QoS Routing in Wireless Mesh Networks

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Wireless Mesh Networking is envisioned as an economically viable paradigm and a promising technology in providing wireless broadband services. The wireless mesh backbone consists of fixed mesh routers that interconnect different mesh clients to themselves and to the wireline backbone network. In order to approach the wireline servicing level and provide same or near QoS guarantees to different traffic flows, the wireless mesh backbone should be quality-of-service (QoS) aware. A key factor in designing protocols for a wireless mesh network (WMN) is to exploit its distinct characteristics, mainly immobility of mesh routers and less-constrained power consumption.

In this work, we study the effect of varying the transmission power to achieve the required signal-to-interference noise ratio for each link and, at the same time, to maximize the number of simultaneously active links. We propose a QoS-aware routing framework by using transmission power control. The framework addresses both the link scheduling and QoS routing problems with a cross-layer design taking into consideration the spatial reuse of the network bandwidth. We formulate an optimization problem to find the optimal link schedule and use it as a fitness function in a genetic algorithm to find candidate routes. Using computer simulations, we show that by optimal power allocation the QoS constraints for the different traffic flows are met with more efficient bandwidth utilization than the minimum power allocations.

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Abbreviations and Symbols

Abbreviations

ACK	Acknowledgment
CDMA	Code division multiple access
CTS	Clear to send
Db	Decibel
dBm	decibel milliwatt
DCA	Dynamic channel assignment
DSDV	Destination sequenced distance vector
DSR	Dynamic source routing
ETX	Link transmission rate
FDMA	Frequency division multiple access
LOS	Line of sight
LQSR	Link quality source routing
MAC	Medium access control
MCR	Multi-channel routing
MFN_RS	Mean field network routing scheme
MR-LQSR	Multi-radio link quality source routing
MRP	Mesh routing protocol
NIC	Network interface card

PLR   Packet loss rate

QoS   Quality of service

RADV   Route advertisement

RDIS   Route discovery

RSV   Reservation

RTS   Request to send

RTT   Round trip time

SSCH   Slotted seeded channel hopping

SINR   Signal to noise plus interference ratio

TDMA   Time division multiple access

VBR   Variable bit rate

VC   Virtual circuit

WLAN   Wireless local area network

WMN   Wireless mesh network

Symbols

$A(l,s)$ The state of link l in slot s: whether active or not

B_E Effective bandwidth

c Speed of light

C_L Load capacity

d Distance between two routers

d_0 A close-in reference distance

d_q The average waiting time for a packet in a queue

D_r End-to-end delay bound requirement for each packet belonging to a route r

f Carrier frequency

f_i Fitness value of chromosome i

$G(.,.)$ Path gain between two nodes

G_r Receiver gain

G_t Transmitter gain

h_r Signal to noise plus interference ration threshold for route r

L System hardware losses, is the

M A big positive number

N Path loss exponent

N_0 Thermal white noise power

N_p Population size

N_s Number of sources to be admitted to the network

p_i Probability of selecting chromosome i for reproduction

$P_L(.)$ Path loss as a function of distance

P_{max} Maximum transmission power

P_{min} Minimum transmission power for an active link

P_r *The* signal power received at the receiver

P_t The signal power at the transmitter

r A route in the network

R The set of all routes in the network

$R(l)$ Receiver node of link l

s A time slot in the data frame

S Number of time slots in one frame

$SINR$ Signal to noise plus interference ratio for a link in a route

$T(l)$ Transmitter node of link l

T_{off} The mean duration of the OFF period

T_{on} The mean duration of the ON period

t_s Service time for a packet

X_σ A zero-mean Gaussian distributed random variable with standard deviation σ

α Probability to switch from the ON to the OFF period

β Probability to switch from the OFF to the ON period

λ Packet arrival rate

Chapter 1

Introduction

Providing broadband access to anyone anywhere is a challenge to today's networking market. Wired connections may not be the best solution in terms of cost, setup and hardware beside the immobility constraint of clients. The wireless mesh networking is introduced to provide the wide scale connectivity with lower cost than the wired alternative [1]. In addition to the cost advantage, wireless mesh networks (WMNs) are easy to maintain, robust and provide reliable service coverage [1]. Also, it can be deployed in difficult terrain where a wireline network is difficult to be deployed. The development of standards such as IEEE 802.11 [2], 802.15 [3] and 802.16 [4] and the decreasing cost of the wireless interface cards have strongly pushed the development and spread of wireless mesh networks. In the next section, we will start by briefly defining the WMN showing its benefits to the community, its types and applications.

1.1 Wireless Mesh Networks (WMNs)

WMNs draw an increasing attention in nowadays research and industry. It is a promising technology in terms of providing wireless broadband services. A WMN operates like a network of fixed routers, except that routers are connected only by wireless links. A WMN

plays mainly the role of a backbone network. It can interconnect or provide access to the Internet or other wireline backbones to its mesh clients.

1.1.1 Architecture

Figure 1 shows the wireless mesh backbone architecture. In this architecture, mesh clients represent other networks such as cellular, IEEE 802.11, IEEE 802.15, and sensor networks. Mesh routers are stationary and they form the backbone of the wireless mesh network. They can be connected to the high speed wireline network via gateways. The gateways, mesh routers and the mesh clients form a three-tier architecture [1], [5], [6]. Mesh clients can form an ad-hoc network that is connected to one or more mesh routers. Mesh routers act as relays to data transmitted between mesh clients or to the wireline network in both directions. Cellular networks, wireless local area networks (WLANs), WiMax networks and other types of access networks can be integrated into the WMN.
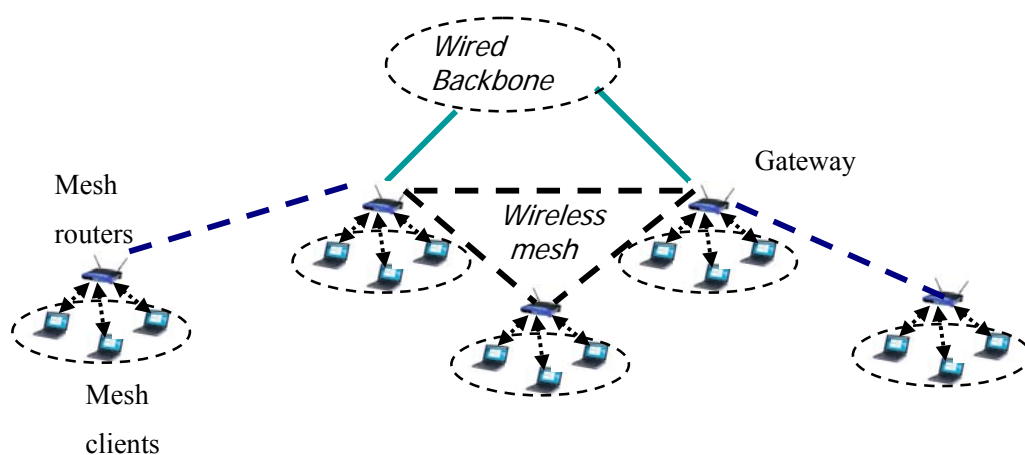
Figure 1.1: Wireless Network Architecture

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1.1.2 Applications

WMNs offer a wide scope of applications including, but not limited to, providing broadband internet access, sharing information on goods and services, gaming, public safety, medical and emergency response, valuable asset security, neighborhood video surveillance, industrial Monitoring. WMNs can also play an important role in disasters reporting and emergency networking.

On the small scale ([7], [8], [9], [10]), such as home or office, wireless mesh networking allows for connections to the internet from anywhere, indoors or outdoors, without wires. Access points are placed in the transmission range of each other to act as packet relays. Technologies such as IEEE 802.11b or IEEE 802.11a are used to provide secure reliable, fast and wireless connectivity. Computers with a wireless card can send and receive data to each other and to the Internet. Small scale WMNs can also be found in coffee shops, hotels, airport lounges and other locations where large crowds gather.

WMNs can cover a metropolitan area to provide broadband access [10], [11], [12], [13], [14], [15], [16]. It provides lower upfront investment cost and less deployment time than the traditional wired network.

These applications differ widely in their QoS requirements. A protocol designed to support one set of requirements may not be good for another set. Therefore designing protocols for such networks should consider the diverse requirements, to provide the best performance for each set while achieving fairness among different sets.

1.2 Motivation

As a backbone network, a WMN is required to maintain the same QoS level as its access networks because it is very hard to provide an end-to-end QoS to the users of these networks using a non QoS-aware backbone. In fact, QoS provisioning problem in the mesh backbone resembles to a great extent providing QoS guarantees over the Internet, which is mainly designed for best effort traffic.

In order to provide QoS guarantees over the Internet, two main approaches are used; namely [17], integrated service (IntServ) and differentiated service (DiffServ). IntServ provides QoS guarantees per flow. Therefore, each router in the system should implement IntServ, and every user should make an individual reservation. This implies that each router has to store a large amount of information and heavy signaling traffic may be exchanged throughout the network. As a result, an IntServ-like approach works well with small scale networks or with very high performance (in terms of processing power and memory) routers. DiffServ provides QoS guarantees per flow-class. Only selected routers at the network boundaries implement DiffServ. The remaining routers at the core of the network provide

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per-hop behavior (PHB). This implies that all complex functions, such as traffic classification and conditioning, are done at the network edges. Core routers are doing the job of routing with a simple DiffServ functionality of per-hop behavior according the class that the packets belong to.

1.3 Objective

The main function of the wireless mesh backbone is to carry the traffic of the access networks and route it to its destination. Our objective in this work is to propose a QoS-aware routing framework for wireless mesh backbones exploiting their unique characteristics. A wireless mesh backbone is different from the Internet architecture in the sense that the wireless links are shared by nature. The links are not isolated; they interfere with each other affecting the quality of transmission and causing packet loss. Also, all the mesh routers are similar in functionalities and capabilities. They can not be divided into core and edge (access) routers. Therefore, it is difficult to apply either the IntServ or the DiffServ QoS models in their current forms proposed originally for the Internet. IntServ requires very powerful routers to handle all the flows' state information coming from every single user in every mesh client. DiffServ distributes the processing between the core routers and the edge routers, which are the same in the wireless mesh backbone. This implies that DiffServ may need also all the wireless routers to be powerful enough to handle traffic classification, shaping and conditioning. On the other hand, wireless mesh backbones are similar in architecture to wireless ad hoc networks in the sense that they are infrastructure-less

networks with shared wireless links. However, the mesh routers are fixed and not battery-powered. Besides, wireless routers carry different traffic pattern from that of ad hoc networks since they interconnect access networks not just mobile users.

In this research, we aim at selecting routes that provide QoS guarantees in terms of delay and signal-to-interference-plus-noise ratio (SINR) to the different traffic aggregates in the wireless mesh backbone. The traffic from the access network is aggregated in the mesh router connected to it based on the service class [5] and then routed to its destination. Each service class has a unique end-to-end delay requirement to be satisfied over the whole route. Each service class also has a minimum SINR to be met at each link of the route.

Our main contribution in this work is a framework for QoS-aware routing in wireless mesh backbone using power control. Our framework is based on a centralized time division multiple access (TDMA) medium access control (MAC) protocol. Our approach for QoS provisioning is to allocate the power of each mesh router optimally in order to discover the routes that maximize the number of simultaneous transmissions in each time slot while meeting both the end-to-end delay and SINR constraints. In general, allocating the resources efficiently for a TDMA-based wireless mesh backbone is a challenging task. It tackles both the QoS routing and scheduling problems taking into consideration the spatial channel reuse. Indeed, power control plays an important role in utilization the bandwidth efficiently. If minimum power is allocated for each hop, this implies that a large number of hops are used

in each route. This decreases the delay share of each hop (end-to-end delay is divided among the large number of hops) and hence more time slots (bandwidth) is needed. On the other hand, if maximum power is allocated, the number of hops in every route will be minimal. However, the interference increases, which limits the number of simultaneous transmissions leading to inefficient wireless bandwidth utilization. Therefore, an optimal power allocation is required to realize QoS provisioning with efficient resource allocation.

1.4 Thesis Organization

The remainder of the thesis is organized into five chapters. Chapter 2 gives a summary of literature review. Chapter 3 describes the system model. The problem formulation is presented in Chapter 4. The simulation results and performance comparisons are discussed in Chapter 5. Chapter 6 concludes the research.

Chapter 2

Background and Literature Review

Routing and link scheduling are important components in satisfying the QoS requirements and utilizing the network bandwidth efficiently. They have long been addressed in wireless and wireline networks. However, few works have been done for WMNs. Power allocation has also been studied in wireless ad-hoc networks and sensor networks from the perspective of saving power. In the following, we review the literature of routing, link scheduling and power allocation to find the problems addressed and the impact of the proposed solutions in the WMNs. We mention here only the research done on WMNs for the routing and link scheduling. Since the power allocation is not addressed in WMNs we mention some work that was done in traditional ad-hoc networks.

2.1 Routing in WMNs

According to our survey of routing protocols, we classify routing protocols developed for the WMNs according to the QoS level that they provide: Best Effort Routing Protocols or QoS-aware Routing Protocols. Under this classification, we further divide routing protocols according to the number of channels used in data transmission and their combination with the type of antenna, mainly the directional antenna.

2.1.1 Best-Effort Routing

Best effort services are those that do not request any QoS guarantees. An example of a best effort application is web browsing in which an internet user requests a web page through a web browser and then waits without any guarantee that the page will not be delayed for a long time, or even though it may not open at all due to network congestion or server overloading. For such type of traffic, the network tries to accommodate as much flows as it can. Therefore increasing network capacity becomes the main concern.

In the wireless environment the main cause for capacity degradation is interference between neighbouring links of the network. In order to increase capacity we should try to alleviate or decrease the effect of interference. Several approaches have been adopted to increase capacity including a better selection of routes, the use of multi-channels, and the use of directional antennas.

Since routing depends on metrics that are mainly measured in the underlying link and physical layers, cross-layer routing has gained much research effort. Routing can be done based on metrics like throughput, delay, packet loss rate, power control, load distribution, and many others that are measured at the link or physical layers. In that case routing protocols are dependent on the underlying structure. So routing protocols can be developed to

work on top of a multi-channel architecture while others developed to benefit from using a directional antenna.

Routing protocols design is also highly jointed with the underlying link and physical layers. For example designing a routing protocol for a network using multi-channel MAC protocol will tend to favour channel diversity and load balancing among channels. While routing in networks with directional antennas will try to benefit from the uni-casting capability of the directional antennas and to alleviate problems that aroused for such type of networks. In the next sections, we present and discuss routing protocols developed for best-effort traffic. The protocols are classified based on the number of channels used throughout the network.

2.1.1.1 Routing Protocols for Single-Channel Networks

These protocols focus on choosing a routing metric that selects routes to increase the total network capacity. In [5], *De Couto* discusses the theory that selecting the minimum hop count as a metric for routing protocols in multi-hop wireless networks tends to achieve poor performance. The reason as declared in the paper is due to the tendency of the routing protocol to include longer links which means distant nodes. The longer the link between two nodes, the more it becomes exposed to fading, noise and other interference. This leads to an increase in packet loss rate and therefore to poor throughput. *De Couto* introduces a new routing metric, called ETX, which accounts for the link loss rate. A route that has the

minimum ETX is selected to be the recommended one. This metric is based on measuring the loss rate of broadcast packets between pairs of neighbouring nodes. A number of small sized packets are sent for the purpose of measuring the link loss rate followed by the reception of replies for these packets. The percentage of successfully received packets out of the transmitted packets indicates the successful transmission rate. The reciprocal of its complementary indicates the estimated number of transmissions required to send a packet on that link.

This metric was adopted by other routing protocols. In [18] it is implemented in two of the well known routing protocols for wireless networks, namely the DSDV [19] and DSR [20] routing protocols. The protocols are implemented in mobile nodes that form an ad-hoc network. A single channel is used and thus if a link is active, all neighbouring links should not be active or there will be interference.

An extension for this work is done by *Draves* in [21]. Five routing metrics are compared including the traditional hop-count, the proposed link transmission rate in [18], ETX, and another two metrics are the per-hop round trip time (RTT) and the per-hop packet-pair metrics. The per-hop RTT is based on measuring the round trip delay seen by unicast probes between neighbouring nodes. The per-hop packet pair is based on measuring the delay between a pair of back-to-back probe signals to the neighbouring node. According to their results, ETX outperforms the other two metrics when all the nodes are stationary while the

traditional minimum hop had the best performance when the sender is mobile. The ETX metric is included in a modified version of DSR which is called Link Quality Source Routing (LQSR) [22].

A simple extension to this work is made by Kulkarni et al in [23]. They modify the previous ETX to suit the multi-rate case. Instead of measuring the number of transmissions using a single rate, they use multiple rates from the set of rates supported by the underlying wireless technology to estimate the transmission time.

2.1.1.2 Routing for Multi-Channel Wireless Networks

In order to increase capacity we should try to alleviate or decrease the effect of interference. Several approaches have been adopted to increase capacity. One active approach is the deployment of multiple channels. Two neighbouring links interfere if they use the same channel. By proper assignment of multiple channels to neighbouring links we can activate more than one link simultaneously on condition that they use different channels. The term "channel" refers to a frequency band, like in FDMA, or an orthogonal code, like in CDMA.

Routing protocols developed for multi-channel wireless networks are often jointed with a channel assignment scheme that enables many neighbouring links to be active simultaneously to increase capacity. Some works are concerned only with channel

assignment [24], [25], [26], [27], leaving the routing problem as a standalone problem to be solved on top of the channel assignment.

The work in [24] presents an integer linear programming formulation for the fixed channel assignment problem in multi-radio multi-channel wireless mesh networks. The goal is to maximize the number of simultaneous transmissions in the network. The channel assignment is supposed to be centralized which puts a restriction on the network topology and limits the scalability of the network. In addition, all nodes have to access the channel assignment server, leading to high congestion in the paths to that server.

In [25], Wu et al. proposes a protocol, namely *Dynamic channel Assignment* (DCA), which utilizes the multi channel capability of the 802.11 physical layer. In this protocol, one channel is dedicated as a control channel for exchanging control messages among all hosts while the other channels are used for data packets. Data channels are assigned dynamically on an on-demand basis. The control channel is assigned to one transceiver while data channels are assigned to the other transceiver(s). By this way a host can listen on the control channel and the data channel simultaneously. The sender uses the control channel to set up connection with the receiver. The request-to-send packet (RTS) includes a list of preferred channels to be used for data transmission. The receiver decides on one of the channels and sends the information to the sender in the clear-to-send packet (CTS). The sender announces the channel used to neighbouring nodes through a reservation packet (RSV). This protocol

does not have the multi-channel hidden terminal problem since there will be always one of the transceivers listening to the channel. In addition there is no need for synchronization between the sender and receiver. The disadvantage is the cost of reserving a channel for the small control messages, thus wasting bandwidth.

A similar protocol is proposed in [26] that uses one control channel and N data channels. The difference is that the decision on the channel to use is based on the channel condition at the receiver side. The best channel condition is selected. Although it has a throughput improvement over [25], it still has the same disadvantages.

The protocol in [27] operates with a single radio (transceiver) per host. It does not separate control channel from data channels. The main disadvantage is that it requires clock synchronization among all hosts. Another disadvantage is that it incurs a bandwidth overhead to exchange traffic indication messages. At that time there will be no exchange of data packets.

In [28], Gupta and Kumar show that using one radio per node extensively degrades the capacity of wireless networks. Moreover, the prices of wireless network adapters are decreasing in a way that makes employing more than one network adapter a more cost effective solution. Most of the recent research effort has been directed towards the employment of more than one interface in a mesh router to increase the network capacity.

In [29], *Draves* suggests implementing a routing metric that accounts for the link loss rate to be used in a multiple radio environment. The proposed metric favours the selection of different channels for neighbouring links which will lead to minimizing the interference and thus increasing the capacity. The new protocol was named MR-LQSR (Multi-Radio Link-Quality Source Routing). The new metric WCETT (Weighted Cumulative Expected Transmission Time) allows to trade off channel diversity and path length by adjusting a control parameter. The WCETT combines the link quality in terms of the expected transmission time and the channel diversity by favouring paths that are more channel diverse.

MR-LQSR uses a number of channels which is equal to number of radio interfaces. Thus in the case of two radios, as in their experiment, only two channels are used. Each radio has a fixed channel which has an advantage in that it does not incur a switching delay. On the other side it is a restriction which if relaxed can yield better performance in terms of throughput and which incurs some delay that are tolerable.

In [30], So et al. proposes an on-demand routing protocol for networks with single transceiver nodes benefiting from the multiple channels offered by the 802.11. The protocol, named MCRP, assigns different channels to neighbouring nodes so as to avoid interference. Each node can switch between channels under the constraint that no two neighbouring nodes

are switching so that to avoid the deafness problem [31]. The protocol works on a synchronous TDMA access technique which is complex to implement.

In [32] Shacham et al. proposes an architecture for multi-channel wireless networks. Although the architecture is developed for network with single radio nodes, it can be extended to multi-radio nodes network. The main restriction in this architecture is the tight coordination it requires among nodes which cannot be easily guaranteed.

An attempt to assign channels to interfaces and schedule flows is made by Bahl in [74]. Bahl proposes a link layer solution named Slotted-Seeded Channel Hopping (SSCH). This work is implemented in networks with single interface nodes but can be extended to multiple interface nodes. In SSCH, nodes hop between channels after fixed intervals based on a schedule. This schedule is published to neighbouring nodes so that two nodes can communicate by adjusting their schedule to have a common channel at some time. The paper includes also a flow scheduling algorithm per each node. Bahl did not discuss a routing protocol to be implemented on top of his work.

A joint channel assignment and routing protocol is proposed in [34], [35]. This work by Raniwala et al. focuses on improving the capacity of wireless mesh networks that is used as an intermediary between the wired backbone and the mobile mesh clients. Thus all the traffic is directed towards specific gateway nodes. They assume each node to have more than one

radio and each radio can switch among the available channels. Two channel assignment and bandwidth allocation techniques are proposed. The first is based on network topology and the other is based on traffic load. They claim that any routing algorithm can work efficiently on their channel assignment techniques. However they implement a routing protocol that has its routing metric as the shortest path and another one with randomized multi-path routing.

In [33], Pradeep proposes a joint channel assignment and routing protocol. This work allows for a free traffic load from any point in the network to the other. He considers switching latency in the work and tries to minimize it by decreasing the channel switching rate for one interface. He also proposes a new routing metric incorporated into an on-demand routing protocol. The proposed Multi-Channel Routing (MCR) metric combines the measured link expected transmission time (ETT) and switching costs into a single path cost.

2.1.1.3 Routing for nodes with Directional Antenna

Another approach for improving wireless network capacity is the use of directional antennas [36], [37], [38], [39], [40]. By beam-forming at the transmitter we can restrict the transmission area, reducing interference and alleviating the exposed terminal problem. Therefore capacity can be greatly improved and we can achieve higher throughputs. Placing the directional antenna at the receiver side can reduce the hidden terminal problem by only listening to the expected area of transmission.

Directional antennas have also an impact on the network layer. They help in finding routes with less hop count [38] due to the longer transmission range of directional antenna. They can also help in finding energy efficient routes [39] and interference-aware [40] routes.

On the other side, using directional antennas has founded new problems including new kinds of hidden terminal problems and deafness [41] and capture [36]. Another problem that arises is the discovery of the neighbours [42]. These new category of problems imposes a tradeoff between gaining benefits of using directional antennas and solving or adapting to the problems.

2.1.2 QoS-aware Routing

With the recent advances in communication technology and the flooding of multimedia services through the internet, QoS consideration in networking is becoming imperative. Providing QoS is a challenge to networking services' providers especially in the wireless environment. Different layers can share in fulfilling QoS requirements individually or integrated with others.

Services guarantees are a typical requirement for applications involving audio and video transmission such as Voice over IP (VOIP), distant learning using online multimedia

transmission and video conferencing. This type of traffic is characterized by having variable bit rate (VBR). Allocating bandwidth is a challenge in that case since if it is allocated according to the maximum rate then resources are wasted and other applications will be blocked while there is unused capacity. In addition, calculating the effective bandwidth in the wirelesss environment is not a trivial task.

Several metrics are used to specify QoS requirements in networks such as minimum required throughput or capacity, maximum tolerable delay, maximum tolerable delay jitter, and maximum tolerable packet loss ratio. An application may request guarantees on one or more metrics for its QoS. In the next sections, we present and discuss the different routing protocols developed to satisfy QoS requirements for traffic flows.

2.1.2.1 General Routing Protocols

A route is scanned for QoS satisfaction in a procedure similar to route discovery in conventional routing protocols. The source node sends a route request packet with the QoS guarantees required on the route such as minimum required bandwidth, total delay bound, packet loss rate (PLR) to the destination. This can be done either by broadcasting (flooding the network) or using a previously discovered route or a list of routes. Every node receiving the route request packet carrying the required QoS guarantees compares its own measured metrics with the required metrics bound found in the packet header. If not satisfying the

requirements, a node failure packet is sent back to the source node to start a new route

discovery or to an intermediate node to perform a route repair procedure.

In [43], a source node initially selects a neighbour that is closest to the destination

according to location information service provided in the network. On the way from source

to destination every node compares its PLR with the maximum PLR in the packet header and

the accumulated PLR so far. If the PLR constraint is violated a route failure is sent back to

the source to start a new QoS route discovery. Once the route request packet reaches the

destination, the available bandwidth required on each intermediate node is calculated and an

admission request message is sent to the source. If the bandwidth requirements are satisfied

then the bandwidth is reserved in that node and this information is broadcasted to

neighbouring nodes. If the bandwidth requirements are not satisfied an admission refused

message is sent to the next node on the route to the source to start a route repair procedure.

The route repair is a partial route discovery from the node received the route repair message

to the destination.

In [44], three versions of a routing protocol schemes are introduced. The protocols are

designed assuming that data flows are established between client nodes and the gateway.

Two client nodes will always communicate through their parent gateway. Therefore every

node needs to know a route to the nearest gateway only. The protocol scheme is named mesh

routing protocol (MRP). The first version of the protocol is MRP On-Demand (MRP-OD). A

new node joining the network broadcasts locally (one hop) a route discovery (RDIS) message. All the nodes receiving the RDIS message will reply with a route advertisement (RADV) message with the metrics of their routes to the nearest gateway. The protocol is benefiting from the fact that all connected nodes already know routes to gateways and the significant routing metrics of those routes. If the joining node did not receive an RADV message it will keep sending RDIS messages. Upon reception of RADV messages the node will selects one or more routes according to its QoS requirements. By this way, the setup of the upstream route from the node to the gateway is completed. The return path does not have to be the reverse. Thus a return path discovery is established by sending a registration request RREG from the node to the gateway. When the gateway receives the RREG message it replies by registration acknowledgment (RACK) message. Loss of any of the RREG or RACK requires re-initiation of the discovery process. Upon reception of the RACK the joining node starts sending and receiving from the internet.

If a link loss is suspected, during the transmission and reception of data packets, the node enters a verify-link state. In the verify-link state, the node keeps sending route check (RCHK) packets unicasted to next hop. If a reply is received then the route is working again, otherwise the node switches to a disconnected state. If a node losses its route to the gateway, all its children will lose their route also. Hence when a node losses its connection with the gateway, it sends a route error (RERR) message to all its children. When losing the connection to a gateway, a node, and therefore all its children, will reinitiate a route discovery process.

The second version of MRP is MRB beacon mode (MRP B). Instead of sending RDIS messages to neighbours to discover a route to a gateway, a node listens to periodic beacons sent by nodes in the network to advertise routes. After collecting beacons from neighbours, the route selection and registration proceeds as in MRP-OD. A link loss is determined by missing a predefined number of beacons. This version reduces the delay of route-break detection but increases routing overhead.

The third version is the MRP hybrid (MRB H) which is a combination of the previous two versions. A new node joining the network or returning from a disconnection state sends RDIS messages to discover routes to gateway instead of waiting for the beacons. While a link loss is detected by not receiving a predefined number of beacons. This version has faster route discovery and link failure detection. However, it imposes more routing overhead than the previous two versions.

2.1.2.2 Location-based Routing

For non-position based routing protocols, a routing protocol has to flood the network with route request packets to discover the route to destination. This overhead can be greatly reduced if the node has information about the destination location. In position based routing protocols [45], the source node sends a packet with the destination position contained in its

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header to the closest neighbours to the destination. The neighbours forward the packet to the next closest neighbours to the destination and so on till the packet reaches the destination. The destination can be a single node or a group of nodes in a certain geographic area which is called geocasting [46]. Location information can be gathered using GPS or other position determination devices [47]. A recent protocol [43] used ultra wideband (UWB) technologies to estimate position. In [43], the source node sends a route request packet to discover a route that satisfies the QoS requirements. The packet is sent in the estimated direction to destination as long as the QoS requirements are satisfied. If the QoS requirements are violated a route failure packet is sent to the source node to begin another QoS route discovery.

2.1.2.3 Routing in Differentiated Service Networks

In [49], an architecture for Differentiated services provision in the wireless mesh backbone is discussed. Hai et al. proposes a QoS routing and MAC scheme for WMN backbone routers. They recommend the routing to be class-based. For each traffic class the routing protocol should select routes that satisfy the QoS requirements of that class. They suggest using an on-demand routing protocol similar to AODV to reduce signalling overhead and they assume the network to work with a single channel. This work is preliminary and is an open issue for further research.

Another approach to provide QoS routing is addressed in [48]. The authors divide the network into clusters and suggested the routing to be done on two levels: inter-cluster routing and intra-cluster routing. Inter-cluster routing aims to route data cluster by cluster. While the intra-cluster routing aims to route data inside the cluster. This coarse granularity routing can prove to be efficient in terms of scalability but is worse in terms of interference and thus throughput and delay.

2.1.2.4 Multiple-Constraints Routing

Traffic flows vary in their requirements. Flows can be bandwidth-sensitive requesting a minimum bandwidth or delay-sensitive requesting a maximum delay bound. Others can request for maximum packet loss rate (PLR) bound. Flows requesting multiple QoS metrics guarantees impose more difficulty. Solving a multi-constrained path problem is a NP-complete [49] in many cases such as when the metrics are additive [50]. Even satisfying one constraint may become NP-complete when link interference is taken into consideration [51], [52].

Solving the multi-constrained routing problem in WMNs is addressed in [53]. The authors propose a routing scheme based on Mean Field Network (MFN_RS). The goal is to find a solution for the routing optimization problem using a computational method that is faster than the Simulated Annealing (SA) approach.

The protocol in [43] uses heuristic algorithms to solve the problem. The researchers divide the two-constraint problem into two one-constraint problems. A QoS route discovery is done on two steps. The first is to discover a route that satisfies the packet loss rate (PLR) requirement. The second step is to check if the discovered route satisfies the other requirement which is either bandwidth or delay.

2.1.2.5 Multi-Channel Routing

Multiple channels are presented as a solution for the interference problem. Channels can be orthogonal codes (CDMA) or frequency bands (FDMA). A routing protocol that is built on a multi-channel network is mostly jointed with the channel assignment problem. Channel assignment was investigated in several works [24], [25], [26], [27]. A centralized channel assignment performs better than a distributed one. However it can be a bottleneck in the network.

A Bandwidth Aware Routing (BAR) protocol is presented in [54] following an interference aware channel assignment. The routing protocol guarantees bandwidth for each flow assuming the bandwidth for each link is known. It is assumed that each node is equipped with two network interface cards (NICs). Each NIC is tuned to a different channel. Different nodes use different channels with the constraint that two neighbouring nodes must

have a common channel to communicate. The channel assignment is centralized and static which means that it will last as long as there are no new nodes added to the network.

2.1.2.6 Multi-Path Routing

Multipath routing is used to maximize utilization of network resources. With multipath routing, a node chooses several links (or routes in case of vitual circuit (VC)) for the same destination. If properly managed, it can aggregate resources of multiple paths, increase admission rate, increase throughput and improve reliability.

The design of a multipath protocol requires much care about routing overhead and coordination among neighbouring flows. The protocol proposed in [55] limits the number of multiple paths to a number specified by the flow. The protocol, named *multi-path dynamic source routing protocol (MP-DSR)*, is based on the existing Dynamic Source Routing protocol (DSR) and takes advantage of its distributed on-demand nature. It seeks to compute a set of unicast disjoint routes that can satisfy a minimum *end-to-end reliability* requirement.

The path reliability is calculated based on the link availabilities of all links along a path. Link availability is defined as the probability that a link is available for a defined period of time. The calculation of link availability is based on the node's movement; a constraint which is not found in WMNs.

The same approach of path limiting is addressed in [56]. Chen et al. proposes a *ticket based multipath routing.* The source node issues probes to discover routes. Each probe is assigned a number of tickets that is equal to the number of required multiple paths. The number of tickets is related to the stringency of the constraint requirements.

2.2 Power Allocation

As the wireless routers in the WMN are not battery-powered, power allocation becomes an important factor in designing a routing protocol. It provides an additional degree of freedom beside the traditional frequency, time and code degrees. Power allocation has been investigated in different research works related to routing problems in WMNs. We classify these protocols into those that concern about saving power and others that use the available power constrained only by the maximum limit.

2.2.1 Power Saving Techniques

Many proposals have been developed that aim at saving power [57], [58], [59]. Reducing both energy and interference is the target of the work done in [57]. The authors discusses the topology control techniques developed in the literature of ad-hoc and sensor networks. They prove that topology control though reduces energy but is not enough to reduce interference. They propose an interference-minimum construction that preserves connectivity of the nodes and provide paths that are longer by a constant factor than the shortest paths in the original

network. In [60], the authors assume a conflict free medium access on which they implement their energy-efficient QoS topology control. They accommodate traffic flows according to the capacity available after applying their energy saving algorithm.

All these works concern about saving energy which limit the QoS satisfaction for the flows in the network. This is acceptable in a network with battery-powered nodes such as in ad-hoc or sensor networks. However, in WMNs the concern is directed towards increasing the network capacity while satisfying the QoS requirements.

2.2.2 Using Available Power

An early work for adjusting transmission power in wireless networks is presented in [61]. The work provides an analytical model to adjust the transmission power for slotted ALOHA packet radio networks for the sake of reducing interference. Three different methods for allocating the power are studied in [61]. The first one is the shortest-hop allocation, which implies the power is allocated just to reach the closest neighbor (shortest hop). The second method allocates the power to reach the longest hop within the transmission range and the third uses the maximum power. It has been shown that the second method causes the smallest interference compared to the other two.

The advantage of these methods is their simplicity. Little computation is required to decide for the next node to receive the packets. The disadvantage can be seen in ignoring the traffic load in computing the relay node. In the three strategies, traffic load is not taken into consideration. In addition, the decision is either the farthest or the nearest, neglecting the

chance of having better decision for an intermediate relay node. This work is done for best effort traffic.

In [62], maximum power allocation is used in order to achieve opportunistic routing. Using a high transmission power enables transmitting to far nodes in one hop. All the nodes (routers) in the transmission range of the transmitting node receive a copy of the transmitted packet. Some may not receive the packet successfully due to wireless channel impairments such as fading and interference. Therefore, the receiver nodes agree on one of them to be the next node in the path and forward a received packet in a similar way till reaching the destination. This work mainly addresses the link quality problem without any QoS considerations.

Wei et al. [63] introduces an interference-aware routing algorithm and a centralized TDMA scheduling scheme. The work in [63] aims at achieving high channel utilization by minimizing the interference. However, it does not address QoS issues in the route construction or in the scheduling scheme.

Tao et al. [64] proposes an algorithm for centralized scheduling and routing using concurrent transmissions. However, the algorithm is based on routing trees where the route of the tree is the centralized controller. This implies that some mesh routers can communicate only to reach others via the controller, which indicates a potential single point of failure in the network. In addition, the paper does not address the QoS issues.

2.3 Summary

In this chapter, we present and discuss the routing protocols developed for the WMNs and the power allocation techniques related to our work. The work done focuses on increasing the network capacity which is achieved by avoiding or reducing interference. Approaches to reduce interference include using multiple channels, directional antennas or properly managing the media in the case of a single channel by introducing new metrics. Most work done addresses the best-effort traffic. Satisfying QoS requirements for the traffic increases the complexity of the problem.

It has been shown that despite the diversity and richness of work done, the existing work does not fully address the unique characteristics of WMNs, mainly: transmission power availability (up to maximum power) and stationary property of the wireless routers. We aim to make use of these characteristics to support QoS routing in WMNs.

Chapter 3

System Model

The network under consideration consists of 25 routers connected to each other through wireless links. The routers are distributed in a grid topology on an area of 1500 m^2. The location of sources and destinations are randomly chosen. Each node (router) knows its location and can adjust its transmission power to any value between zero and its maximum power level P_{max}. We assume line-of-sight (LOS) transmission is available in all backbone links and also in all access links (between mesh routers and mesh clients).

All the backbone wireless router transceivers are assumed to work in a half-duplex manner; they cannot send and receive at the same time.

3.1 Path Loss Model

Since all the backbone and the access links are static, it is reasonable to assume a free space path loss model. At any distance d from the transmitter, the path loss $P_L(d)$ at a particular location is random and distributed log-normally (normal in decibel units, dB) about the mean distance-dependent value [65]. That is

$$P_L(d)[dB] = \overline{P_L}(d) + X_\sigma = \overline{P_L}(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma$$

where $\overline{P_L}(d)$ is the path loss due to distance, X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB), d_0 is a close-in reference distance (close to the transmitter) and n is the path loss exponent which indicates the rate at which the path loss increases with distance. The distance-dependent path loss can be calculated using the formula

$$\overline{P_L}(d) = -10\log\left(\frac{G_t G_r \lambda^2}{L(4\pi)^2 d^2}\right), \quad \lambda = \frac{c}{f}$$

where G_t and G_r are the transmitter gain and receiver gain respectively, L is the system hardware losses, c is the speed of light, f is the carrier frequency. The signal power received at the receiver, P_r, can then be calculated using the formula

$$P_r(d)[dBm] = P_t[dBm] - P_L(d)[dBm]$$

where P_t is the signal power at the transmitter (in decibel milliwatt, dBm) and d is the distance between transmitter and receiver.

In order to define a path loss for a link, we will use a slightly different notation which is the path gain G. We will define path gain for each pair of transmitter-receiver. Therefore, for a transmitter $T(l)$ of link l and a receiver $R(l)$ of link l, we have a path gain $G(T(l),R(l))$. With this notation, we can define the signal-to-noise-plus-interference ratio for a link l to be

$$SINR(l) = \frac{G(T(l),R(l))P(T(l))}{\sum_{k \in L, k \neq l} G(T(k),R(l))P(T(k)) + N_0}$$

where N_0 is the thermal noise power at the receiver which is normally considered to be constant, and $G(T(k),R(l))$ is the path gain between the transmitter of link k and receiver of link l.

3.2 Traffic Model

Since a wireless mesh backbone connects different networks such as cellular, IEEE 802.11, IEEE 802.15 and sensor networks, it is expected to have traffic with different characteristics and different QoS requirements. Each router has traffic flows aggregated from different sources and going to different destinations. The packet traffic often follows an on-off behaviour. During the on period a burst of packets is generated. The distribution of on and off periods is the burst level description of the traffic. For example voice-packets' modelling assumes on and off periods to be exponentially distributed.

Packet level description of the traffic, such as packet arrival and packet size, is of more complexity due to the many factors affecting it including different applications, users' profiles and network protocols. Traditional modeling assumes a Poisson process or periodical arrival for the packets. However, it is found in [66] that these models are not accurate for aggregate traffic. It is found in [67], through real measurement and statistical analysis of traffic data gathered from wide area network (WAN) and Ethernet, that the aggregate packet arrivals from multiple sources can be well modelled by self-similar processes with long range dependence and heavy-tailed distribution. A self-similar model for traffic means that a

segment of the traffic at sometime scale looks or behaves just like an appropriately scaled version of the traffic measured over a different time scale.

Several processes can be used to generate the self-similar traffic. In [66], an M/G/∞ queue model is suggested for generating self-similar traffic. In [68], it is proved that self-similar traffic can be generated by superposition of multiple i.i.d. on-off sources which have a heavy tailed distribution with infinite variance for the on and off periods. The work done in [69] proves through real measurement and statistical analysis that self-similar nature is found to exist in cellular networks with mobile nodes. In [70], the author proves that using a Markov Modulated Poisson Process (MMPP) for modelling the traffic accurately approximates the characteristics of Internet traffic.

No work so far, until this thesis was written, had been done to model the aggregate traffic in wireless mesh networks. We will assume that the traffic follows an MMPP model with ON and OFF periods following an exponential distribution. The probability to switch from the ON to the OFF period is α, and that from the OFF to the ON is β. Packets arrival during the ON period is a poisson process with arrival rate λ. The arrival rate varies for each traffic flow and for different experiments.

The following figure shows the 2-state Markov model used for packet arrival. During the ON period, a series of packets are generated. In the OFF period, no packets are generated.

Duration of each ON and OFF period is estimated by independent exponential laws of parameters α and β. The mean duration of the ON period (T_{on}) and the OFF period (T_{off}) periods are $T_{on} = \dfrac{1}{\alpha}$ and $T_{off} = \dfrac{1}{\beta}$
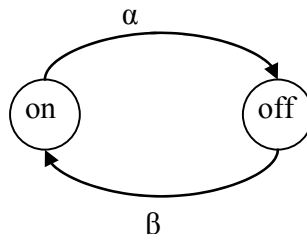
Figure 3.1: The on-off traffic Model

The activity factor for the packets' source can be calculated as

$$\text{Activity factor} = \frac{T_{on}}{T_{on} + T_{off}} = \frac{\beta}{\alpha + \beta}$$

We consider two different classes of service with different end-to-end delay bound requirements $D_r(1)$ and $D_r(2)$. The two classes also have different SINR requirements, *SINR(1)* and *SINR(2)* respectively, at each link so their data can be decoded correctly (with sufficient bit error rate) at each forwarding hop. We assume that the data will be decoded at each forwarding hop and then re-sent so the bit error rate will not be accumulated over the whole route causing severe degradation in the SINR at the final destination.

3.3 Medium access

We consider a centralized control TDMA MAC protocol. The control is done by one of the wireless routers with special capabilities. The exchange of control information is done by direct communication between the routers and the controller for specific or common control messages. However, for data transmission, all the routers communicate directly with each other in an peer-to-peer manner.

In the TDMA-based MAC, time is partitioned to fixed length frames. The frame structure contains a beacon period (control sub-frame) in addition to the contention-free period (data sub-frame), which is partitioned to time slots with equal duration. The controller allocates the time slots and the power for each wireless router via signaling messages broadcast on the beacon period. We assume the controller is aware of its location and the location of each wireless router.

The time frame structure is shown in figure 2 where the frame is divided into two sub-frames: a control sub-frame and a data sub-frame. The control sub-frame is where the communication control part takes place. This includes synchronization of slots and frames, clustering, routing messages, power measurement, VC setup, ACKs, etc.
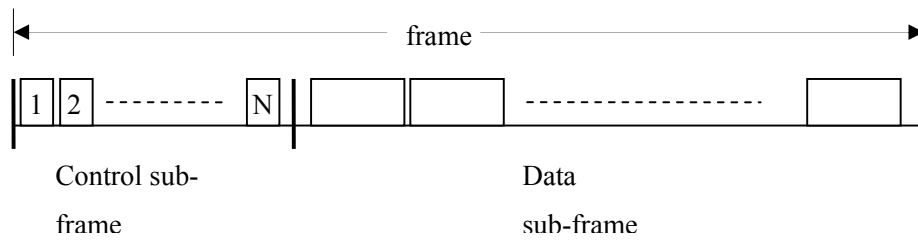
Figure 3.2: Time frame structure

At the end of the control sub-frame, each node has learned the data slots assigned to it. In order to support real-time traffic, data slots must be reserved prior to the data sub-frame. The number of data slots is determined according to the bandwidth requirement of the traffic flows.

3.4 Effective Bandwidth and Admission Control

An important approach that is considered in the admission control for multiplexing variable bit rate (VBR) traffic is the effective bandwidth. It captures the statistical multiplexing gain achieved from aggregating a large number of bursty sources. Given the traffic characteristics of each source and its QoS requirements, we can obtain the relation between the required capacity, C_L, and the number of sources to be admitted, N_s. The effective bandwidth

$B_E = \dfrac{C_L}{N_s}$ ranges between the peak rate and the average rate to achieve a balance between

QoS assurance and high utilization.

We use simulation to find the effective bandwidth that achieves the acceptable packet loss rate for all the traffic flows.

3.5 Summary

In this chapter, we propose a network model to provide QoS for VBR traffic. The network is assumed to be clustered. Each cluster is managed by the cluster head. A deterministic TDMA is used to take advantage of the interference-free medium. A transmitted signal is subject to free-space path loss which is a function of the distance the signal travels. Packet arrivals follow an MMPP model in which there are 2 states: ON and OFF state. During the ON state, inter-arrival times between packets follow an exponential distribution.

Chapter 4

Problem Formulation

In this chapter, we present our formulation for the joint routing and link scheduling problem. We first define some variables that will be used in the formulation. Then the problem is formulated as an optimization problem.

4.1 Variable Definition

The variables used in the formulation are as follows:

(i)   A route $r \in R$, where R is the set of all routes in the network, consists of L_r links. Any two subsequent links cannot be active at the same time because each node has only one transceiver.

(ii)   Each route r has a maximum end-to-end delay requirement D_r. to each of its packets. The end-to-end delay of a packet is the time it takes to travel from the source node to the destination node including intermediate links' transmission delays and nodes' queuing delays. Each link transmission delay equals the reciprocal of the link bandwidth (data transmission rate) which is constant. For the estimation of queuing delay, we use the average queuing delay at each node. Because we have fixed packet size and frame size, the M/D/1 can be used to

model the queues in our network [1]. Therefore the average waiting time for a packet in a queue, d_q can be calculated as

$$d_q(\lambda) = \frac{t_s(1 - \lambda t_s / 2)}{1 - \lambda t_s}$$

where t_s is the service time, and λ is the arrival rate.

(iii)   *A(l,s)* is a binary variable which is equal to 1 if link *l* is active in time slot *s*; otherwise, it is 0.

(iv)   A set *L* of wireless links connects the nodes of the network. A link $l \in L$ can be represented by its two nodes *l = (T(l), R(l))*, where *T(l)* is the transmitter node, and *R(l)* is the receiver node. The transmitter node *T(l)* uses a power *P(T(l))* to transmit on link *l*. The path gain for link *l* is given by *G(T(l),R(l))*, and models the transmitter and the receiver amplification gains, as well as the attenuation of the signal due to distance, fading and shadowing.

(v) P_{min} is the minimum power required to transmit a signal on a link given the link distance and the sensibility of the receiver. P_{max} is the maximum transmission power.

4.2 Problem Formulation

The problem is divided into two parts; the first part is obtaining all combinations of all the possible routes for all source-destination pairs; the second part is to solve the link scheduling problem for each combination of routes which is then used to find the best combination. The first part is very time consuming and requires a heuristic to reduce its large time complexity. The second part is formulated by an optimization problem and can be solved in a reasonable time (hundreds of milliseconds to few seconds) on current computers' configuration. We start our problem formulation by presenting the optimization problem to solve for the link scheduling. After that, we discuss the heuristic we used to reduce the time complexity of finding the best combination of routes.

The link scheduling problem can be formulated as:

$$\text{maximize } \frac{1}{S.t_s} \sum_{l=1}^{L} \sum_{s=1}^{S} A(l,s) \tag{6}$$

subject to

$$\sum_{l \in L_r} (t_s + d_q) \leq D_r \, ; \forall r \in R \tag{7}$$

$$SINR(l,s) = \frac{G(T(l),R(l))A(l,s)P(T(l))}{\sum_{k \in L, k \neq l} G(T(k),R(l))A(k,s)P(T(k)) + N_0} \geq h_r \tag{8}$$

where h_r is the *SINR* threshold for route r, and N_0 is the white noise power

$$A(l,s)P_{\min} \leq P(l,s) \leq A(l,s)P_{\max} ; \forall l \in L \qquad (9)$$

$$\sum_{\{i,j\}\in L} A(\{i,j\},s) + \sum_{\{j,k\}\in L} A(\{j,k\},s) \leq 1 \qquad (10)$$

$$\sum_{\{i,j\}\in L} A(\{i,j\},s) \geq 1 \qquad (11)$$

$$A(l,s) \in \{0,1\}; \forall l \in L \qquad (12)$$

The objective function is the maximization of the average network throughput, where S is the number of slots in one frame, L is the set of all links in the network, and t_s is the duration of one time slot. Constraint (7) is the delay constraint. Each link delay is the summation of transmission and queuing delays. The constraint ensures that the summation of delays over all the links of one route (flow) during the slots allocated to that route does not exceed the delay bound. Constraint (8) ensures that the signal to interference noise ratio (SINR) is greater than the required threshold. Constraint (9) is the upper and lower bound for the link power. Constraint (10) ensures that no two links having a common node can be active at the same time slot. Constraint (11) states that at least there should be one link active given that the packet queue is not empty.

4.3 Reducing problem complexity

The problem is a mixed integer non-linear programming (MINLP) problem which is difficult to solve and takes too long time for a large number of links in the network; therefore, in order to reduce the time to solve the problem, we take two consecutive steps: the first step is to remove the non-linearity of the problem; and the second is to find a heuristic to reduce the search time in the solution set.

4.3.1 First step: linearization

Looking into the problem formulation, we can find that *SINR* constraint is the only one that introduces non-linearity; this is due to the presence of the product of the two variables, the link binary variable and the link power variable. A common way to eliminate the non-linearity of this kind is to use the big-M method [3]. The SINR constraint should be verified if the link explored is active, otherwise it should be redundant. This can be formulated as follows:

$$G(T(l), R(l))P(T(l)) \geq h(\sum_{k \in L, k \neq l} G(T(k), R(l))P(T(k)) + N_0) - M(1 - A(l,s))$$

where *M* is a big positive number; if the link *l* is active at slot *s*, then *A(l,s)*=1 and the second term in the right hand side is of zero value; however, if link *l* is not active, then *A(l,s)*=0 and the second term of the right hand side is of a very large value that the formula will be verified

in all cases. Since variables are not multiplied by each other, the formula is linear and hence of lower complexity than the original one.

4.3.2 Second step: Finding a heuristic

A heuristic is a technique used to solve a problem with a high computational complexity in a reasonable time but without guaranteeing to achieve the best solution. One of the wide-spread techniques is the genetic algorithm.

A Genetic Algorithm (GA) is a search technique. It is mainly used as a heuristic to find sub-optimal solutions from within a large set of possible solutions in a reasonable time. A GA involves operations that help evolve towards better solutions. It starts by selecting an initial population of chromosomes representing a subset of the large set of all possible solutions. Each of the population chromosomes is evaluated using a fitness function that is defined according to the problem. Some of the chromosomes are selected from the population to undergo a crossover operation. This operation results in new chromosomes that inherit the characteristics of its parents. A mutation operation may occur according to some probability which alters one of the chromosomes to yield a slightly different new chromosome. These operations are repeated for several generations till we are satisfied about the fitness of the last generation. The chromosome with the highest fitness value in the last generation is the best solution obtained from the algorithm.

4.4 Mapping to our routing problem

Our problem is to find the best set of routes for all source-destination pairs that maximize the network throughput. Each chromosome represents a set of possible source-destination routes, one route for each source-destination. A gene in the chromosome represents a node ID; therefore, the chromosome is a chain of node IDs that constitute the different routes of the network. A set of possible solutions are chosen randomly from the set of all possible solutions to produce the initial population. Operations that are done on the population are selection, crossover, and mutation. The generation is then evaluated and the process is repeated.

4.4.1 Selection

Two chromosomes are selected using the roulette-wheel selection to undergo a crossover operation. The roulette-wheel selection selects chromosomes in proportion to their fitness value; the more the fitness value, the more the chance to be selected. In order to achieve that, all the population chromosomes are evaluated using the fitness function. The probability of selecting chromosome i with fitness value f_i is thus

$$p_i = \frac{f_i}{\sum\limits_{j-1}^{N_p} f_i}$$

where N_p is the population size.

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4.4.2 Reproduction (Crossover)

Each two selected chromosomes are then combined to generate two new chromosomes. A part of one chromosome that is selected randomly is replaced by another random part from the other chromosome and the same for the other chromosome. The new chromosomes are validated so that they do not evolve to an unfeasible solution. Then they are evaluated and join the population only if they have a fitness value that is higher than then the smallest fitness value of the population. By doing that, we guarantee that the crossover operation does not worse the population fitness; either improves or leaves it as it is. The two new chromosomes, then, replace the least-fitness chromosomes in the population so that the population size remains constant.

4.4.3 Mutation

Mutation is the process of altering a gene (a node ID) so that it becomes any other valid gene (another node ID). This operation helps in introducing new solutions that may not be reached through crossover operations. We perform mutation with a probability of 0.1; a typical value as mentioned in [75]. The gene is selected randomly (uniform random) from all the genes in the chromosomes other than the first and last gene of each route (source and destination).

Solution steps

We assume our network to be a cluster within a clustered network. The optimization problem

is to be solved in the cluster head which acts as a controller for its cluster. The results are sent

to the cluster members to act upon. The cluster controller collects the required information

(QoS requirements(delay, SINR), traffic rate) from its cluster members and from other

clusters through communication with the other cluster controllers.

The following procedure describes our framework:

1. The controller polls the other routers in its cluster and the other cluster controllers via
   signaling messages to get the location information and QoS parameters. The location
   information is acquired for new members only since the network members are static. The
   current source routers aggregate the traffic from the mesh clients connected to them based on
   the class of service required. Then, they respond to the network controller by appropriate
   signaling message with the required information.

2. Based on the location information of the routers and the maximum power P_{max}, the controller
   obtains all the possible routes for each source router according to the distance between this
   router and the other routers.

3. The controller tries the possible combinations of the different routes of all the source routers.
   It tries to find the links slot scheduling (which links can be active at each slot) and also the
   combination of routes that satisfies the QoS requirements and maximizes the network
   throughput. At each combination and for every time slot, all the links that can operate
   simultaneously are selected taking into consideration that consecutive links from the route

cannot work simultaneously in the same time slot. The links that can share a certain time slot are selected based on the SINR value at each receiver of these links.

4. The different combinations are compared and the combination that maximizes the network throughput is selected by the controller.

5. The routes information together with the links' schedule is sent to the nodes participating in the process to begin transmitting at the next data slot.

6. In order to admit any new mesh client, the controller goes again to Step 3 until no other flows from any service class can be admitted, which implies that the maximum possible number of flows is reached.

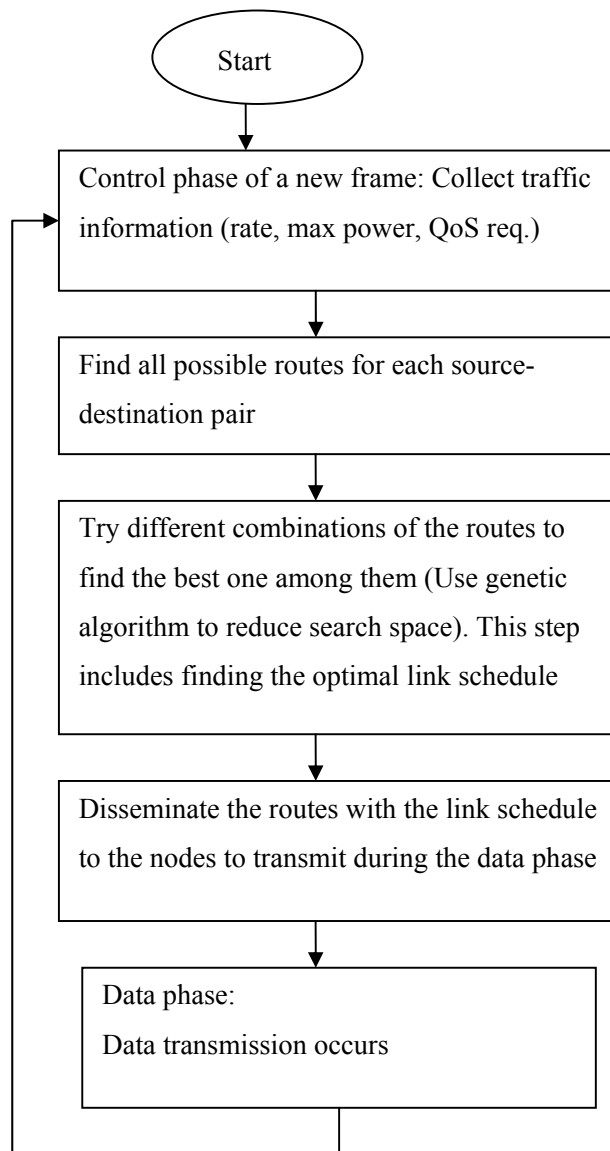Figure 4.1 is a flow chart that summarizes the previous steps.

```
                    ┌─────────────┐
                    │    Start    │
                    └──────┬──────┘
                           │
                           ▼
        ┌──────────────────────────────────────────┐
        │ Control phase of a new frame: Collect traffic │
   ┌───▶│ information (rate, max power, QoS req.)    │
   │    └──────────────────┬───────────────────────┘
   │                       │
   │                       ▼
   │    ┌──────────────────────────────────────────┐
   │    │ Find all possible routes for each source- │
   │    │ destination pair                          │
   │    └──────────────────┬───────────────────────┘
   │                       │
   │                       ▼
   │    ┌──────────────────────────────────────────┐
   │    │ Try different combinations of the routes to │
   │    │ find the best one among them (Use genetic │
   │    │ algorithm to reduce search space). This step │
   │    │ includes finding the optimal link schedule │
   │    └──────────────────┬───────────────────────┘
   │                       │
   │                       ▼
   │    ┌──────────────────────────────────────────┐
   │    │ Disseminate the routes with the link schedule │
   │    │ to the nodes to transmit during the data phase │
   │    └──────────────────┬───────────────────────┘
   │                       │
   │                       ▼
   │       ┌───────────────────────────────────────┐
   │       │ Data phase:                           │
   │       │ Data transmission occurs              │
   │       └───────────────┬───────────────────────┘
   │                       │
   └───────────────────────┘
```

Figure 4.1: Flow chart of solution procedure

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Chapter 5

Simulation and Results

In our simulations, we consider a network cluster of 25 static nodes in a 1500x1500 m^2 area. We assume the carrier frequency to be 2.4 GHz. Speed of light is $3x10^6$m/s. The transmitter and receiver amplification gains are 100 each; therefore, a link of distance d has a link gain (path loss) of

$$G = 100x100x\left(\frac{3x10^8}{4x3.14x2.4x10^9}\right)^2 \frac{1}{d^2}$$

The ambient thermal noise at each node $N_0 = 10^{-12}$ W. The minimum *SINR* threshold h=10. The maximum transmission power P_{max} = 300 mW. Simulation run-time is 100,000 time slots. Receiver sensibility is -120 dB. The delay requirement of each route, D_r, is a random integer.

We compute optimal solutions by simulating the network in Matlab and solving the optimization problem using lpsolve [2].

5.1 Experiment 1

In this experiment, we consider the 25 nodes to be randomly distributed over an area of 1500m^2. We randomly set 12 source-destination pairs in the network. Traffic sources are modulated as a Markov-modulated Poisson Process (MMPP) with ON and OFF states. Transition probabilities are 0.1 from the ON to OFF state and 0.9 from the OFF to the ON state. During the ON state, packet arrivals are modeled by a Poisson process. The Twelve traffic flows vary in their average arrival rate and bandwidth requirement. Several runs are performed to find the average packet losses. Packet losses occur due to the buffer overflow and packets' delay expiration. Packet queue at each node can store up to 50 packets. Simulation time is 100,000 time slots. Delay deadlines are set to be equal to double the average inter-arrival time, i.e. a packet can wait for only 2 packets' average arrival. Results are represented as per the traffic load. Traffic load is defined to be the ratio of total average bandwidth of all traffic to the network bandwidth, or in mathematical notation

$$Load = \frac{\sum_{f=1}^{F} B_f}{C}$$

where B_f is the estimated average bandwidth for flow f, F is the set of all flows, and C is the network bandwidth.
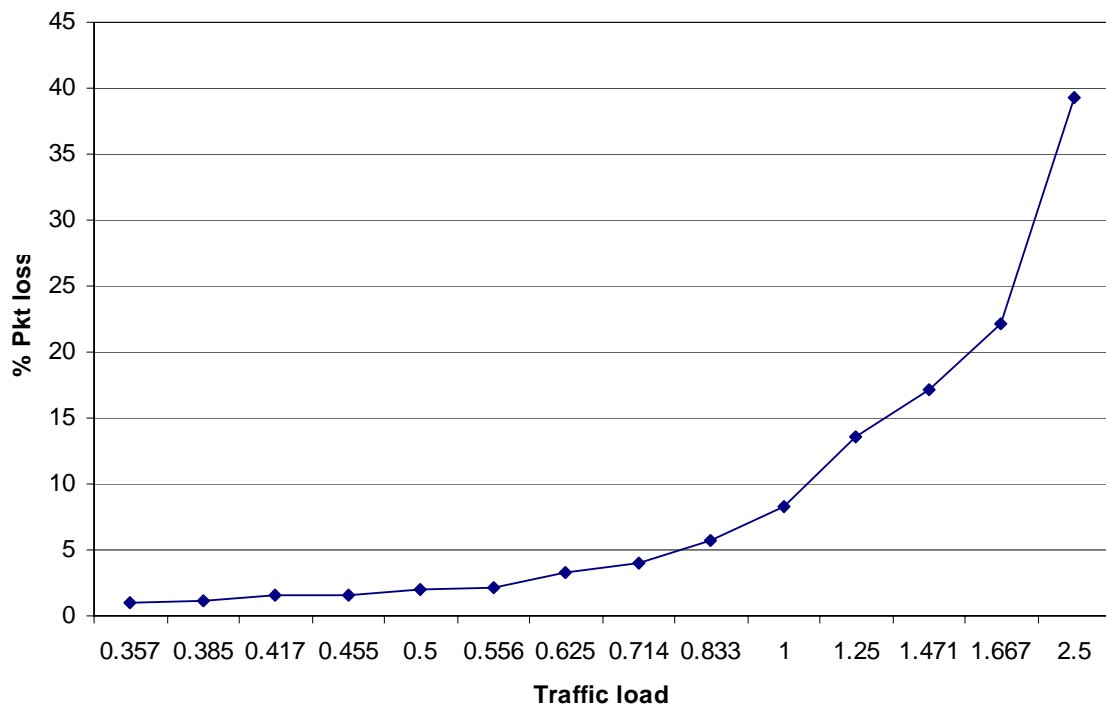
Figure 5.1: Percentage of packet Loss vs traffic load

It can be seen from the figure that packet losses exist in all traffic load values even in the light traffic loads; this can be justified by the fluctuation of the packet arrival around its average arrival times.

In the figure, it is shown that at a unity traffic load, i.e. the network bandwidth is equal to the total average bandwidth of all flows, the flows experiences a packet loss of about 8.5%. It is up to the flows' sources to specify the acceptable loss rate. If the loss rate required is less than 8.5% (assuming all flows have the same packet loss requirement) then we should go

further left in the traffic load access, which means the effective bandwidth is going towards the peak rate of the flows.

5.2 Experiment 2: Frequency Reuse

In this experiment, we run several runs with different number of flows (source-destination pairs). In each run, we calculate the number of active links working in one frame. We define the frequency re-use index to be the number of active links in one frame divided by the number of slots in one frame. The simulation results are shown in figure 5.2.

It can be noticed that the trend of the frequency reuse index is to increase by increasing the number of running flows in the network. This can be justified by the tendency of the flows to have shorter hops which is illustrated in figure 5.3. When the number of flows increases in the network, and hence the number of links, over the same network area, it becomes difficult to run more links simultaneously; thus, frequency re-use is seen to stabilize at the higher number of flows.
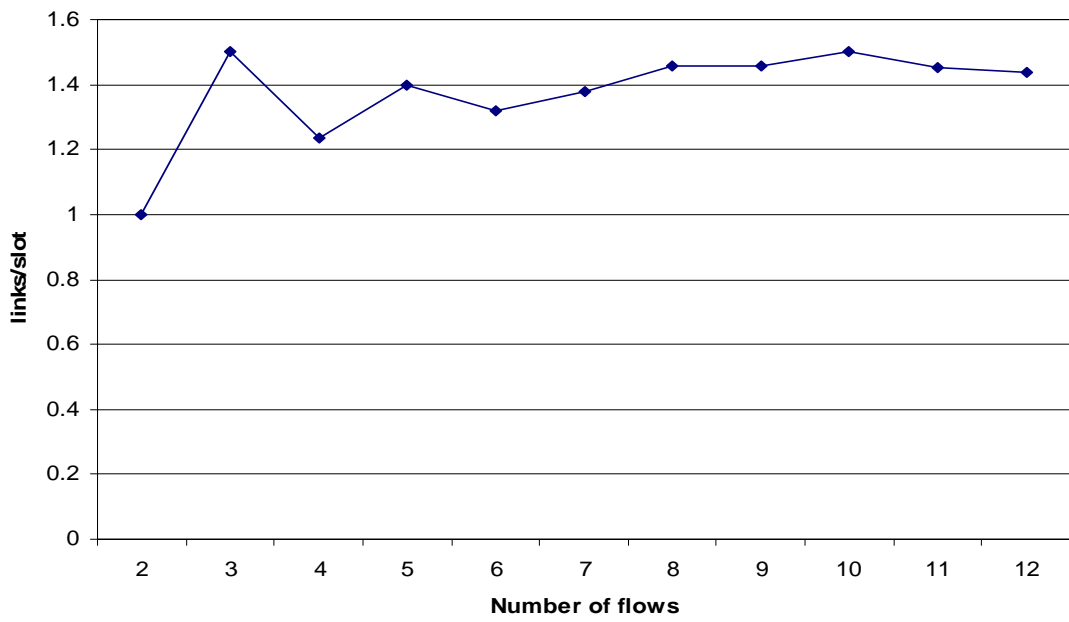
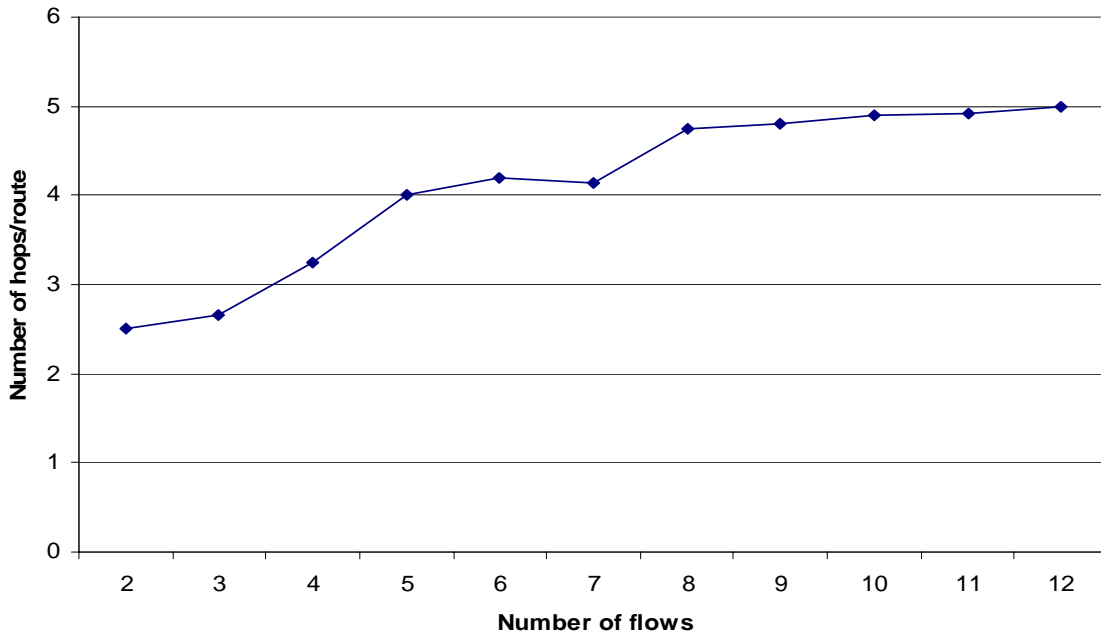**Figure 5.2: Frequency re-use index**

Figure 5.3: Average number of hops per route

It is observed that by increasing the flows in the network, flows tend to have more links. This is due to the tendency to have shorter hops in crowded networks.

5.3 Experiment 3: Maximum throughput versus Minimum power

In this experiment, we compare the results of the maximum-throughput algorithm to that of a power-saving algorithm in terms of packet loss. Both algorithms satisfy the QoS requirements. Results are shown in figures 5.4 and 5.5.
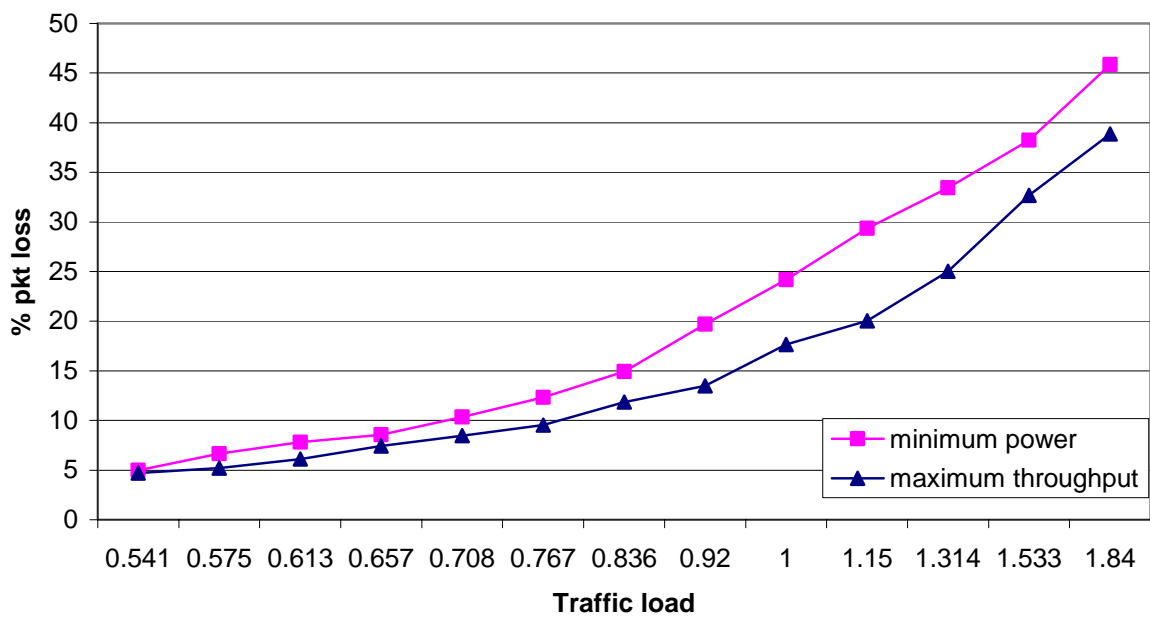

Figure 5.4: Packet loss of minimum power and maximum throughput

It can be seen from the figure that maximizing the throughput results in a packet loss decrease of about 5% than that of minimizing power; the same applies for throughput. We should note that this performance is achieved by consuming more power which is not a main concern in the wireless mesh network.

5.4 Summary

We conduct three experiments to evaluate the performance of our proposed algorithm. The first experiment shows the packet losses for a network of 25 nodes and 12 source-destination flows chosen randomly versus the traffic load. From the first experiment, we can calculate the effective bandwidth given the acceptable packet loss rate for each traffic flow in the network with homogeneous traffic.

The second experiment shows the effect of adding more flows to the network on the frequency re-use index. It is found that the frequency re-use index increases by increasing the number of flows in the network up to some point where the network saturates and there is no room for more links to work simultaneously. Also in this experiment, it is shown that the number of hops per route increases by increasing the number of flows in the network. This indicates the tendency of the routes to have shorter links to reduce interference.

The third experiment shows the results of the comparison between maximizing throughput and minimizing power on the packet throughput and loss rate. It is found that the maximizing throughput approach outperforms the minimizing power approach in terms of packet loss rate

and consequently in network throughput. These improvements are on the account of

consuming more power which is not an issue in our case of a network with stationary nodes.

Chapter 6

Conclusions and Future Work

WMNs are envisioned as a key solution to the increasing demand on multimedia networking and providing broadband access. The lower cost and easier installation of the WMNs than the wireline counterpart pushes industry and academia to pay more attention to this promising technology. Most of the work done focused on increasing the network capacity for best effort traffic. Few works have been done for satisfying the QoS and many research areas are still open in all the network stack layers.

We focus on the network layer to find the best routes and links' schedule for all the traffic flows in the network subject to the constraint of satisfying their QoS requirements. We consider TDMA in the medium access layer. The QoS requirements are in terms of delay and signal to noise plus interference ratio. We formulate an optimization problem to solve for the link schedule. The problem is a mixed integer and non-linear which is difficult to solve. We simplify the problem to a mixed integer problem using one of the optimization techniques. We use genetic algorithm to search for the best routes since finding the optimal routes is very time consuming.

Our results show that routes tend to have fewer hops from the source to the destination in order to maximize the network throughput. While in case of increasing the network flows, routes tend to have more hops with shorter lengths to reduce interference and allow for frequency re-use. Frequency re-use is shown to increase with the number of flows in the network up to some point where the network is found to be saturated and there is no space for more links to work simultaneously.

Another experiment is conducted to compare the results of maximizing the network throughput with minimizing the power of the nodes. The results are shown for two metrics: the network throughput and the packet loss rate. It is shown that the former outperforms the later due to its usage of the power relaxation property.

This work is done using a centralized controller which is considered to be a cluster head in a clustered network. An important extension to this work is to find a distributed implementation. In addition scalability of the network is worth to be addressed. We notice that by increasing the network size and number of flows in the network, calculations are getting more complex and require a long time to solve. In that case, a heuristic to reduce the complexity is required. The heuristic may decrease the accuracy of the results, which is acceptable to allow for large networks to be tested.

In our implementation, we use a genetic algorithm to reduce the complexity of finding the routes. We set the parameters of the genetic algorithm according to previous works done in the routing problem. However, in order to obtain better results, more research work has to be done to adjust the parameters specifically for this problem.

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