference between the MRs whereas no other CA scheme has used topology control based on power control for CA.

Another significant difference between TICA and most other existing CA schemes is that TICA performs routing in addition to CA whereas most other CA schemes rely on routing protocols and complicated routing metrics for route selection.

Unlike TICA and D-HYA, other well-known CA schemes do not possess fault tolerance and have not provided any mechanism for recovery after a node failure.

Table 6.31: Features' Comparison of Related CA Schemes

Scheme Feature	TICA	C-HYA [18]	BFS-CA [27]	MesTiC [21]	D-HYA [24]	HMCP [25]
CA control	Centralized	Centralized	Centralized	Centralized	Distributed	Distributed
Knowledge of traffic load	Not required	Required	Not required	Required	Required	Not required
Channel switching	Required for failure recovery	Not required	Periodic channel switching required	Not required	Required as CA changes with traffic	Per-packet channel switching required
Topology	Topology controlled using TCA	Fixed	Fixed	Fixed	Topology defined by spanning tree	Topology changing due to channel switching
Power control	Yes	No	No	No	No	No
Connectivity	Ensured by common control radio, Ensured by the CA scheme	Ensured by the CA scheme	Ensured by common control radio	Ensured by common control radio	Ensured by the CA scheme	Ensured by channel switching
Routing	Performed by the CA scheme	No	No	No	Performed by the CA scheme	No
Failure recovery	Yes	No	No	No	Yes	No

CHAPTER 7

CONCLUSION AND FUTURE WORK

This chapter presents what has been accomplished in this thesis and what remains to be addressed in the future.

7.1. Conclusions

- A new topology control algorithm for multi-radio WMNs, *Select x for less than x* , is proposed in this thesis. It controls the network topology by selecting the nearest neighbors for each node in the network. The proposed TCA not only minimizes the interference among the mesh routers but should also result in causing minimum interference to other co-located IEEE 802.11a-based wireless networks.
- A high average node degree indicates a stronger connectivity but results in a higher interference in the network. On the other hand, interference is less in the case of a lower average node degree, but it also affects the connectivity of the network and may result in a disconnected network. A high average node degree in the results for minimum power TR average node degree and minimum power IR average node degree for random and controlled random topologies in the case of *Select 3 for less than 3* and *Select 4 for less than 4* TCAs, indicates a stronger connectivity and leads to a connected network but also results in a higher interference in the network. On the other hand, a lower average node degree in case of *Select 1 for less than 1* and *Select 2 for less than 2* TCAs translates to less interference but also affects the connectivity of the network and results in a disconnected network. This indicates the trade-off between connectivity and interference. An adequate level of connectivity with low interference can be achieved by selecting the appropriate TCA.
- A new channel assignment algorithm for MRMC IEEE 802.11a-based WMNs, TICA, is proposed in this thesis which is based on topology control. As verified by a comprehensive performance evaluation, the improvement in the overall network throughput with TICA is significantly higher than the CCA scheme but is

much higher than SRSC scheme in all three topologies. This is due to the fact that topology control based on power control results in an efficient frequency reuse during CA which leads to an overall improvement in the network throughput.

- The placement of the nodes and the length of links in the MPSPT affects the interference range and hence the channel assignment. In random and controlled random topologies, the random placement of nodes and the gateway results in variation in the length of links in the MPSPT. This can lead to LICs which may cause significant interference in the network and degrade the overall throughput, as indicated by the results for the average throughput of some seeds of random and controlled random topologies of a 36-node network.
- Due to the high degree of randomness in the location of nodes and gateway in the random topology, the resulting LICs cause significant interference and result in low throughput with TICA. Since the degree of randomness in the controlled random topology is relatively low, so the resulting LICs cause relatively less interference and result in a relatively better throughput with TICA. In the grid topology, there is no variation in the length of links in MPSPT which results in LICs with minimum interference and a high throughput with TICA, as shown by the results in Figures 6.9 and 6.10.
- For TICA, the maximum traffic that can reach the gateway depends on the number of links emanating from the gateway and the number of traffic sources using those links. So, the maximum traffic that can reach the gateway limits the actual throughput achieved by TICA as shown by the throughput analysis in Tables 6.16, 6.19, 6.22 and 6.26.
- It is observed that throughput achieved by CCA and SRSC schemes depends on the location of the gateway and traffic sources. In seeds of the random and controlled random topology where the gateway is located such that some traffic sources are located close to the gateway as compared to other traffic sources, the CCA and SRSC schemes exhibit a relatively high throughput. Since some traffic sources are located close to the gateway and outside the interference range of other traffic sources, so their traffic experiences less interference which leads to a relatively high throughput for these schemes.

- The results show that *Select 1 for less than 1* TCA always leads to a connected network in case of grid topology which is due to the symmetric nature of the grid topology.
- The results show that *Select 1 for less than 1* TCA always leads to a disconnected network in case of random and controlled random topologies which is due to the random nature of these topologies. It is observed that *Select 2 for less than 2* TCA leads to a disconnected network in case of random and controlled random topologies in most cases. However, in cases where it leads to a connected network for these topologies, the results show that the average throughput with *Select 2 for less than 2* TCA is less than that with *Select 3 for less than 3* TCA for TICA. This is due to the fact that *Select 2 for less than 2* TCA results in a connectivity graph with low average node degree in TICA which leads to low throughput. Therefore, in case the *Select 1 for less than 1* TCA leads to a disconnected network, this indicates that the topology is either random or controlled random and it is concluded that the next higher TCA for the gateway should be *Select 3 for less than 3* in this case.
- As per the specification of the IEEE 802.11s standard for wireless mesh networks, the mesh routing protocol has to reside in the MAC layer. TICA not only performs channel assignment but performs routing as well by providing each node with the next hop information to reach the gateway node and hence, conforms to the requirements of IEEE 802.11s.
- The proposed CA algorithm, TICA, works with small-scale as well as large-scale networks. This is verified by the results of throughput comparison of TICA with other schemes for networks of 36 nodes and 144 nodes respectively. In comparison to CCA and SRSC schemes, the throughput improvement with TICA in a large-scale network of 144 nodes is significantly higher than the throughput improvement with TICA in a small-scale network of 36 nodes. The CCA and SRSC schemes perform poorly in 144-node network due to the large number of traffic sources. More traffic sources means more nodes competing for medium access. Increased contention for medium access combined with lack of power

control in these schemes leads to more collisions and reduced throughput for these schemes.

- A centralized Failure Recovery Mechanism for TICA is proposed in this thesis which supports automatic and fast failure recovery. In case of node failure, after detecting the failed node, deleting the MPNT of the failed node and deleting it from the MPNT of its neighbors, the gateway runs the TCA and builds the MPSPT. Based on the new MPSPT, the gateway calculates the link rankings and the channel assignments. The new channel assignments are communicated to the mesh nodes by the gateway via a new CARM using the control radio over the control channel.
- TICA has shown a better performance as compared to BFS-CA and C-HYA schemes for similar scenarios. However, in these scenarios, it should be noted that the transmission range of mesh nodes in CCA and SRSC schemes is controlled by controlling either their transmission power or receiver sensitivity.
- The proposed CA algorithm, TICA, does not require modifications to the MAC protocol and therefore, can work with existing IEEE 802.11a-based interface hardware.

7.2. Future Work

Following are some aspects of this work which can be extended to improve the performance of the proposed algorithm.

- Since TICA uses the new approach of building the interference level for all the frequency channels, it can be enhanced to model and account for the interference from the co-located IEEE 802.11a-based wireless networks.
- Other algorithms for building the tree topology, such as Prim's algorithm [37] and Kruskal's algorithm [38], can be used for building the minimum power based tree which may lead to a further enhancement in the overall network throughput.
- The propagation model used is free-space model or two-ray model depending upon the cross-over distance. The performance of the proposed algorithm may be tested under more realistic propagation models such as Shadowing and Rayleigh-fading.

- Other schemes for building the tree topology with the required node degree, such as the one proposed in [39], can be used which may lead to a better performance.
- The carrier sensing range is generally assumed to be twice the transmission range. However, carrier sensing range is a tunable parameter and an optimally tuned carrier sensing range can improve the network throughput in wireless mesh networks by enhancing the spatial frequency reuse and reducing collisions [40]. Therefore, the effects of carrier sensing range on the MAC layer performance in MRMC WMNs needs to be investigated and the performance of the proposed algorithm can be improved by controlling the carrier sensing range.
- The phenomenon of topology control based on power control impacts the per-node fairness of medium access based on CSMA/CA and hence the per-flow end-to-end throughput fairness [41]. Therefore, the effects of power control on the per-flow end-to-end throughput fairness in multi-radio multi-channel wireless mesh networks needs to be investigated and the proposed algorithm can be extended to ensure per-node and hence per-flow fairness without sacrificing the gain in the overall network throughput.
- All the traffic in a WMN is directed towards the gateway. Depending on the number of links emanating from the gateway, the gateway has a fixed capacity which limits the maximum traffic that can reach the gateway. This gateway capacity is shared by all the traffic sources and throughput per traffic source is reduced as the number of traffic sources increases. Therefore, the traffic bottleneck at the gateway is the main reason of the capacity limitation of a WMN. The use of multiple gateways can increase the capacity of the WMN by preventing the formation of traffic bottlenecks [42]. Therefore, the capacity gains possible with the deployment of multiple gateways need to be investigated and the performance of the proposed algorithm can be improved by extending it for multiple gateways.
- The proposed algorithm can be extended for multiple gateways in a way such that each gateway is responsible for a subset of nodes in the network and the algorithmic computation and complexity is distributed among the gateways.

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APPENDICES

Appendix A. Final Neighbor Table (FNT)

A.1. FNTs from Select 1 for Less Than 1 TCA

Table A.1: FNTs of all nodes resulting from Select 1 for less than 1 TCA

Node ID	Neighbor ID	Distance (m)	Power (mW)	Node ID	Neighbor ID	Distance (m)	Power (mW)
1	30	44	37	19	29	53	53
2	23	94	166	20	33	51	49
3	7	30	17	21	8	33	21
3	11	49	45	22	6	52	51
4	36	35	23	23	26	85	136
5	30	125	293	23	2	94	166
6	14	46	40	24	18	23	10
6	22	52	51	25	32	28	15
7	3	30	17	26	34	78	114
8	21	33	21	26	23	85	136
9	12	24	11	27	35	38	27
10	34	40	30	28	13	53	53
11	3	49	45	29	12	52	51
11	33	49	45	29	19	53	53
12	9	24	11	30	1	44	37
12	29	52	51	30	5	125	293
13	28	53	53	31	14	47	42
13	16	66	82	32	25	28	15
14	6	46	40	32	33	32	20
14	31	47	42	33	32	32	20
14	17	59	66	33	11	49	45
15	18	42	33	33	20	51	49
16	13	66	82	34	10	40	30
17	14	59	66	34	26	78	114
18	24	23	10	35	27	38	27
18	15	42	33	36	4	35	23

A.2. FNTs from Select 2 for Less Than 2 TCA

Table A.2: FNTs of all nodes resulting from Select 2 for less than 2 TCA

Node ID	Neighbor ID	Distance (m)	Power (mW)	Node ID	Neighbor ID	Distance (m)	Power (mW)
1	30	44	37	20	33	51	49
1	7	103	199	20	32	56	59
2	23	94	166	21	8	33	21
2	16	106	211	21	15	81	123
3	7	30	17	22	6	52	51
3	11	49	45	22	29	81	123
4	36	35	23	23	26	85	136
4	35	53	53	23	2	94	166
5	30	125	293	24	18	23	10
5	27	126	297	24	15	46	40
6	14	46	40	25	32	28	15
6	22	52	51	25	33	46	40
6	31	71	95	26	34	78	114
7	3	30	17	26	10	81	123
7	11	75	106	26	23	85	136
7	1	103	199	27	35	38	27
8	21	33	21	27	36	84	132
8	15	51	49	27	5	126	297
9	12	24	11	28	13	53	53
9	29	57	61	28	36	101	191
10	34	40	30	28	16	104	203
10	26	81	123	29	12	52	51
11	3	49	45	29	19	53	53
11	33	49	45	29	9	57	61
11	7	75	106	29	22	81	123
11	19	88	145	30	1	44	37
12	9	24	11	30	5	125	293
12	29	52	51	31	14	47	42
13	28	53	53	31	6	71	95
13	16	66	82	31	17	83	129
14	6	46	40	32	25	28	15
14	31	47	42	32	33	32	20
14	17	59	66	32	20	56	59
15	18	42	33	33	32	32	20
15	24	46	40	33	25	46	40
15	8	51	49	33	11	49	45
15	21	81	123	33	20	51	49
16	13	66	82	34	10	40	30
16	28	104	203	34	26	78	114
16	2	106	211	35	27	38	27
17	14	59	66	35	36	46	40
17	31	83	129	35	4	53	53
18	24	23	10	36	4	35	23
18	15	42	33	36	35	46	40

19	29	53	53	36	27	84	132
19	11	88	145	36	28	101	191

A.3. FNTs from Select 3 for Less Than 3 TCA

Table A.3: FNTs of all nodes resulting from Select 3 for less than 3 TCA

Node ID	Neighbor ID	Distance (m)	Power (mW)	Node ID	Neighbor ID	Distance (m)	Power (mW)
1	30	44	37	19	29	53	53
1	7	103	199	19	11	88	145
1	25	122	279	19	9	93	162
2	23	94	166	20	33	51	49
2	16	106	211	20	32	56	59
2	31	133	331	20	11	72	97
3	7	30	17	21	8	33	21
3	33	48	44	21	15	81	123
3	11	49	45	21	18	93	162
3	25	66	82	22	6	52	51
4	36	35	23	22	29	81	123
4	35	53	53	22	34	84	132
4	27	85	136	22	23	124	288
5	30	125	293	23	26	85	136
5	27	126	297	23	2	94	166
5	35	150	421	23	22	124	288
6	14	46	40	24	18	23	10
6	22	52	51	24	15	46	40
6	12	58	63	24	8	90	152
6	31	71	95	25	32	28	15
7	3	30	17	25	33	46	40
7	11	75	106	25	3	66	82
7	33	76	108	25	1	122	279
7	30	101	191	26	34	78	114
7	1	103	199	26	10	81	123
8	21	33	21	26	23	85	136
8	15	51	49	27	35	38	27
8	18	74	103	27	36	84	132
8	24	90	152	27	4	85	136
9	12	24	11	27	10	119	265
9	29	57	61	27	5	126	297
9	15	60	68	28	13	53	53
9	19	93	162	28	36	101	191
10	34	40	30	28	16	104	203
10	26	81	123	29	12	52	51
10	27	119	265	29	19	53	53
11	3	49	45	29	9	57	61
11	33	49	45	29	22	81	123
11	20	72	97	30	1	44	37
11	7	75	106	30	7	101	191
11	19	88	145	30	5	125	293

12	9	24	11	31	14	47	42
12	29	52	51	31	6	71	95
12	6	58	63	31	17	83	129
12	17	100	187	31	2	133	331
13	28	53	53	32	25	28	15
13	16	66	82	32	33	32	20
13	36	154	444	32	20	56	59
14	6	46	40	33	32	32	20
14	31	47	42	33	25	46	40
14	17	59	66	33	3	48	44
15	18	42	33	33	11	49	45
15	24	46	40	33	20	51	49
15	8	51	49	33	7	76	108
15	9	60	68	34	10	40	30
15	21	81	123	34	26	78	114
16	13	66	82	34	22	84	132
16	28	104	203	35	27	38	27
16	2	106	211	35	36	46	40
17	14	59	66	35	4	53	53
17	31	83	129	35	5	150	421
17	12	100	187	36	4	35	23
18	24	23	10	36	35	46	40
18	15	42	33	36	27	84	132
18	8	74	103	36	28	101	191
18	21	93	162	36	13	154	444

Appendix B. Failure Recovery Mechanism of TICA

B.1. Scenario 2 - Node 3 Fails

In this scenario, Node 3 is supposed to have failed. After detecting its failure, the gateway deletes the MPNT of Node 3 and deletes Node 3 from the MPNT of its neighbors. The gateway runs the Select 3 for less than 3 TCA, builds the FNTs for all nodes and builds the connectivity graph as shown in Figure B.1. Note that the network resulting from Select 3 for less than 3 TCA is connected.

Since the connectivity graph resulting from Select 3 for less than 3 TCA is connected, the gateway builds the MPSPT with a MND of 4, as shown in Figure B.2.

Since the resulting MPSPT is connected, the gateway builds the link ranking for each link of the MPSPT, as shown in Table B.1.

Figure B.1: Connectivity Graph with Select 3 for less than 3 TCA after Node 3 fails

Figure B.2: MPSPT with a MND of 4 after Node 3 fails

Table B.1: Link Ranking of MPSPT after Node 3 fails

Link		Distance (m)	Power (mW)	RANK	Power from the farthest node of the link to the gateway (mW)
15	9	60	68	30	68
9	12	24	11	19	79
12	6	58	63	18	142
6	22	52	51	11	193
9	29	57	61	10	129
29	19	53	53	9	182
22	34	84	132	9	325
19	11	88	145	8	327
34	10	40	30	7	355
6	14	46	40	6	182
10	27	119	265	6	620
14	31	47	42	4	224
11	33	49	45	4	372
27	35	38	27	4	647
11	7	75	106	3	433
31	2	133	331	3	555
15	8	51	49	2	49
33	32	32	20	2	392
35	36	46	40	2	687
2	16	106	211	2	766
15	18	42	33	1	33
15	24	46	40	1	40
8	21	33	21	1	70
14	17	59	66	1	248
32	25	28	15	1	407
33	20	51	49	1	421
34	26	78	114	1	439
22	23	124	288	1	481
7	30	101	191	1	624
7	1	103	199	1	632
35	4	53	53	1	700
16	13	66	82	1	848
36	28	101	191	1	878
27	5	126	297	1	917

Based on the link ranking, the gateway assigns a channel to each link of the MPSPT, as shown in Table B.2.

Table B.2: Channel Assignment for links of MPSPT after Node 3 fails

Node	Neighbor	Channel
15	9	1
9	12	2
12	6	3
6	22	4
9	29	5
29	19	6
22	34	7
19	11	8
34	10	9
6	14	10
10	27	11
14	31	11
11	33	11
27	35	10
11	7	10
31	2	8
15	8	11
33	32	9
35	36	9
2	16	6
15	18	10
15	24	9
8	21	8
14	17	9
32	25	10
33	20	7
34	26	2
22	23	8
7	30	4
7	1	3
35	4	8
16	13	11
36	28	7
27	5	5

Before its failure, Node 3 was part of the 11th-ranked link. As shown in Table B.1, the link rankings and hence the channel assignment of all links from the 4th-ranked link and onwards, change after the failure of Node 3.

B.2. Scenario 3 - Node 30 Fails

In this scenario, Node 30 fails. After detecting its failure, the gateway deletes the MPNT of Node 30 and deletes Node 30 from the MPNT of its neighbors. The gateway runs the Select 3 for less than 3 TCA, builds the FNTs for all nodes and builds the connectivity graph as shown in Figure B.3. Note that the network resulting from Select 3 for less than 3 TCA is connected.

Since the connectivity graph resulting from Select 3 for less than 3 TCA is connected, the gateway builds the MPSPT with a MND of 4, as shown in Figure B.4.

Since the resulting MPSPT is connected, the gateway builds the link ranking for each link of the MPSPT, as shown in Table B.3.

Figure B.3: Connectivity Graph with Select 3 for less than 3 TCA after Node 30 fails

33	32	32	20	2	392
35	36	46	40	2	687
2	16	106	211	2	766
15	18	42	33	1	33
15	24	46	40	1	40
8	21	33	21	1	70
14	17	59	66	1	248
32	25	28	15	1	407
33	20	51	49	1	421
34	26	78	114	1	439
22	23	124	288	1	481
7	1	103	199	1	588
35	4	53	53	1	700
16	13	66	82	1	848
36	28	101	191	1	878
27	5	126	297	1	917

Based on the link ranking, the gateway assigns a channel to each link of the MPSPT, as shown in Table B.4.

Table B.4: Channel Assignment for links of MPSPT after Node 30 fails

Node	Neighbor	Channel	Node	Neighbor	Channel
15	9	1	3	7	9
9	12	2	33	32	7
12	6	3	35	36	9
6	22	4	2	16	6
9	29	5	15	18	10
29	19	6	15	24	9
22	34	7	8	21	8
19	11	8	14	17	9
34	10	9	32	25	10
6	14	10	33	20	6
10	27	11	34	26	2
14	31	11	22	23	8
11	33	11	7	1	3
27	35	10	35	4	8
11	3	10	16	13	11
31	2	8	36	28	7
15	8	11	27	5	5

Before its failure, Node 30 was part of the 20th-ranked link. As shown in Table B.3, the link rankings and hence the channel assignment of all links from the 4th-ranked link and onwards, change after the failure of Node 30.

B.3. Scenario 4 - Node 5 Fails

In this scenario, I suppose that Node 5 fails. After detecting its failure, the gateway deletes the MPNT of Node 5 and deletes Node 5 from the MPNT of its neighbors. The gateway runs the Select 3 for less than 3 TCA, builds the FNTs for all nodes and builds the connectivity graph as shown in Figure B.5. Note that the network resulting from Select 3 for less than 3 TCA is connected.

Since the connectivity graph resulting from Select 3 for less than 3 TCA is connected, the gateway builds the MPSPT with a MND of 4, as shown in Figure B.6.

Since the resulting MPSPT is connected, the gateway builds the link ranking for each link of the MPSPT, as shown in Table B.5.

Figure B.5: Connectivity Graph with Select 3 for less than 3 TCA after Node 5 fails

Figure B.6: MPSPT with a MND of 4 after Node 5 fails

Table B.5: Link Ranking of MPSPT after Node 5 fails

Link		Distance (m)	Power (mW)	RANK	Power from the farthest node of the link to the gateway (mW)
15	9	60	68	30	68
9	12	24	11	18	79
12	6	58	63	17	142
9	29	57	61	11	129
29	19	53	53	10	182
6	22	52	51	10	193
19	11	88	145	9	327
22	34	84	132	8	325
6	14	46	40	6	182
34	10	40	30	6	355
10	27	119	265	5	620
14	31	47	42	4	224
11	3	49	45	4	372
11	33	49	45	4	372
27	35	38	27	4	647
3	7	30	17	3	389
31	2	133	331	3	555
15	8	51	49	2	49

33	32	32	20	2	392
35	36	46	40	2	687
2	16	106	211	2	766
15	18	42	33	1	33
15	24	46	40	1	40
8	21	33	21	1	70
14	17	59	66	1	248
32	25	28	15	1	407
33	20	51	49	1	421
34	26	78	114	1	439
22	23	124	288	1	481
7	30	101	191	1	580
7	1	103	199	1	588
35	4	53	53	1	700
16	13	66	82	1	848
36	28	101	191	1	878

Based on the link ranking, the gateway assigns a channel to each link of the MPSPT, as shown in Table B.6.

Table B.6: Channel Assignment for links of MPSPT after Node 5 fails

Node	Neighbor	Channel	Node	Neighbor	Channel
15	9	1	15	8	11
9	12	2	33	32	8
12	6	3	35	36	9
9	29	4	2	16	10
29	19	5	15	18	10
6	22	6	15	24	9
19	11	7	8	21	8
22	34	8	14	17	10
6	14	9	32	25	11
34	10	10	33	20	6
10	27	11	34	26	2
14	31	11	22	23	7
11	3	11	7	30	3
11	33	10	7	1	1
27	35	10	35	4	8
3	7	9	16	13	11
31	2	7	36	28	6

Before its failure, Node 5 was part of the 34th-ranked link. As shown in Table B.5, the link rankings and hence the channel assignment of all links from the 11th-ranked link and onwards, change after the failure of Node 5.

Appendix C. MPSPT

C.1. MPSPT for Random Topology – 36-node Network

C.1.1. Seed 2

For the 2nd-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.1.

C.1.2. Seed 3

For the 3rd-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36 node-network is shown in Figure C.2.

C.1.3. Seed 4

For the 4th-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.3.

C.1.4. Seed 5

For the 5th-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.4.

C.1.5. Seed 6

For the 6th-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.5.

C.1.6. Seed 7

For the 7th-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.6.

C.1.7. Seed 8

For the 8th-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.7.

C.1.8. Seed 9

For the 9th-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.8.

C.1.9. Seed 10

For the 10th-random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.9.

Figure C.1: MPSPT for 2nd RT

Figure C.2: MPSPT for 3rd RT

Figure C.3: MPSPT for 4th RT

Figure C.4: MPSPT for 5th RT

Minimum Power based Shortest Path Tree Graph for 36 node network

Figure C.5: MPSPT for 6th RT

Minimum Power based Shortest Path Tree Graph for 36 node network

Figure C.6: MPSPT for 7th RT

Minimum Power based Shortest Path Tree Graph for 36 node network

Figure C.7: MPSPT for 8th RT

Minimum Power based Shortest Path Tree Graph for 36 node network

Figure C.8: MPSPT for 9th RT

Figure C.9: MPSPT for 10th RT

C.2. MPSPT for Controlled Random Topology – 36-node Network

C.2.1. Seed 2

For the 2nd-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.10.

C.2.2. Seed 3

For the 3rd-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.11.

C.2.3. Seed 4

For the 4th-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.12.

C.2.4. Seed 5

For the 5th-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.13.

C.2.5. Seed 6

For the 6th-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.14.

C.2.6. Seed 7

For the 7th-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.15.

C.2.7. Seed 8

For the 8th-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.16.

C.2.8. Seed 9

For the 9th-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.17.

C.2.9. Seed 10

For the 10th-controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 36-node network is shown in Figure C.18.

Figure C.10: MPSPT for 2nd CRT

Figure C.11: MPSPT for 3rd CRT

Figure C.12: MPSPT for 4th CRT

Minimum Power based Shortest Path Tree Graph for 36 node network

Figure C.13: MPSPT for 5th CRT

Minimum Power based Shortest Path Tree Graph for 36 node network

Figure C.14: MPSPT for 6th CRT

Minimum Power based Shortest Path Tree Graph for 36 node network

Figure C.15: MPSPT for 7th CRT

Minimum Power based Shortest Path Tree Graph for 36 node network

Figure C.16: MPSPT for 8th CRT

Figure C.17: MPSPT for 9th CRT

Figure C.18: MPSPT for 10th CRT

C.3. MPSPT – 144-node Network

C.3.1. Random Topology

For the random topology, the MPSPT with a MND of 4 resulting from Select 4 for less than 4 TCA for a 144-node network is shown in Figure C.19.

C.3.2. Controlled Random Topology

For the controlled random topology, the MPSPT with a MND of 4 resulting from Select 3 for less than 3 TCA for a 144-node network is shown in Figure C.20.

C.3.3. Grid Topology

For the grid topology, the MPSPT with a MND of 4 resulting from Select 1 for less than 1 TCA for a 144-node network is shown in Figure C.21.

Figure C.19: MPSPT for RT – 144-node network

Figure C.20: MPSPT for CRT – 144-node network

Figure C.21: MPSPT for GT – 144-node network

C.4. MPSPT – 100-node Grid Network

The MPSPT with a MND of 4 resulting from Select 1 for less than 1 TCA for a 100-node grid network is shown in Figure C.22.

Figure C.22: MPSPT – 100-node grid network

C.5. MPSPT – 30-node Grid Network

The MPSPT with a MND of 4 resulting from Select 1 for less than 1 TCA for a 30-node grid network is shown in Figure C.23.

Figure C.23: MPSPT – 30-node grid network