Interference-Aware Routing in Wireless Mesh Networks

by

Sonia Waharte

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Abstract

User demand for seamless connectivity has encouraged the development of alternatives to traditional communications infrastructure networks. Potential solutions have to be low-cost, easily deployable and adaptive to the environment. One approach that has gained tremendous attention over the past few years is the deployment of a backbone of access points wirelessly interconnected, allowing users to access the wired infrastructure via wireless multi-hop communication. Wireless Mesh Networks (WMN) fall into this category and constitute a technology that could revolutionize the way wireless network access is provided. However, limited transfer capacity and interference resulting from the shared nature of the transmission medium will prevent widespread deployment if the network performance does not meet users' expectations. It is therefore imperative to provide efficient mechanisms for such networks.

Resource management encompasses a number of different issues, including routing. Although a profusion of routing mechanisms have been proposed for other wireless technologies, the unique characteristics of WMNs (i.e. fixed wireless backbone, with the possibility to embed multiple interfaces) prevent their straight forward adoption in WMNs. Moreover, the severe performance degradations that can result from the interference generated by concurrent data transmissions and environmental noise call for the development of interference-aware routing mechanisms.

In this thesis, we investigated the impact of interference on the network performance of wireless mesh networks. We designed algorithms to associate routers to gateways that minimize the interference level in single-channel and multi-channel networks. We then studied the performance of existing routing metrics and their suitability for mesh networks. As a result of this analysis, we designed a novel routing metric and showed its benefits over existing ones. Finally, we provided an analytical evaluation of the probability of finding two non interfering paths given a network topology.

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I am deeply thankful to my supervisor Raouf Boutaba for his support, advice and encouragement through all these years. He let me the freedom to explore diverse research subjects and showed me that academic life can be both challenging and rewarding. I would also like to thank my committee members for their valuable time and comments on my research work.

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Chapter 1

Introduction

Extending high-speed IP connectivity to the “last mile” is an open and on-going research problem with no satisfactory solution. A number of potential solutions have been proposed, including full end-to-end optical networks and wireless access networks. However, deploying these networks requires the installation of a large amount of wire/fibre. The initial investment costs for deployment, and the difficulty of deployment in some environment settings (established urban areas, wilderness, etc.), have prevented the widespread realization of such access networks.

Wireless Mesh Networks (WMNs), consisting of wireless access networks interconnected by a wireless backbone, present an attractive alternative. Compared to optical networks, WMNs have low investment overhead and can be rapidly deployed. The wireless infrastructure is self-organizing, self-optimizing, and fault tolerant. It can extend IP connectivity to regions otherwise unreachable by any single access technology. To foster the deployment of WMNs, a clear understanding of their characteristics is necessary. It is also crucial to realize that the design of resource management and service provisioning mechanisms are of paramount importance to cope with consumers' increasing demands for quality-of-service (QoS). Delivering on QoS requires efficient resource management framework, including an effective routing protocol. The multihop wireless nature of a WMN demands a different approach to routing from conventional wireless access networks. It has much more in common with the ad hoc and sensor network fields. However, the overall properties of the individual nodes and the overall network are very different in many ways.

The focus of this thesis is to provide efficient routing mechanisms for Wireless Mesh Networks. We show that better resource usage can be achieved if interference is taken into account in the design of routing mechanisms. We study in this context how to route traffic flows from routers to gateways. We also derive an interference-aware routing metric. Finally we investigate the benefits of single path routing versus multipath routing.

The organization of the rest of this chapter is as follows. We present in Section 1.1 some background information on Wireless Mesh Networks and position them among the set of existing wired and wireless technologies. In Section 1.2, we describe the challenges inherent to routing in WMNs. The contributions of this thesis are listed in Section 1.3. Finally, the organization of the thesis is outlined in Section 1.4.

1.1 High-Capacity Last Mile Access Networks

The growing demand for fast, low latency and high volume data communication to homes and businesses has made the economical distribution and delivery of digital information increasingly important. With the widespread adoption of the Internet, the need to provide high speed access to end-users located at millions of different locations becomes even more pressing. Among all the steps involved in the data delivery process, one major challenge is to find cost-effective solutions to provide last mile connectivity between a communications provider and a customer.

Existing last mile delivery solutions include wired and wireless systems. Wired systems such as full end-to-end optical networks are often impractical as they usually require the installation and maintenance of a large amount of wire and fibre. In addition, deploying a wired network in some environments such as urban areas or wilderness can turn into an arduous and expensive operation. Wireless technologies such as satellite or cellular networks are also costly options that involve high up-front investments. Satellite networks present the additional drawback of demanding a long deployment phase. Moreover, the high latency in satellite connections resulting from the distance of geostationary satellites from the earth prohibits the support of real time applications. In addition, the offered throughput (around 10 kbps) and the number of supported users (hundreds per satellite) can not satisfy the growing number of customers; particularly when compared with what wired networks can offer. The technological advances in cellular networks with 3G and High Speed Downlink Packet Access (HSDPA) technologies now allow users a theoretical downlink data transfer rates of several Mbps. Despite this promise, there are numerous issues which might still limit their adoption as access technologies for data applications. In particular the cost of the infrastructure required supporting 3G services, the expensive input fees for the 3G service licenses, and the high prices of mobile services and terminals might constrain their adoption as access technologies. Wireless Local Area Networks (WLAN) are also very popular as access technology. They are however limited in terms of coverage (in the order of 250m for IEEE 802.11 Standard). Every access point also requires physical connection to the wired infrastructure in order to provide access to the Internet.

As an alternative, wireless mesh technologies have received a growing interest for the past few years. Low-cost and easy-to-deploy Wireless Mesh Networks (WMNs) are particularly attractive solutions in places that do not (or cannot) support a wired backhaul. Originally, the term WMN was used to describe wireless co-operative communication infrastructures composed of a high number of individual wireless transceivers. This co-operative wireless array concept was first proposed in 1995 under a Canadian patent called Massive Array Cellular System (MACS). It was designed solely as a disruptive technology to replace all chargeable communication services, such as landline telephones, cellular phones, and cable TV with an entirely free service - a user-based, solely user-owned communication infrastructure. Nowadays, a wireless mesh network refers more generally to a packet-switched network with a static wireless backbone composed of access points wirelessly interconnected (e.g. see Fig. 1.1). Each access point may be equipped with one or several network interfaces. A subset of the access points serve as gateways between the wireless backbone and the wired infrastructure. WMNs present the advantage of offering low investment overhead and are easily deployable. Initial field tests [115] [120] [139] have demonstrated WMNs' tremendous potential and market value. Several universities have started deploying WMNs on campus (e.g. MIT and University of Arkansas). WMNs can also offer inexpensive internet connections in low-income community networks by sharing the internet access between the members of the community. One example is the NetEquality project in Oregon, US, that offers hardware and access to the Internet for less than one dollar per month [93]. WMNs can also be deployed in hot spots such as shopping centres, airports, sporting venues and during special events, military operations, and disaster recovery. They can serve as temporary installations and public safety. They can be particularly adequate for open areas such as parks etc. Many companies, such as Nokia [96], Microsoft [88], Motorola [21] and Intel [58], actively promote wireless mesh networks as a full IP-based solution.

Nonetheless, the lack of a clear understanding of wireless mesh network char-

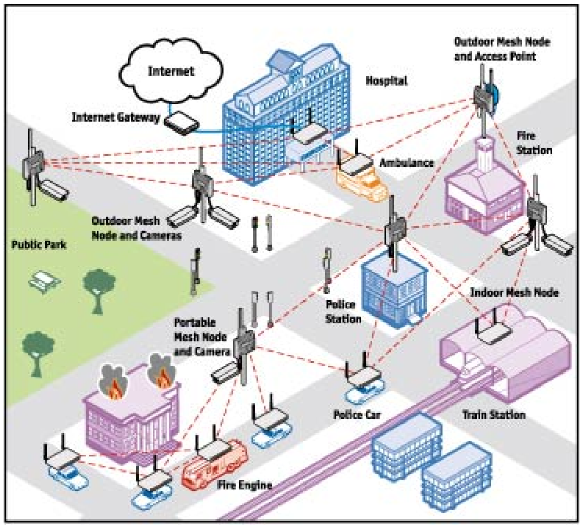


Figure 1.1: Example of community network (source: Shanix Inc.)

acteristics and the absence of better tailored resource management and service provisioning mechanisms can hamper their successful development. The multihop wireless nature of a WMN demands a different approach to routing from conventional wired networks due to factors such as limited bandwidth and interference effects. Although WMNs draw some similarities with other multihop wireless networks, such as ad hoc and sensor networks, their characteristics are different enough to prevent the direct application of existing routing protocols to WMNs.

To better understand these disparities, it is important to position this technology in the landscape of wireless communications. Depending on the network coverage, four distinct groups of wireless network technologies can be identified:

- WPAN (Wireless Personal Area Network): WPANs are used for communication between devices as cable replacement. Technologies enabling WPAN include Bluetooth, ZigBee, Ultra-wideband (UWB), IrDA, HomeRF, etc. Currently, Bluetooth is the most widely used technology for WPAN communication. The range of a WPAN is typically around 10 meters and throughputs vary from several 100kbps (e.g. Bluetooth) to several Mbps (e.g. UWB).
- WLAN (Wireless Local Area Network): WLANs are mainly used in home and office environments. In infrastructure mode, access to the wired network is achieved through 1-hop wireless transmission. In ad hoc mode, users interconnect without the support of any infrastructure. IEEE 802.11 [1] is the most prevalent Standard for WLANs.

- WMAN (Wireless Metropolitan Area Network): WMANs are designed to cover large areas such as cities. The throughput provided is of the same order of magnitude as for WLANs but WMANs offer a greater transmission coverage. Standardization efforts have been carried on as part of IEEE 802.16 (also referred to as WiMAX). WiMAX is often described as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL". WiMAX offers QoS reservations mechanisms different from WLANs as WiMAX is based on the scheduling of connections between end users and base stations whereas WLANs resembles Ethernet operations with the enforcement of priorities through the use of tags or delayed access mechanisms [5].
- WWAN (Wireless Wide Area Network): WWANs target at data transmission over large areas such as cities or countries using satellite systems or cellular networks. Although several satellite systems have been launched (Iridium [61], Globalstar [45], etc.), the low offered throughput (around 10kbps) restricts their practical use to voice applications. In contrast, high throughput cellular networks (up to several Mbps) are able to support a much broader range of applications.

Wireless Sensor Networks (WSN) are another wireless technology that has been intensively studied for the past few years. WSNs consist of an interconnection of tiny nodes, whose function is to retrieve specific information from the environment and to transmit this information to remote stations for processing. Network sizes vary greatly depending on the target application and can be of the size of a WMAN or a WLAN. However, the data-centric nature of WSNs (the focus is on the data collected by possibly multiple redundant sources) entails resource management protocols radically different from other wireless technologies. Consequently they have been excluded from our categorization.

The architectural differences between the above network technologies are summarized in Table 4.1. The comparisons are performed considering only the parts of the networks involving wireless communications.

From an architectural standpoint, WMNs characteristics can be seen as a combination of the characteristics of WMANs, WLANs and to a certain extent wire-

	WWAN		**WMAN**	**WLAN**		**WPAN**
	Cellular Net	**Satellite Net**		**Infrastructure**	**Ad Hoc**	
Transmission	1-hop	multihop	1-hop	1-hop	multihop	multihop
Network Entities	Base Stations Mobile Nodes	Satellites Mobile Nodes	Base Stations Mobile Nodes	Access Points Mobile Nodes	Mobile Nodes	Mobile Nodes
Max. Offered Throughput	∼10Mbps	∼10kbps	∼1.5Mbps	∼54Mbps	∼54Mbps	∼100kbps
Traffic	Multimedia	Voice	Multimedia	Multimedia	Multimedia	Multimedia
Users Capacity	Hundreds (per cell)	Hundreds (per satellite)	Hundreds	Dozens (per AP)	Hundreds	Hundreds
Trans. Range	∼km	$\sim 10^5$km	$\sim$ 50km	∼250m	∼250m	∼10m
Frequency Bands	GSM: 800MHz UMTS: 2GHz	Iridium: 2GHz	IEEE 802.16a: 2-11GHz	2.4/5GHz	2.4/5GHz	2.4GHz
Limitations	- Fixed Deployment Cost	- Cost - Long-term Deployment - Delay	Fixed Deployment	- Fixed Deployment - Bandwidth	- Energy - Bandwidth	- Bandwidth

Table 1.1: Comparison of wireless network architectures

less sensor networks. Data transmission is performed through multi-hop wireless communications and involves mobile nodes, network gateways and access points. WMNs share similarities with WLANs and WMANs in terms of fixed infrastructure, and suffer from the same bandwidth limitations. The achievable throughput is highly dependent on the deployed hardware and data transfer technologies. For a single network interface with an omni-directional antenna, throughput in the order of 50Mbps can be reached. However, this still remains far below the data rates achievable in wired networks. In addition, the traffic mix may include multimedia streams and the network is expected to support thousands of mobile users.

Despite the architectural commonalities that can be exhibited between WMNs and other wireless technologies, we need to further investigate how the characteristics of WMNs impact the routing mechanisms. We show that accounting for these unique characteristics opens new research directions, some of which we investigate in this thesis.

1.2 Routing Challenges in Wireless Mesh Networks

Routing is an active research topic in wireless multi-hop networks as the wireless bandwidth still remains limited compared to its wire-based counterpart. The impact of environmental conditions and the shared nature of the transmission medium further exacerbate this problem. To meet users' quality-of-service expectations and to optimize the use of the scarce wireless medium, efficient routing mechanisms have to be designed.

From a routing perspective, Wireless Mesh Networks exhibit unique properties that differentiate them from other wireless and wired technologies (Table 1.2). The main differences are:

- *Network topology.* A fixed wireless backbone differentiates WMNs from other network infrastructures. Therefore communication is performed through multihop wireless transmissions (in a similar way to MANETs). However, unlike MANETs, node mobility in the backbone infrastructure is not a concern.
- *Traffic patterns.* In cellular networks and WLANs, data is exchanged between users and access points. In MANETs, traffic can flow between any pair of nodes. In WMNs, data transmission is primarily between the mobile nodes and the network gateway (some similarities can therefore be drawn with sensor networks where communications are between sensor nodes and a sink), but traffic between two nodes in a mesh, although less prominent, should also be considered.
- *Inter-path interference.* WMNs differ from wired networks because of the possibility of interference between disjoint paths. When considering the use of omni-directional antennas communication on a wireless link is point-to-multipoint as opposed to point-to-point communications in wired networks. Therefore, a communication between two nodes can impact the transmission of neighboring nodes, leading to the well-known problems of hidden and exposed terminals.
- *Link capacity.* WMNs differ from wired networks as the link capacity can vary over time due to the sensitive nature of wireless communications to surrounding interference. This problem is even more critical when multiple technologies use the same frequency band (e.g. ISM band).

- *Channel diversity.* WMNs can benefit from the possibility of introducing channel diversity in the routing process, which is not possible in other wireless networks due to node mobility (MANETs) or energy constraints (WSNs). This technique can significantly reduce inter-node interference and increase the overall throughput.

	Wired networks	**MANETS**	**WSNs**	**WMNs**
Topology	static	mobile	static	static
Traffic	any pair of nodes	any pair of nodes	Sensor to Sink	Node to GW
Inter-path interf.	No	Yes	Yes	Yes
Link capacity	Fixed	Varying	Varying	Varying
Channel diversity	NA	No	No	Yes

Table 1.2: Routing characteristics summary

WMNs present sufficient similarities with ad hoc networks (in particular data communication over multiple wireless hops) so that the research accomplished on multi-hop routing in ad hoc networks can be of benefit to WMNs. Early works on ad hoc networks date back to 1972 and recently, dozens of routing protocols have been proposed [55]. However, directly applying these protocols to WMNs may not yield the best results in terms of network performance. For example, in the early deployment stage of the MIT mesh network (Roofnet project [117]), DSDV (Highly Dynamic Destination-Sequenced Distance Vector) [108], a proactive ad hoc routing protocol, was implemented. It rapidly appeared that the data traffic was severely interfering with the transmission of the control packets causing slow path convergence. As a result, whenever data transfers were occurring in the backbone, DSDV ended up choosing random paths.

Interference is a phenomenon which is difficult to account for in the design of routing mechanisms. In this thesis, we intend to address this issue from different research perspectives. Our primary concern is to evaluate and study the impact of interference on routing and to devise interference-aware mechanisms in order to improve the network performance.

1.3 Thesis Contributions

The primary goal of this thesis is to devise routing mechanisms tailored for wireless mesh networks. As the network grows and the number of users increases, the need for efficient routing protocols becomes more critical to prevent network congestion and ensure users' satisfaction.

Our main contributions are in the three following areas:

- *Routers-to-Gateways Association*
  We studied the problem of routing traffic flows from routers to gateways. As the traffic flows are mainly directed to/from the network gateway, we can assume the existence of a central entity (possibly one of the gateways) that has complete information about the traffic transiting through the network. This information can be used to decide which routes the traffic flows should follow in order to minimize the interference and network congestion level, and optimize the network resources usage. We proved that the problem of minimizing the maximum link utilization is NP-hard. We then studied this problem with different constraints on the number of channels available and under different interference models. We presented a linear-programming solution for the single channel case. For the multi-channel case, we proposed several heuristics. Performance evaluation has been performed via simulations.

- *Interference-Aware Routing Metric*
  Although many routing metrics have been designed for wireless networks, real-world implementations have shown that these metrics yield poor performance compared to a simple minimum-hop routing strategy. We therefore conducted a study of the most popular routing metrics in wireless mesh networks. By analyzing the strengthes and weaknesses of existing routing metrics, we designed a novel interference-aware routing metric (IAR metric) and demonstrated through simulations the improved performance over existing metrics.

- *Multipath Routing vs. Single Path Routing*
  With respect to WMN routing strategy, we have also studied the conditions under which multipath routing is preferable over single path routing, if applicable. In the context of ad hoc networks where link and node unreliability is an issue, spreading traffic over multiple paths has been shown to enhance network performance compared to single path routing. However, in the context of mesh network, where the backbone nodes are fixed and unlikely to

suffer from frequent failures, the benefits of a multipath routing approach seem questionable. Therefore, we compared the performance of a multipath routing algorithm against a single path routing algorithm under various scenarios. This allowed us to determine the cases under which a multipath routing strategy may be beneficial over single path routing in a wireless mesh network.

1.4 Thesis Organization

The remainder of this thesis is organized as follows.

We first provide in Chapter 2 background information on inter- and intra-flow interference and discuss its impact on the design of routing protocols as it can significantly decrease the nominal network capacity. We illustrate this fact in several scenarios analytically and conduct simulations to confirm the analytical results. We also describe some existing interference models that we use in our work.

In Chapter 3, we present our analysis of the routers-to-gateways association problem and show its complexity when trying to minimize the maximum congestion level (i.e. the maximum link utilization). We then describe our solutions in single-channel and multi-channel scenarios and evaluate their performance using simulations.

In Chapter 4, we describe the characteristics of the most commonly used routing metrics in wireless mesh networks and give some insights into the reasons why none has been adopted so far. Based on the results of this analysis, we propose an interference-aware routing metric and use simulations to assess its performance compared to a set of existing routing metrics.

In Chapter 5, we present an analysis on the theoretically achievable throughput in wireless mesh networks when spreading the traffic over multiple paths. We show that multipath routing can result in a better network utilization if interference is accounted for and if traffic loads are properly estimated.

Finally, we summarize our contributions and conclude this thesis in Chapter 6.

Chapter 2

Wireless Interference: Analysis and Performance Evaluation

2.1 Introduction

One main distinguishing characteristic of a transmission over a wireless channel compared with a transmission over a wired infrastructure is related to the fact that wireless devices can not transmit and receive at the same time. This peculiarity has a significant consequence on the achievable network throughput. If two nodes i and j are exchanging data packets, every other node that wants to send data to i or j has to wait until the end of the communication between i and j before to be able to proceed with its own data transmission. In addition, in order for the data transfer between i and j to be considered successful, j should correctly receive the data packet sent by i (i.e. with no data corruption), and should send back an acknowledgment notification to i without any collisions occurring. A collision (interference) occurs when a node receives several packets simultaneously, which prevents it from retrieving the content of these packets. This constraint implies that, if we assume that all nodes are equipped with omni-directional antennas, all the nodes at interference range of the sender and of the receiver should remain silent during the data transmission (Fig. 2.1).

In this chapter, we provide further insights on the achievable throughput in wireless networks, from an analytical and experimental viewpoint. We show that limits on the maximal achievable throughput can be enhanced by routing data flows over multiple paths if interference is accounted for in the design of the routing protocols. We also describe some interference models that can be used in the design of routing protocols.

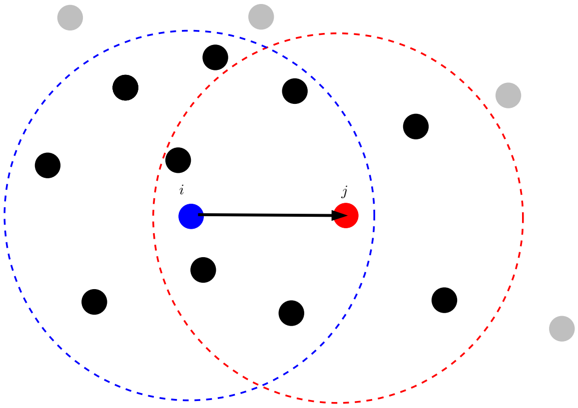


Figure 2.1: Illustration of a data transmission between node i and j. For simplicity, transmission ranges are represented by circles. All the nodes in the vicinity of i and j (black nodes) should remain silent in order not to interfere with i and j.

2.2 Chapter Organization

The remainder of the chapter is organized as follows. We present in Section 2.3 some theoretical bounds on the achievable capacity in wireless networks. We show that if interference is accounted for, the achievable throughput is reduced significantly. We analytically determine the nominal capacity reachable if a traffic flow is routed over one single path or over multiple paths and illustrate the quantitative impact of these results via simulations. Finally, we present in Section 2.4 several interference models that have been proposed in the literature, in particular the ones which are relevant to this work. We conclude this chapter in Section 2.5.

2.3 Interference in Wireless Communications

Wireless interference can have several origins that all contribute to decreasing the nominal transmission rate. Environmental noise and signal degradation due to path loss represent some factors responsible for the decrease in capacity. The shared nature of the transmission medium also contributes to the performance degradation experienced by users. When a data exchange takes place between two nodes, all the neighboring nodes at interference range of the sender and receiver should remain silent until completion of the on-going communication. This impacts the transmission rate within a single flow (Fig. 2.2) and is referred to as *intra-flow interference*, as well as the transmission rate of flows on different paths (Fig. 2.3), referred to as *inter-flow interference*.

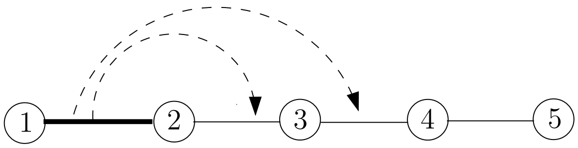


Figure 2.2: Intra-flow Interference: Communication on Link 1-2 blocks Link 2-3 and Link 3-4

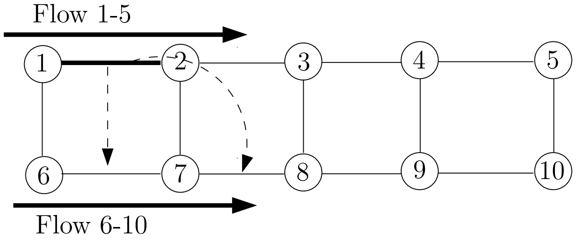


Figure 2.3: Inter-flow Interference: 2 flows transit between Node 1 and Node 5, and between Node 6 and Node 10. Communication on link 1-2 blocks Link 6-7 and Link 7-8

In their seminal work [50], Gupta and Kumar have shown that in a wireless network with n identical nodes, the achievable per node throughput is $\Theta(1/\sqrt{n \log n})$ with a random node placement and random communication pattern. Under the assumption of an optimal node placement and communication pattern, this throughput becomes $\Theta(1/\sqrt{n})$.

To illustrate more concretely how interference can reduce the maximal achievable throughput, let us consider the following example (Fig. 2.4). We position two nodes 5 hops apart and we assume that all links have the same nominal network capacity B (throughput that can be achieved at the MAC layer in one hop [65]). One single flow is sent between the source node and the destination node. The maximum achievable throughput is therefore at most $B/5$ because of the bottleneck link (highlighted in bold) which blocks four other links.

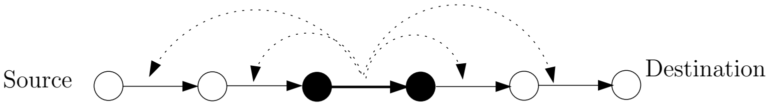


Figure 2.4: Throughput is bounded by B/5 if the path length exceeds 4 hops

If traffic flows are routed over multiple paths, we show that in order to improve the nominal throughput beyond what single path routing offers, it is necessary to guarantee that the chosen paths do not interfere with each other.

Let us assume that there exists k paths $P_1, .., P_k$ between a source node s and a destination node t, $P_1, .., P_k$ can be of two sorts:

- link-disjoint paths (Fig. 2.5): paths with no communication link in common (shared). If, along a path P_i, a node $x_{n,i}$ also belongs to a set of paths $\mathbb{P}$ s.t. $\mathbb{P} \subset \{P_1, ..P_k\} \backslash P_i$, then $x_{n-1,i}$ and $x_{n+1,i}$ can not belong to any path in $\mathbb{P}$.

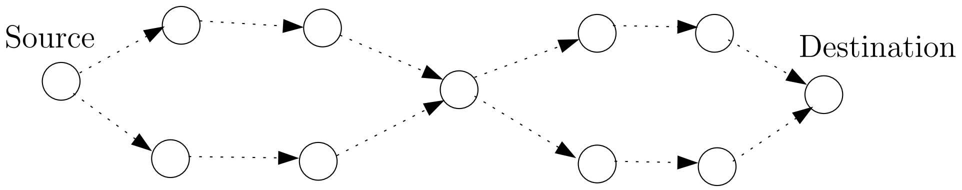


Figure 2.5: Link-disjoint paths

- node-disjoint paths: paths that do not share any node. Let $i \in [1, k]$, if $x_i \in P_i$, then $x_i \notin P_n, n \in [1, k] \backslash \{i\}$.

  Assuming a single-frequency wireless broadcast network, a data transmission between two nodes prevents channel access to any node located within the interference range of the sender or the receiver. Owing to these specific characteristics of wireless communications it is important to distinguish the two following subcases. The sets composed of the nodes along each path (excluding the source node and the destination node) can be (Fig. 2.6):

  1. edge-connected and therefore interfering. This interference between two (or more) paths is known as *route coupling*.
  2. 0-edge-connected and do not interfere. This latter case will be referred to as *totally disjoint paths* in the remainder of this report.

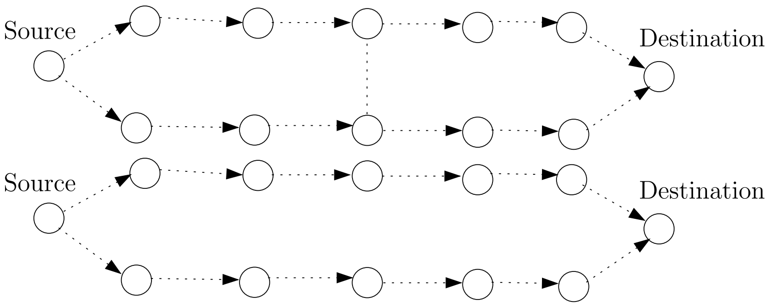


Figure 2.6: Node-disjoint paths

Let us consider the example depicted in Fig. 2.7. Two traffic flows are sent along different paths, from S_1 to D_1, and from S_2 to D_2. One node on one path interferes with another node on the second path (nodes in the shaded area in Fig. 2.7). In this case, the maximal throughput is reduced to $B/7$.

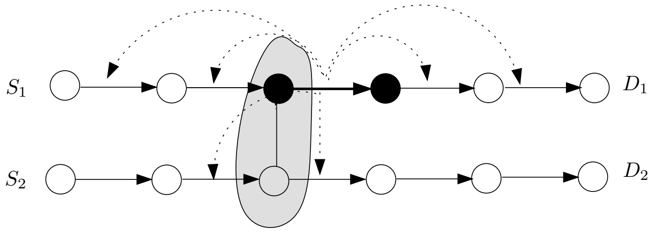


Figure 2.7: Throughput is bounded by B/7 when 2 paths are interconnected by 1 link

If these two flows traverse the same node along their respective paths, the maximal achievable throughput decreases to $B/9$ (Fig. 2.8).

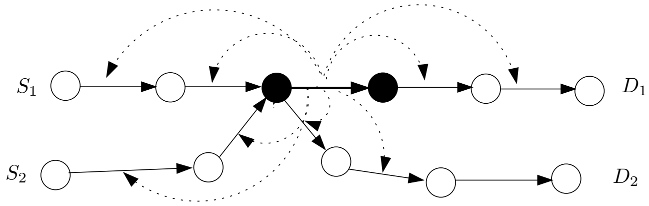


Figure 2.8: Throughput is bounded by B/9 when 2 paths share a same node

These simple examples illustrate the importance of interference awareness in the routing decisions as this significantly impacts the network performance. To further corroborate these results, we implemented different routing approaches and evaluated their performance through simulations.

Bounding the capacity gain with non-interfering multipath routing for a single isolated flow is a straightforward operation. The difficulty is to factor in the traffic generated by other pairs of nodes. To support the claim that a non-interfering multipath routing algorithm can outperform other routing techniques in terms of network utilization and load balancing even in the presence of multiple flows, we implemented three routing algorithms: a single shortest path routing algorithm, a link-disjoint multipath routing algorithm and a non-interfering multipath routing algorithm. For the sole purpose of focusing on the performance of the algorithms, we assume the presence of a central controller responsible for the computation of the paths. The shortest path routing algorithm is an implementation of Dijkstra's algorithm over a graph in which the nodes represent the network devices and the unit weighted edges represent the network connectivity. The link-disjoint multipath routing we implemented is similar in spirit to Split Multipath Routing (SMR) presented in [80]. Paths are chosen as follows. We first compute a shortest path between the source and destination. If multiple choices exist, ties are broken randomly. We construct the set of edges that are either part of the first path or connected to any node on the first path. We then remove this set of edges from the initial graph as they can not be part of the second path since a path containing any of these edges would violate the condition according to which both paths should not be connected by any link. The non-interfering multipath routing algorithm is based on geographic node positioning. The idea consists in defining a safeguard band in which none of the paths should be located, therefore guaranteeing that they are distant enough from each other not to interfere.

During the simulations implemented in Matlab, we generated the test topologies randomly in a 1000x1000 m^2 area with the only constraint that the nodes be connected. We evaluated the effect of the network density (number of nodes in the test area) and the effect of the number of flows on network utilization. We consider that all the links have the same capacity. For a given link (i, j), the link utilization represents the sum of traffic loads of all links at interference range of i and j.

Impact of Network Density

We generate 10 random flows, each sending 1 unit of traffic. We then measure the maximum link utilization (in terms of unit of traffic) and the load distribution for different network configurations. The results of the simulations averaged over 50 runs are depicted in Fig. 2.12.

We observe in Fig. 2.12 (a) that the link utilization can be 50% less with a non-interfering multipath routing approach than with other routing algorithms thanks to a better load balancing. This is confirmed by a closer look at the load distribution for 100-node and 200-node networks (Fig. 2.12 (b) and (c)). The graphs show the cumulative number of links for the topologies considered as a function of the link utilization. The cumulative number of links represent the total number of links whose utilization is above a certain value. We can see that with a non-interfering multipath routing, a greater number of links carry a smaller load and that overall

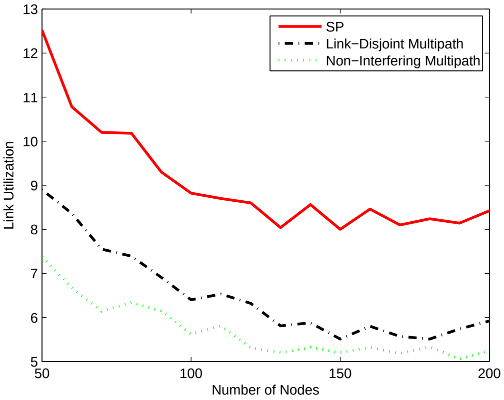
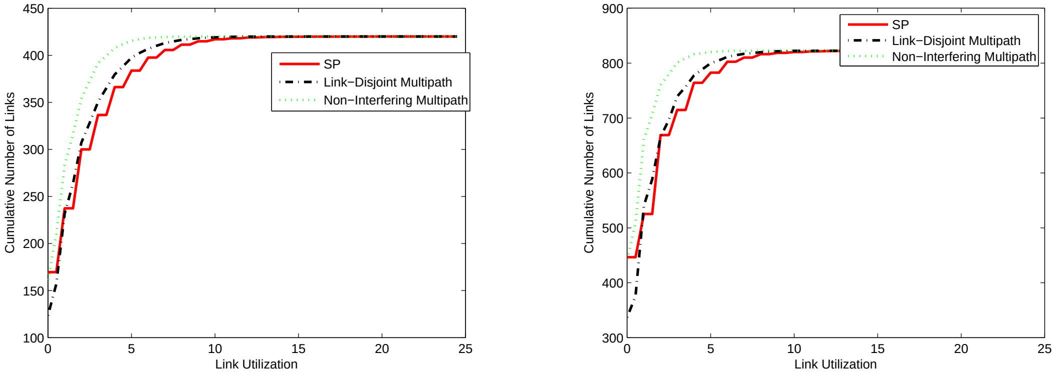
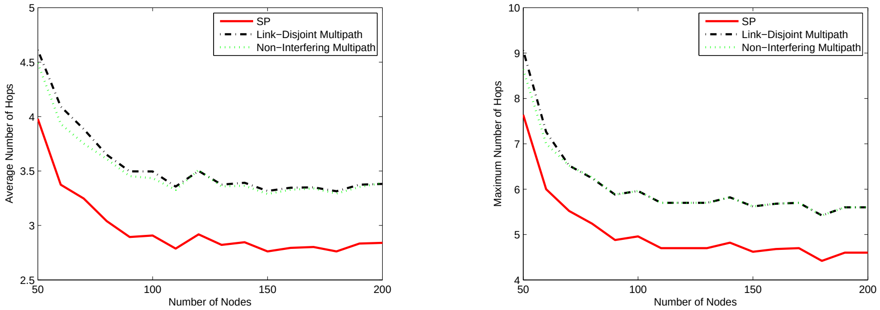


Figure 2.9: Impact of the network Density on the link utilization



(a) Load distribution for 100 nodes
(b) Load distribution for 200 nodes

Figure 2.10: Routing Algorithms: Impact of the network density on the network utilization



(a) Average Number of Hops
(b) Max Number of Hops

Figure 2.11: Routing Algorithms: Impact of the network density on the path length

the maximum link utilization is less than with a link-disjoint multipath routing protocol or a single-path routing protocol. As the network density increases, the performance of the multipath routing algorithms progressively converges. This can be explained by the fact that a greater number of paths become available and consequently the impact of inter-flow interference is lessened.

As expected, the average and maximum number of hops of paths in the paths obtained with multipath routing algorithms is greater than what can be obtained with the implementation of a single path routing algorithm (see Fig. 2.11). In the scenarios considered, both link-disjoint and non-interfering paths routing lead to paths one or two hops longer. We can also observe that when the network density is low, the non-interfering routing algorithm performs slightly better than the link-disjoint routing algorithm due to the possibility not to find non-interfering paths. By default, in our implementation, if there does not exist two non-interfering paths, routing is performed over a single path.

Impact of Number of Flows

We study next the impact of the number of flows on 50-node networks, each flow carrying 1 unit of traffic.

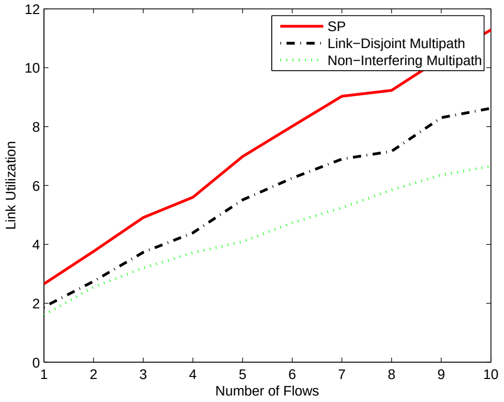
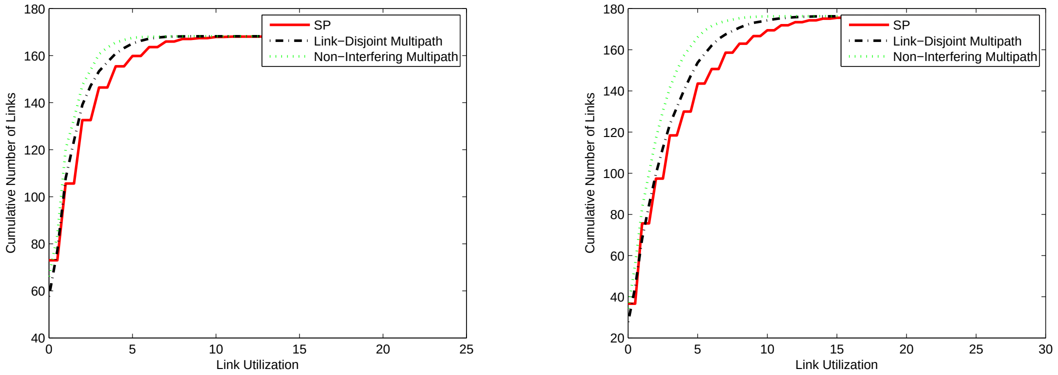


Figure 2.12: Impact of the number of network flows on the network utilization

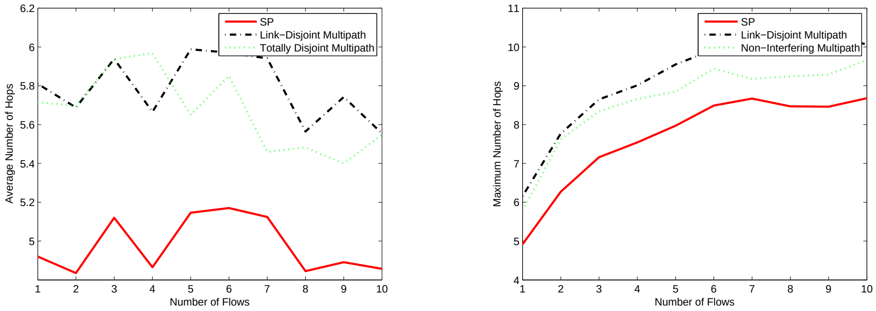
Fig. 2.13 depicts the impact of the number of flows on link utilization and traffic load distribution. As observed previously, the multipath routing algorithms



(a) Load distribution for 5 flows

(b) Load distribution for 10 flows

Figure 2.13: Routing Algorithms: Impact of the number of flows on the network utilization



(a) Average Number of Hops

(b) Max Number of Hops

Figure 2.14: Routing Algorithms: Impact of the number of flows on the path length

lead to better network utilization. This is reflected by a lower link utilization than the one achieved with a single path routing algorithm. We also evaluated the load distribution for 5 and 10 flows. We can observe that the load is distributed more evenly with the non-interfering multipath routing algorithm.

These results corroborate our previous analysis showing that significant performance improvement can be achieved when traffic flows are routed over multiple non-interfering paths. In order to capture the impact of interference in the design of routing protocols, several interference models with different levels of complexity have been designed. We present in the following section the most popular ones.

2.4 Wireless Interference Models

Four main interference models have been commonly adopted in the literature. In these models, for simplicity of explanation, it is always assumed that the nodes are transmitting on the same channel.

2.4.1 Protocol model

In the Protocol model [50], a transmission between node i and node j is considered as successful if the two following conditions are satisfied:

1. Node j is within the transmission range of node i, i.e.,

   $$d(i, j) < r$$

   where $d(i, j)$ represents the distance between node i and node j, and r is the transmission range.

2. Every other node k that is simultaneously transmitting over the same channel is at a distance $d(k, j)$ from j such that:

   $$d(k, j) \geq (1 + \Delta)d(i, j)$$

   with $\Delta > 0$. This condition guarantees a guard zone around the receiving node to prevent a neighboring node from transmitting on the same channel at the same time.

2.4.2 Physical model

In the Physical model [50], a transmission is considered successful if the signal to interference ratio (SIR) at the receiver is greater than a minimum threshold β.

2.4.3 Receiver Conflict Avoidance model (RCA)

In the Receiver Conflict Avoidance model [72], a transmission is considered successful if all the nodes at interference range of the receiver remain silent. This is a generalization of the Protocol Model previously described as there is no assumption on the geographic location of the nodes.

2.4.4 Transmitter-Receiver Conflict Avoidance model (TRCA)

In the Transmitter-Receiver Conflict Avoidance model [72], all the nodes within transmission distance of both the sender and receiver should remain silent. This additional constraint is due to the fact that for a transmission to be considered successful, an acknowledgment must be received by the sender. Also in 802.11-like networks, a handshake can be enabled between the sender and receiver via the exchange of Request-To-Send (RTS) / Clear-To-Send (CTS) packets.

For each of these interference models, two subcategories can be further derived depending on how interference is computed.

- Link-based interference models: In these models, interference is computed for each link. If we consider a link (i, j), the interference level of (i, j) can be computed as the number of links interfering with it, or the amount of traffic carried by the links in the interference domain of (i, j).
- Node-based interference models: Interference is computed for each node. Different approaches have been proposed. The interference can be computed as the sum of the traffic of the links interfering with the node considered [73] or as the number of nodes in the interference domain [138].

The majority of work on WMNs has adopted the link-based interference model (e.g. [63] [72]) as it provides a more precise representation of the effects of interference on the network performance; whereas a node-based interference only gives a coarse and local estimation of the network conditions.

2.5 Conclusion

In this chapter, we showed that significant performance variations can occur depending on the level of interference between concurrent data transmissions. We analytically evaluated the achievable throughput and confirmed its accuracy using simulations.

We also showed that splitting the traffic over multiple paths can be a sound routing approach if interference is properly accounted for. We then presented the different interference models that have been proposed in the literature notably those we use in Chap. 3 when studying the router-to-gateway allocation problem, as well as in Chap. 4 when designing our interference-aware routing metric. We chose a link-based interference model as it more precisely captures the conflicts that can occur between geographically close data transmissions.

In the next chapter, we investigate the problem of routers to gateways association in single channel and multi-channel networks.

Chapter 3

Routers-to-Gateways Association

3.1 Introduction

One challenging issue in traffic management is to minimize the network congestion level so as to accommodate future traffic growth. This relates in WMNs to the problem of associating routers to gateways such that the maximum link utilization is minimized. We define link utilization as the amount of bandwidth used by all traffic demands routed through and interfering with a given link with respect to the total capacity of the link. In this context routers are network devices which have the primary role of aggregating traffic from users directly associated with them and forwarding the aggregated traffic towards the destination node. Gateways are routers that establish a bridge between different networks, typically between a wired network and a wireless network. The association algorithm that determines to which gateway a router directs its traffic can, in certain cases, lead to a radically different network performance. For instance, many routers can be geographically close to one particular gateway. However, sending the traffic of some of them to a more distant but lightly-loaded gateway might lead to a better use of network resources. Router to gateway association is a type of congestion control problem that can be reduced to minimization of the maximum link utilization.

As previously mentioned, one of the main challenges in wireless mesh networks is the limited channel capacity. Besides the physical data transfer limitations, interference resulting from transmissions over multiple hops (intra- and inter-flow interference) [65] can significantly reduce the available throughput. Several solutions have been proposed to address this issue. Routers and end devices can be equipped with multiple interfaces and therefore transmit over multiple channels simultaneously [72]. This approach can result in a significant improvement in network performance. But it also complicates the network management process as it requires efficient router-to-channel assignment algorithms. Another approach is to associate one user to multiple routers (access points) [78] in order to balance the traffic load more efficiently according to the utilization level of the routers and the data traffic requirements. For instance, unicast traffic can be sent to a router that supports high data rates, whereas broadcast traffic can be sent at a lower data rate to a different router. In order to be effective, this approach requires some tight synchronization between end systems and routers. Another approach is to take advantage of the presence of multiple gateways. A router can send its traffic to several gateways instead of directing it to a single one. In [77], the authors studied the problem of maximizing the aggregate throughput under fairness constraints and showed that splitting a router's traffic and sending it to several gateways can improve the network capacity by enabling better load balancing. This, however, comes at the cost of added complexity in reassembling and reordering data packets at the gateways. Also it was assumed in [77] that the gateways are always the bottlenecks.s We can show in a similar scenario to the one used in [77] (Fig. 3.1 and Fig. 3.2) that splitting the traffic and sending it to different gateways may not improve the network performance as the central link is the bottleneck. Finally the focus of [77] was on addressing the problem for single channel networks.

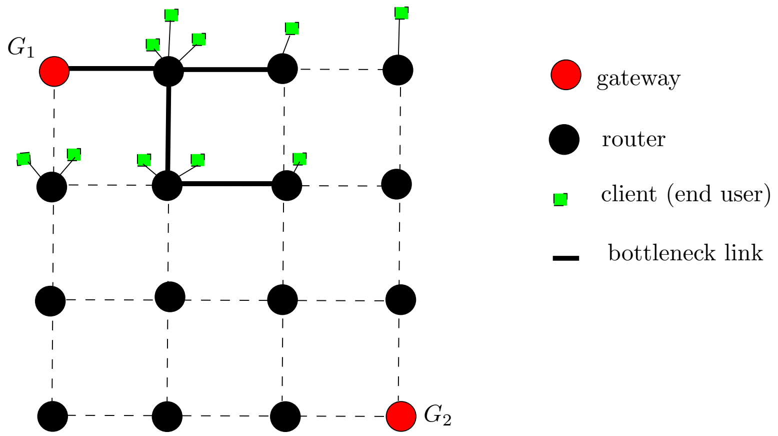


Figure 3.1: Case 1: All flows are sent to G_1. Under the Edge-to-edge interference model (all nodes at interference distance of the sender or receiver should remain silent for the transmission to be successful), there exist 4 bottleneck links (bold links).

In our work, we consider a more general case of associating routers to gateways when multiple channels are available and we allow gateways to be assigned non-overlapping channels.

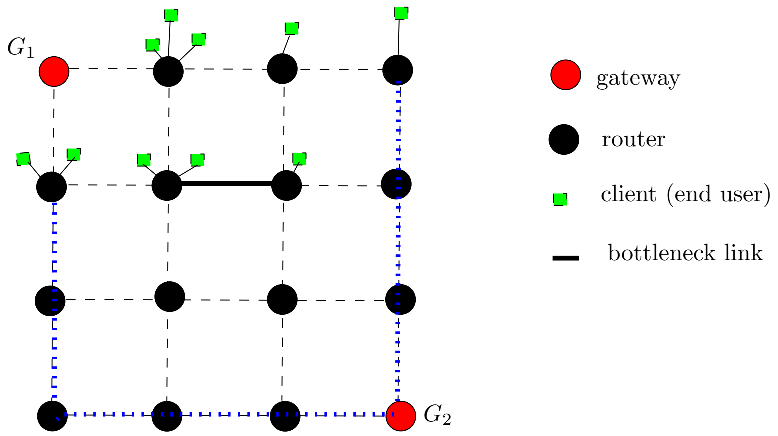


Figure 3.2: Case 2: some of the flows are sent to G_2 (bold, dashed links). The middle link remains the bottleneck.

In this chapter, we investigate the problem of minimizing the maximum link utilization in wireless mesh networks with M gateways, $M \geq 2$. In particular, we prove that the problem of minimizing the maximum link utilization is NP-hard under both the Edge-to-Edge and Edge-to-Node interference models. We present solutions to this problem in single channel and multi-channel environments.

3.2 Chapter Organization

The remainder of the chapter is organized as follows. We define more precisely the problem of routers to gateways association in Section 3.3. The complexity analysis of the problem is presented in Section 3.4. We describe our solutions to the single channel scenario under different sets of constraints in Section 3.5. The multi-channel case is addressed in Section 3.6. Section 3.7 concludes this chapter.

3.3 Problem Definition

3.3.1 Definitions

Wireless communications differ from their wired counterparts as interference can occur within a single flow (*intra-flow interference*) as well as between paths located within interference range (*inter-flow interference*). To account for this phenomenon, we define the following terminology that we will use in the rest of the chapter.

Definition Given a link (i, j), the *interfering set of (i,j)* called Inf_{ij} is defined as the group of links for which at least one endpoint is at interference range of i and/or j (including link (i, j)).

Definition Given a directed graph $G(V, E)$ in which each link $(i, j) \in E$ carries traffic $f(i, j)$, the *normalized link utilization* I_{ij} of (i, j) is defined as the sum of the traffic on the links in the interfering set of (i, j) divided by their respective capacities.

$$I_{ij} = \sum_{(k,l) \in Inf_{ij}} \frac{f(k,l)}{C(k,l)}$$

A link utilization of *1* means that the link is fully utilized and that no further traffic can be supported by this link.

3.3.2 Problem Statement

The characteristics of wireless mesh networks open new perspectives on how to tackle the problem of minimizing the maximum link utilization. First the presence of multiple gateways enables more efficient load balancing strategies. For instance, a router can choose a specific destination gateway that satisfies its requirements in terms of link utilization, end-to-end delay, number of nodes supported, etc. Second, the existence of non-overlapping channels can be utilized to create connected clusters of routers, each operating on a different channel and being served by a single gateway.

The problem we are studying referred to as $MIN\_MAX\_LINK\_UTILIZATION$, can consequently be expressed as follows:

Problem Given a connected network topology and a traffic demand vector, determine the load distribution that minimizes the maximum link utilization.

More specifically, we study this problem in the two following cases:

Case 1 (1 interface - 1 channel) *All routers are equipped with one single network interface and are configured to transmit on the same channel.*

Case 2 (1 interface - K channels) *All routers are equipped with one single network interface and each router is configured to one of the K available channels. Gateways are assigned to distinct channels, and serve non-overlapping networks.*

We first start by analyzing the complexity of the problem and demonstrate that in the general case, minimizing the maximum link utilization in wireless networks is NP-hard. We then propose solutions to this problem under different sets of constraints in single channel and multi-channel networks.

3.4 Min-Max Link Utilization in WMNs: Problem Complexity

We consider a restricted problem, where we assume that all our traffic is symmetric, that is there are no designated sources and sinks, or so called nowhere-zero flow [48]. This implies that the traffic flows on each edge are strictly positive, and at each vertex, the sum of the incoming flows equals the sum of the outgoing flows (flow conservation). We also make an additional restriction that the traffic for each link is 1 in both directions (uniform unit flow). We show that even in this restricted scenario, the problem of minimizing the maximum utilization is NP-hard. That is, there exists another problem which is known to be NP-complete which may be reduced to this problem in polynomial time.

Moreover, we can show that the solution to this problem is hard to approximate to within factor 7/6 (47/46, respectively) for Edge-to-Node (for Edge-to-Edge, respectively) interference models unless $P = NP$.

More precisely, the problem is stated as follows: Given a set of nodes V on a plane, and the transmission distance R (we use Euclidean distance here), a node $x \in V$ can communicate with $y \in V$ directly if $d(x, y) \leq R$. All pairs of nodes that can communicate form an undirected graph $G(V, E)$. The problem of minimizing the maximum congestion can be stated as follows:

OBJECTIVE: Find a subgraph G' of G such that

1. G' connects all the nodes (i.e. G' is a spanning tree); the edges of G' are called *links*;
2. the maximum link utilization is minimized.

We study the problem under the two following interference models. These models are similar to the ones introduced in [50].

- *Edge-to-Node interference model*: In this model [72], a transmission is considered successful if all the nodes at transmission distance of the receiver remain silent. Therefore, the interference set of a given node is composed of the links (edges of graph G') that interfere with this node. This set of links includes all the links located at most 2 hops away from the receiver node in question. An example is depicted in Fig. 3.3. The set of links interfering with the central node (depicted in bold) consists of the four surrounding links (in bold), which globally contribute to a utilization of 4 at the central node.

- *Edge-to-Edge interference model*: In this model [72], all the nodes within transmission distance of the sender and receiver should remain silent as reflected in the operations of IEEE 802.11 MAC protocol. In 802.11-like networks, virtual carrier-sensing is performed between a sender and receiver via the exchange of Request-To-Send (RTS) / Clear-To-Send (CTS) messages. Consequently, all the nodes that receive these messages are blocked therefore avoiding simultaneous transmissions that would result in data collisions. Similarly to the previous model, given a link (i, j), all links located at most 2 hops away can interfere with (i, j). An example is depicted in Fig. 3.4. The 4 links in bold can interfere with the central link (in dotted) contributing to an utilization of 4 on this link.

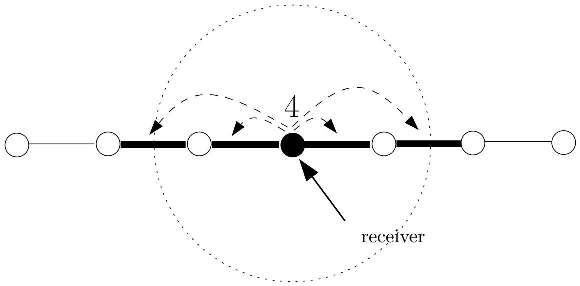


Figure 3.3: Edge-to-Node interference: all links located at most two hops away from the receiver node should remain inactive for the transmission to be considered as successful.

Theorem 3.4.1 *Under the Edge-to-Node interference model (and Edge-to-Edge interference model), MIN_MAX_LINK_UTILIZATION is NP-hard to approximate within factor* $7/6$ *(and* $47/46$ *respectively).*

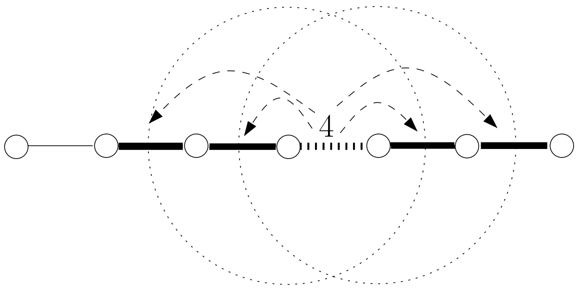


Figure 3.4: Edge-to-Edge interference: all links located at most two hops away from the sender and receiver node should remain inactive for the transmission to be considered as successful.

Proof We reduce a known NP-complete problem, the Hamiltonian path problem on grid graphs [62], to our problem. Given a grid graph H, we construct an instance of the $MIN\_MAX\_LINK\_UTILIZATION$, G, given an integer K, and $R > 0$, such that H has a Hamiltonian path with specified endpoints if and only if $MIN\_MAX\_LINK\_UTILIZATION$ of G with transmission distance R is at most K.

Definition [62] A *grid graph* is composed of a set of points with integer coordinates, such that two nodes are connected if the euclidian distance between them is equal to 1.

Definition A *Hamiltonian path* is a path between two vertices of a graph that visits each vertex exactly once.

The instance G can be constructed in two steps: (i) we replace edges of H by the gadget represented in Fig. 3.5; (ii) we replace each of resulting vertices by a *city* consisting of several nodes that are located very close to each other (distance less than 1/100).

We define the *sizes* and the number of nodes of these cities later. The transmission radius R can be set to any value between $1/3 + 1/50$ and $\sqrt{2}/3 - 1/50$, so that only neighboring cities can interfere with each other, e.g. see Fig. 3.6. This avoids that a transmission between middle nodes on one edge interferes with a middle node on a perpendicular edge.

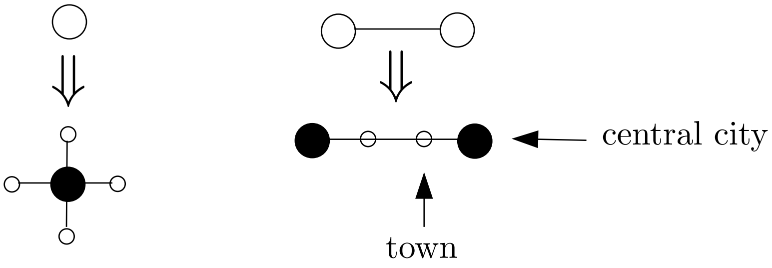


Figure 3.5: Gadget used in the reduction: each node in the initial graph H is replaced by a central city surrounded by 4 towns.

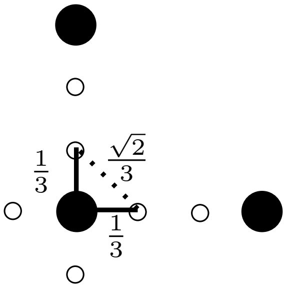


Figure 3.6: The transmission radius is set such a node is connected only to its direct neighbors along the x-axis and y-axis (at most a total of 4)

Since nodes inside a city are very close to each other, we can show that in the optimal solution to the $MIN\_MAX\_LINK\_UTILIZATION$ the links inside a city form a spanning tree.

We say that two cities are *connected directly* if there is a link between a node x in one city and a node y in the other city. Note that the choice of x and y inside their respective cities does not affect the interference level of any node or link, since the nodes are located very close to each other inside any city (distance less than 1/100), that is, if we happen to choose another pair of nodes x' and y', x' close to x and y' close to y, for the link, the interference levels on all the nodes and edges would not change). We call cities that correspond to the original nodes of H *central* and the newly created ones *towns*, edges between towns are called *middle edges* and edges between central cities and towns are called *local edges*. We say that two central cities are connected if all the three links in the gadget are present (one middle edge and two local edges). Now we study the two cases corresponding to the two models of interference considered.

Interference Model 1: Edge-to-Node interference

We set the size of all cities and all towns to 1 except for the two *special* central cities that correspond to the two end points of the Hamiltonian path of H. In order to get the same order of interference in these special cities as the ones we get in the other cities and given that they should only be connected to another city, we need to increase their size by 1. We therefore set the size of the special cities to 2. Note that the interference (utilization) level of the only node in a town is at most 6 even if all the neighbor cities are directly connected. Hence, by setting $K = 6$ we only need to consider the interference at central cities. For each pair of central cities that are not connected, we have three links between them and exactly one of which is not present, since we need to make sure that the two intermediate towns are connected.

If we focus on the central cities (Fig. 3.7), we can see that the interference at each city results from transmissions on at most:

1. 4 local edges
2. 4 middle edges

Note that, each missing local edge affects the interference level of its adjacent central city only, while each missing middle edge affects the interference of the two surrounding central cities at once. Thus, we can assume that all local edges are linked and some of the middle edges are not linked. The local edges create interference 4 at each central city. The edge between the two nodes of the two special central cities creates interference 1 for both of these nodes. Therefore, if we have a connecting graph G' with $MIN\_MAX\_LINK\_UTILIZATION$ at most $K = 6$, then at most 2 middle edges can be linked for each regular central city and at most 1 middle edge can be linked for the two special cities. Note that this is only possible if the central cities are connected in a path with the end points at the special central cities. This condition can be true if and only if the original graph H has a Hamiltonian path with the specified end points.

Interference Model 2: Edge-to-Edge interference

We set the size of every central city to $C = 1$, except for special cities for which we set the size to be $C + 1 = 2$. Let T be the size of a town. We use a similar approach as for the Edge-to-Node interference model.

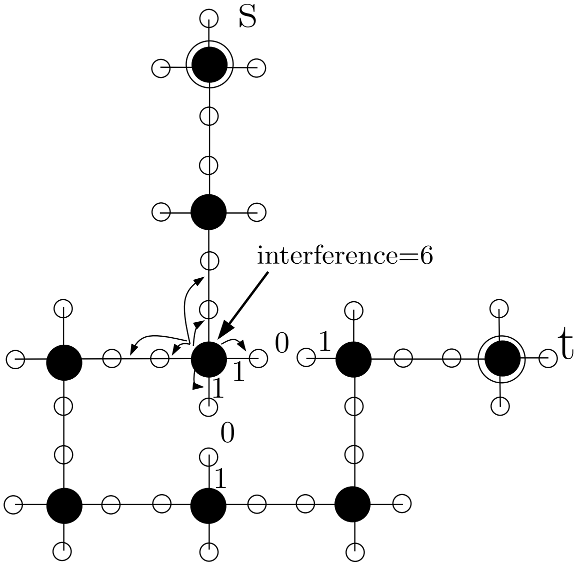


Figure 3.7: Edge-to-Node interference: to limit the interference at the central cities, at most two middle edges should be linked for each central city.

The interference at various edges is computed as follows:

- Middle edge: it interferes with 2 cities (or special cities) and 2 towns. The interference at a middle edge is therefore at least $2(C-1)+2(T-1)$. If all the towns and cities are connected, the maximum additional for a middle edge is 8. In addition, if it connects 2 special cities, then there is a special additional interference of 2.

- Local edge: it interferes with 1 city (or special city) and 5 towns. The interference at a local edge is therefore at least $(C-1)+5(T-1)$. If all the towns and cities are connected, the maximum additional for a local edge is 8. If it is connected to one special city, then there is a special additional interference of 1.

- Inside a special central city: if there are $C+1$ nodes inside a special central city, then one edge inside a special central city interferes with at least $C-1$ edges. It also creates an interference of $4(T-1)$ with the edges in each of the 4 surrounding local towns. If all the towns and cities are connected, the maximum additional interference at a local edge is 8.

- Inside a town: if there are T nodes inside a town, then one edge inside a town interferes with at least $T-2$ edges. It also creates an interference of $(T-1)$ with the edges of the neighboring town, and $(C-1)$ with the edges of

Type	Base Interf.	Max Extra Interf. + Max Special Interf.
inside a special central city	$4(T-1)+(C-1)=32$	$8+0$
inside a town (if $T \geq 2$)	$(T-1)+(C-1)+(T-2)=15$	$6+1$
local edge	$(C-1)+5(T-1)=40$	$8+1$
middle edge	$2(C-1)+2(T-1)=16$	$8+2$

Table 3.1: Interference table for general grid graphs with T=9. The base interference accounts for the edges inside cities. The extra interference is calculated based on the maximum possible interference if all the middle and the local edges are all linked. The special interference accounts for the fact that some of the central cities that affect an edge can be special.

> he neighboring city. If all the towns and cities are connected, the maximum additional for a local edge is 6.

Table 3.1 summarizes the interferences at various edges.

We can observe that the base interference at the local edges can be forced to be greater than for any other type of edges by choosing T big enough compared to C. For example, we can choose $C = 1$ and $T = 10$ (so the base at local edges are at least 45, and for the special central cities is at most 44 including extra). Note that, there are at least 1 local edge per central city, so that the set of present local edges is not empty. Also observe that a middle edge affects the interference of the 8 local edges around the two surrounding central cities; while a local edge only affects the other three local edges adjacent to its central city, and one local edge that is adjacent to the next closest central city. Therefore, for each two central cities that are not connected, it is always more beneficial to choose the two local edges to be linked, and the middle edge to be not linked.

The smallest value of T for which the maximum interference remains on local edges is for $T = 9$.

We set

$$K = \underbrace{40}_{base} + \underbrace{4}_{local} + \underbrace{2}_{middle} = 46$$

so that we only allow at most two middle edges to interfere with local edge e that is adjacent to a regular central city, and only one middle edge if e is adjacent to a special central city. So that we have the same situation as in the case of Edge-to-Node interference: The solution with $MIN\_MAX\_LINK\_UTILIZATION \leq K$ exists if and only if at least 2 middle edges are not linked around each central city;

Type	Base Interf.	Min Extra Interf.
inside a special central city	$4(T-1)+(C-1)=16$	5
inside a town (if $T \geq 2$)	$(T-1)+(C-1)+(T-2)=7$	3
local edge	$(C-1)+5(T-1)=20$	4
middle edge	$2(C-1)+2(T-1)=8$	2

Table 3.2: Interference table for connected graphs

and at least 3 middle edges are not linked around the two special cities. Therefore, the case of Edge-to-Edge interference is NP-hard as well.

In fact, we proved a stronger result: we cannot decide between cases $K = 6$ and $K = 7$ in the first case and between $K = 46$ and $K = 47$ in the second case. In other words, a polynomial time approximation algorithm within constant better than 7/6 (47/46, respectively) for Edge-to-Node (for Edge-to-Edge, respectively) interference model does not exists unless $P = NP$.

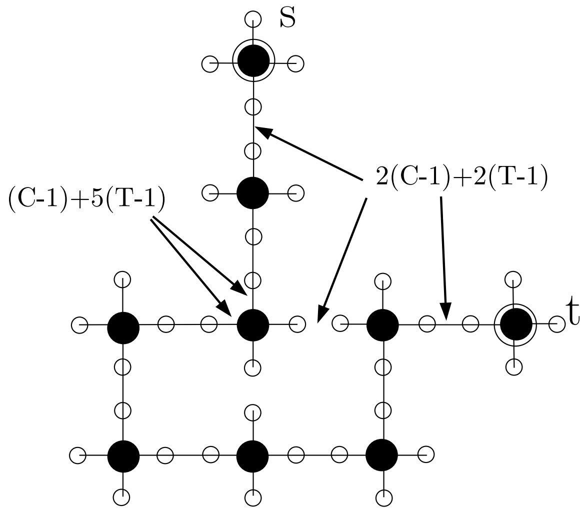


Figure 3.8: Edge-to-Edge interference: the base interference for local edges and middle edges is shown as a function of the size of the towns and cities

It is is worth noting that in this latter case, the bound on the approximation ratio has been determined without relying on any assumptions of the structure of the network graph considered. However, if we assume that the graphs are connected, the bound is worst due to the additional interference resulting from the activation of some edges.

Table 3.2 gives the interferences at various edges.

Let us set the size of every central city to $C = 1$, except for special cities for which we set the size to be $C + 1 = 2$; and we set the size of all towns to $T = 5$.

The same analysis is performed as for non-connected graphs. The base interference on local edges consequently becomes 20.

Similarly, we set

$$K = \underbrace{20}_{base} + \underbrace{4}_{local} + \underbrace{2}_{middle} = 26$$

so that we only allow at most two middle edges to interfere with local edge e that is adjacent to a regular central city, and only one middle edge if e is adjacent to a special central city. Consequently, under the constraint that the graph is connected, a polynomial time approximation algorithm within constant better than 27/26 for the Edge-to-Edge interference model does not exist unless $P = NP$. In the following section, we propose some centralized solutions to $MIN\_MAX\_LINK\_UTILIZATION$ for a different set of constraints on the routing paths.

3.5 Case 1: 1 interface - 1 channel

We assume that all routers are equipped with one single network interface and all are configured on the same frequency channel.

Definition A link e is defined as *active* if the traffic flow f on e is such that $f(e) > 0$.

Two different scenarios can be distinguished depending if the most congested link (with the highest utilization) is carrying a positive traffic load (and therefore can be considered as active) or not. To illustrate the importance of making such a distinction, let us consider the following example depicted in Fig. 3.9.

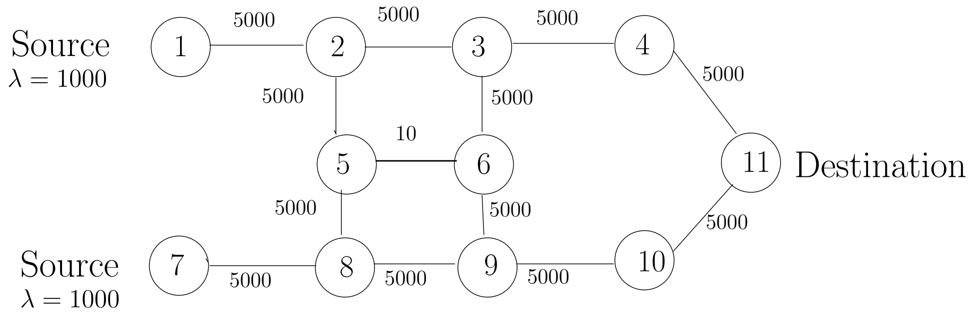


Figure 3.9: 2-source network: Node 1 and Node 7 are sending their traffic to Node 11. The link capacities are reported on the graph.

Node 1 and Node 7 are sending 1000 units of traffic to Node 11. In this particular example, Link 5-6 is congested if the traffic flows follow the paths as highlighted in

Fig. 3.10. If we account for the interference of all links regardless of their activity, then Link 5-6 is the bottleneck. Indeed, the utilization level on Link 5-6 is:

$$I_{5,6} = \sum_{(k,l) \in Inf_{5,6}} \frac{f(k,l)}{C(k,l)}$$

where $Inf_{5,6}$ is defined as the group of links for which at least one endpoint is at interference range of Node 5 or Node 6, $f(.)$ is the traffic flow and $C(.)$ the link capacity. We therefore have $I_{5,6} = 6 * 1000/5000 = 6/5$.

Consequently, given our traffic characteristics, to remain under the congestion level (*i.e.* to remain below a link utilization of 1), only 5/6 of the initial traffic load can be supported by the network. However, if we restrict the problem to considering only the active links, all the traffic demands can be accommodated as none of the active links is over utilized.

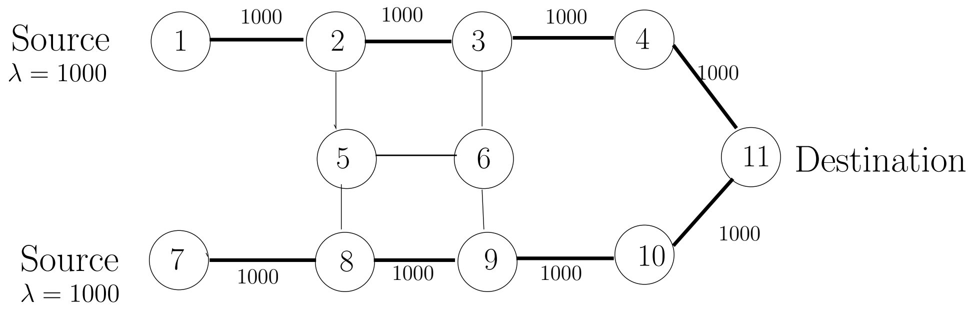


Figure 3.10: 2-source network: Link 5-6 is congested

3.5.1 General Case: Linear Programming Formulation

We first consider that the utilization on all links is accounted for, regardless of their actual traffic load. The problem can be formulated as a linear programming problem and therefore can be solved in polynomial time. The basic idea of the algorithm consists of determining the optimal capacity ratio α to apply to the link capacities that minimizes the maximum link utilization with respect to the flow conservation and interference constraints. The rationale behind this approach relies on the observation that the utilization I_{ij} of a link (i,j) is bounded by 1. Therefore, in order to minimize the maximum link utilization, it is sufficient to find the minimum value of α such that $I_{ij} \leq \alpha$.

The network can be abstracted by a directed graph $G = (V, E)$ in which each edge $(u, v) \in E$ has a capacity $C(u, v) \geq 0$. Given a traffic demand matrix in which source node s_i has a traffic demand d_i strictly positive, $i = 1, .., k$, $k \leq |V|$, the resulting linear problem is similar to the maximum-flow problem with additional constraints on the interference and a new objective function minimizing the cost:

$$\begin{cases} \text{Minimize} & \underline{c^T X} \quad \text{subject to:} \\ \\ \sum\limits_{v \in V} f(u,v) & = \quad \sum\limits_{v \in V} f(v,u) \qquad \forall u \in V \backslash \{s_1, .., s_k, t\} \\ \sum\limits_{v \in V} f(s_i,v) & = \quad \sum\limits_{v \in V} f(v,s_i) + d_i \\ \sum\limits_{u \in V} f(u,t) & = \quad \sum\limits_{u \in V} f(t,u) - \sum\limits_{i=1..k} d_i \\ I_{uv} & \leq \quad \alpha \qquad\qquad \forall (u,v) \in E \end{cases}$$

where $X = [f(1,2), .., \alpha]$, and $c^T = [\underbrace{0; 0; ..; 0}_{2m}; 1]$.

Let m be the number of links and n the number of nodes. The interfering sets for each link can be easily computed in $O(m \log m)$. The most complex subroutine is to solve the linear program as defined above. Linear programs have been shown to be solvable on the worst case in $O((m+n)^3 L)$ arithmetic operations [47] [130], where L is a parameter measuring the precision needed to perform the arithmetic operations exactly [125]. Therefore, computing a load-balanced flow allocation with Min-Max interference can be achieved in $O(m \log m + (m+n)^3 L) = O((m+n)^3 L)$.

3.5.2 Problem Extension with Active Links Only

In this problem, we ignore the links that are not carrying any strictly positive load. Indeed, if no traffic is exchanged between two directly connected nodes it is not meaningful to consider the utilization level of the link between these two nodes. We showed in Section 3.4 that this instance of the problem is NP-Hard. Therefore finding an optimal solution to this problem requires us to compute, for all subsets of links, the minimum achievable utilization while ignoring the interference on the remainder of the links that are considered as inactive. As finding the solution takes exponential time, we propose a heuristic (Alg. 1) that runs in polynomial time. The algorithm iteratively determines the link with the highest utilization. It then applies one of the following two cases depending on the actual traffic load on this link.

1. **Case 1: Link is Inactive**. This link is ignored in the subsequent iterations, its flow is set to zero and its capacity is set to infinity.
2. **Case 2: Link is Active**. Either there exists another feasible flow assignment in which the flow on this link is null but this link still has the highest interference level. In that case Case 1 applies. If there is no such alternative, the algorithm terminates.

This algorithm requires $O(m)$ additional iterations to terminate.

Algorithm 1 Minimize the Maximum Utilization with Active Links Only

```
Calculate the interfering set for each link
Calculate the optimal load assignment, which yields a capacity ratio CapacityRatio
CurrentCapacityRatio=CapacityRatio
while true do
    Set the flow on the bottleneck link to 0
    Calculate the optimal load assignment
    if CapacityRatio $\leq$ CurrentCapacityRatio then
        CurrentCapacityRatio = CapacityRatio
    else
        Return traffic flow matrix
    end if
end while
```

3.5.3 Problem Extension with Paths Length Constraints

We then study $MIN\_MAX\_LINK\_UTILIZATION$ by adding a constraint on the path length. The feasible set of paths between a source and a destination should only include disjoint paths with bounded length. The path disjointness constraint ensures some degree of network reliability, whereas the maximum path length constraint enforces that the end-to-end delay remains within certain bounds. If the path length exceeds a certain number of hops, even without congestion, the end-to-end delay can exceed the requirements of delay-sensitive applications.

The k-shortest-paths problem has been studied for different scenarios and different networks environments [34, 53]. In this work, we use a simple implementation described in Algorithm 2 that performs well for a small number of paths. More complex algorithms can be implemented if the number of paths required becomes more important. To determine the running time of this algorithm, let us consider an undirected graph $G = (V, E)$ with n vertices and m edges, and k a positive

Algorithm 2 k-shortest simple paths algorithm with minimum path length

```
k=1
Compute minimum path length
while $k \leq min(edge - connectivity(s), edge - connectivity(t))$ do
    Compute paths
    if Maximum path length > Minimum path length then
        break
    end if
end while
```

integer. Let s and t be the source node and destination node respectively. The k-shortest paths between s and t can be found in $O(k(m + n\log n))$ [146] [147]. As k can not exceed the degree of s and t, in at most m iterations, k-shortest paths with minimum path length can be found.

Due to the path constraint, the problem needs to be reformulated as a multicommodity-flow problem [25]. Let W be the set of all Origin-Destination (OD) pairs. To a given OD pair w is associated a traffic demand d_w. P_w represents the set of all shortest paths for this OD pair with each path $p \in P_w$ carrying a traffic flow x_p. Let f_i be the flow originated by the OD pair i and f the aggregate traffic flow. For each OD pair w, we therefore have the following constraints:

$$\left| \begin{array}{l} \sum\limits_{p \in P_w} x_p = d_w, \qquad \forall w \in W \\ x_p \geq 0, \qquad \forall p \in P_w, w \in W \\ f(u,v) = \sum\limits_{1,..,k} f_i(u,v) \end{array} \right.$$

The optimal routing problem as previously described can therefore be formally expressed as:

$$\left\{ \begin{array}{lcl} \text{Minimize} \quad \underline{c^T X} \quad \text{subject to:} & & \\ & & \\ \sum\limits_{v \in V} f_i(u,v) & = & \sum\limits_{v \in V} f_i(v,u) \qquad \forall u \in V \backslash \{s_i, t\} \\ \sum\limits_{v \in V} f_i(s_i,v) & = & \sum\limits_{v \in V} f_i(v,s_i) + d_i \\ \sum\limits_{u \in V} f(u,t) & = & \sum\limits_{u \in V} f(t,u) - \sum\limits_{i=1,..,k} d_i \\ I_{uv} & \leq & \alpha \qquad \forall (u,v) \in E \end{array} \right.$$

$$\text{where } X = [f_1(1,2),..,\alpha], \text{ and } c^T = [\underbrace{0;0;..;0}_{2km};1].$$

3.5.4 Problem Extension with Path Lengths Constraints and Active Links Only

This problem combines the two problems previously described. For each source, the set of feasible paths is restricted to those respecting the path length constraints. In the optimization problem, only the links carrying a strictly positive traffic flow can be eventually selected as most congested links. The implementation details are given in Alg. 3.

Algorithm 3 Minimize the Maximum Interference for Maximum Network Utilization with Bounded Number of Hops

```
Calculate the interfering set for each link
Calculate the k-shortest simple paths with minimum length for each source to the destination
Calculate the optimal load assignment that yields a capacity ratio CapacityRatio
CurrentCapacityRatio=CapacityRatio
while true do
  Find the most interfering links
  for each of these interfering links do
    Remove the link from the connectivity graph
    Calculate the optimal load assignment
    if CapacityRatio $\leq$ CurrentCapacityRatio then
      CurrentCapacityRatio = CapacityRatio
    end if
  end for
  if CurrentCapacityRatio $\geq$ CapacityRatio then
    Return traffic flow matrix
  end if
end while
```

3.5.5 Evaluation

Simulation Setups

We evaluated the performance of our algorithms via simulations for different network configurations. In particular we tried to determine the impact of the network size and of the traffic demand on the network utilization. The network topologies were randomly generated in an area of 1000x1000 m^2. All nodes have equal transmission range set to 20 and the interference range is assumed to be of the same order as the transmission range. Note that although we assume a uniform signal propagation, which is not a realistic assumption, it does not impact the validity of our results as we are only dealing with adjacency and interference matrices. The network topologies used are generated without any additional constraints other than to ensure network connectivity (and that therefore there exists a path between any pair of nodes). Link capacities are randomly chosen between 1 and a maximal capacity C_{max} such that the maximum traffic demand is k times smaller than the maximal capacity (in order to favor the appearance of congestion points when the network grows). k has arbitrarily been set to 50. Simulations have been performed 50 times for each configuration set.

The goal of these simulations is to establish:

1. The influence of the network size on the interference level with a constant percentage of sources generating some traffic load.
2. The influence of an increasing traffic demand on the interference level for a fixed number of nodes.

For simplicity, we refer to the schemes we implemented by:

1. *MLU*: Algorithm minimizing the maximum link utilization;
2. *MLU-A*: Algorithm minimizing the maximum utilization with active links only;
3. *MLU-PC*: Algorithm minimizing the maximum utilization with paths length constraints;
4. *MLU-APC*: Algorithm minimizing the maximum utilization with active links only and path length constraints;
5. *SP*: Shortest path routing algorithm.

Influence of Network Size

Figure 3.11 depicts the variation of the link utilization when the number of nodes varies from 10 to 50. The proportion of sources is set to 33% of the total number of nodes. It is worth noting that we do not constrain the link utilization level to be less than 1 in order to differentiate the degrees of network congestion in the different scenarios considered.

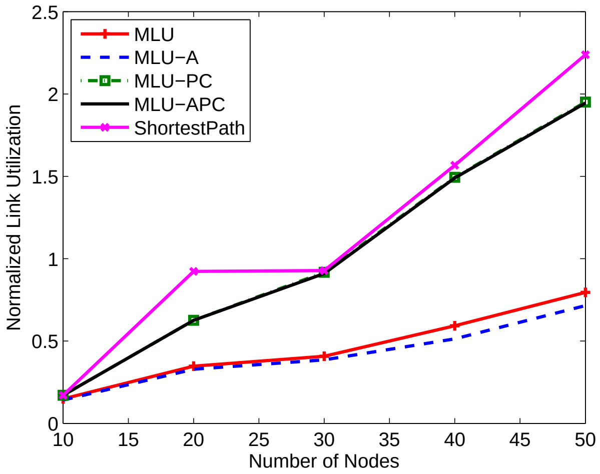


Figure 3.11: Normalized Link Utilization vs. Network Density

We can observe in Fig. 3.11 that the five algorithms perform as expected. *MLU* and *MLU-A* outperform *MLU-PC* and *MLU-APC* due to the path constraints that prevent the use of longer paths less prone to congestion. The shortest path routing algorithm, without load balancing strategy, leads to higher link utilizations. Compared to *MLU-PC* and *MLU-APC*, the shortest path routing algorithm does not perform as poorly as one could expect as the topologies considered initially are very small (10 nodes). Therefore the number of possible shortest paths for each source-destination pair is limited. But we can observe that as the network grows, the difference in performance becomes more significant. The advantage of the optimization introduced with *MLU-A* appears more distinct compared with *MLU* as the network size increases.

Table 3.3 reports the standard deviation for the simulation sets. As previously mentioned, we ran 50 simulations for each scenario. *MLU-PC*, *MLU-APC* and *SP* are very sensitive to the topology, and if it appears that a link of low capacity is on the shortest path to the destination, the congestion level increases drastically.

Nb Nodes	MLU	MLU-PC	MLU-A	MLU-APC	SP
10	0.19	0.19	0.37	0.37	0.37
15	0.35	0.34	0.76	0.76	0.76
20	0.22	0.22	0.44	0.43	0.43
25	0.28	0.28	0.53	0.53	0.57
30	0.78	0.78	0.99	1.0	0.98
35	0.32	0.32	0.82	0.82	0.93
40	0.44	0.44	0.96	0.96	1.03
45	0.52	0.52	1.15	1.14	1.18

Table 3.3: Standard Deviation: Influence of the network size

Influence of Increasing Traffic Demand

We then study the impact of an increasing traffic demand on the performance of the algorithms. We consider a network topology of 30 nodes, and progressively increase the percentage of sources to up to 50% of the total number of nodes.

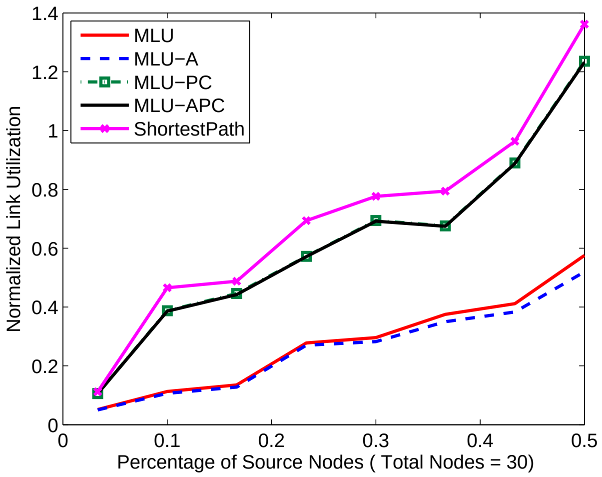


Figure 3.12: Normalized Link Utilization vs. Number of Source Nodes

Figure 3.12 depicts the normalized link utilization averaged over 50 simulation runs with an increasing number of source nodes. We can observe that although the relative performance of the algorithm remains the same, *MLU* (and therefore *MLU-A*) exhibits a more stable behaviour and less sensitivity to an increasing traffic load as a result of a better load repartition. *MLU-PC* and *MLU-APC* rapidly suffer from congestion and we can observe that their performance progressively degrades as the number of source nodes increases.

The standard deviation reported in Table 3.4 supports the conclusion drawn previously and illustrates the lack of adaptability of pure shortest paths schemes

Src (%)	MLU	MLU-PC	MLU-A	MLU-APC	SP
2	0.04	0.04	0.31	0.31	0.31
6	0.08	0.09	0.22	0.22	0.44
10	0.13	0.13	0.93	0.93	1.21
14	0.29	0.29	0.74	0.74	0.81
18	0.12	0.12	0.58	0.58	0.54
22	0.98	0.99	1.34	1.34	1.24
26	0.59	0.59	1.11	1.11	1.30
30	0.89	0.88	1.37	1.37	1.33

Table 3.4: Standard Deviation: Influence of the traffic demand

to congestion situations.

We demonstrated that with a proper flow assignment, significantly more traffic can be injected into the network than with multipath or shortest-path routing algorithm. Although many variants of these routing algorithms have been proposed and can be compared, our aim was to provide some indication of the link utilization that can be reached under various scenarios. This highlights the benefits of exploiting the salient characteristics of the network (presence of a centralized administration) to distribute the traffic load more efficiently resulting in more effective network utilization. In the following section, we design and investigate the efficiency of several algorithms when multiple non-overlapping channels are available.

3.6 Case 2: 1 interface - K channels

3.6.1 Clustering Algorithms for Routers to Gateways Association

Assume that the number of channels available is greater than the number of gateways so that each gateway can be assigned a dedicated channel. We design several clustering heuristics that associate routers to gateways such that the resulting clusters are connected and each contains exactly one gateway. The solutions presented are centralized. A centralized approach is particularly appropriate in wireless mesh networks given the static nature of the backbone network and the specific traffic characteristics as previously discussed.

We explore different directions in designing the algorithms depending on criteria such as distance, number of hops, traffic load or interference level. We categorize the algorithms as follows:

- Geographic approaches: routers are assigned to gateways based on their proximity either in terms of hops (Shortest path algorithm), or in terms of Euclidean distance (Voronoi algorithm).
- Load-balanced approaches: routers are assigned to gateways so that the traffic load oriented towards the gateways is distributed as uniformly as possible (Load-based and Node-based Voronoi algorithms).
- Interference-based approaches: routers are assigned to gateways so that the inter-node interference is minimized (Forces-based and Potential-based algorithms).

More precisely, the algorithms we derived work as follows:

- *Shortest paths*: A router is associated to the closest gateway in terms of hops (on a graph it corresponds to the number of edges of unit weight between two nodes). If several gateways are at the same distance from the router considered, one may be selected at random.

- *Voronoi Diagrams*
    1. *Euclidean Voronoi clustering*: a node is associated to the closest gateway (geographically).
    2. *Load-adaptive Multiplicatively Weighted Voronoi clustering*: for each gateway p and for each node X we compute the distance $d(p, X)w(p)$ where $d(p, X)$ is the Euclidean distance and $w(p)$ is a weight. $w(p)$ is computed as follows: $w(p) = (\sum \delta(i, p)L(i))/\sum L(i)$ with $L(i)$ the load at node i and $\delta(i, p) = 1$ if node i is associated with gateway p, 0 otherwise. A more heavily loaded gateway will consequently have a greater weight. At each iteration, a router (randomly chosen among the ones at shortest distance from a gateway) is associated to a gateway and the weight of the remaining routers (not already assigned) is recomputed.
    3. *Node-adaptive Multiplicatively Weighted Voronoi clustering*: Assuming a unit traffic load, i.e. that $L(i) = 1$ for all i, we apply the same algorithm as for the Load-adaptive Multiplicatively Weighted Voronoi clustering.

- *Forces-based clustering*: Each node has a charge $-f_i$, that corresponds to its traffic demand. The rationale behind this setting is that the greater the load at a node, the more resource it consumes. Therefore, other neighboring nodes would have to compete more to access the medium, which might impact their performance. A better load balancing avoiding the congested zones would consequently result in a better nework performance. We model this competition for network resources by repulsive forces. An example is depicted in Fig. 3.13. Since traffic flows are directed towards gateways, the gateways exert an attractive force on the routers. Each gateway has a charge $-g_i \sum f_i / \sum_i g_i$, where g_i is the available bandwidth. The gateways with higher bandwidth consequently have a greater attraction force. For each router i, we calculate the force applied to it, which corresponds to the sum of all the repulsive forces exerted by the remaining routers ($\sum f_i f_j / d(i,j)^2 \vec{u_{ji}}$) plus the attractive forces from the gateways, with $d(i,j)$ the number of hops between router i and j. The sum of these forces results in a force that points towards a direction along which a router should direct its traffic. The gateway that is the closest to this direction is selected by the router as destination.

- *Potential-based clustering*: We use the same underlying idea to derive this algorithm as the one used for the Forces-based algorithm except that we assign to each edge (i,j) a weight called *potential(i,j)* which represents the difference of potentials between the two endpoints. For edge (i,j), $\mathit{potential}(i,j) = ||-f_i - f_j||/d(i,j)$, with $-f_i$ and $-f_j$ the traffic demands of node i and node j respectively. The potential on each edge therefore reflects the intensity of the traffic load it is susceptible to carry. Edges with high potential should therefore be avoided. The gateways are interconnected by wires of infinite capacity which can be represented on a graph by edges of weight 0. We then run Kruskal's algorithm to define the minimum spanning tree therefore removing the edges with high potential. This defines the gateway a router should send its traffic its.

3.6.2 Algorithms Illustration

To illustrate the difference in outputs obtained with the aforementioned algorithms, even in scenarios involving simple topologies and limited number of nodes, we show the clusters obtained for a grid topology composed of 49 routers. The routers located at the corners of the network are gateways (node with IDs 1, 7, 43 and 49). We also positioned 9 traffic sources at predetermined positions (bold nodes in the

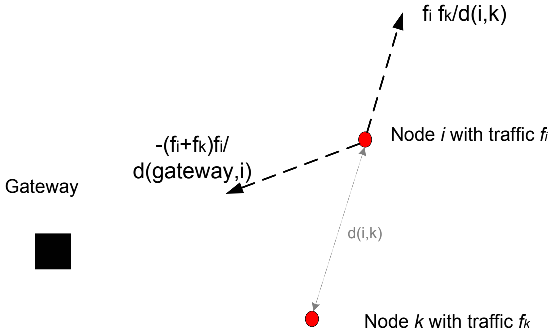


Figure 3.13: Example of forces interaction: the gateway exerts an attractive force on Node i whereas Node k exerts a repulsive force

Algorithm 4 Shortest-Path Clustering

```
INPUT: Graph (V,E)
OUTPUT: Clusters
$Vtemp = \emptyset$
while $V \neq \emptyset$ do
    for each node $i$ in $V$ do
        for each gateway do
            calculate shortest path
            if $path < infinity$ then
                $Vtemp = Vtemp \bigcup i$
                $V = V \backslash \{i\}$
            end if
        end for
    end for

    Sort nodes according to the possible number of destination gateways
    while $Vtemp \neq \emptyset$ do
        currentNode=Vtemp(1)
        if number of gateways = 1 then
            $Vtemp = Vtemp \backslash \{currentNode\}$
            Associate currentNode to gateway
        else
            randomly associate node to one possible solution gateway
        end if
    end while
end while
```

Algorithm 5 Force-based clustering

```
INPUT: Graph (V,E)
OUTPUT: Clusters
for each node $i$ in $V$ do
    for each node $j$ in $V \setminus \{i\}$ do
        calculate attraction force
        associate nodes to the gateway it is attracted the most
    end for
end for
Calculate nb Nodes not connected
while Nb Nodes not connected $> 0$ do
    for each node not connected do
        nbNodesNotConnected –;
        check connectivity with other gateway and associate to the one it is the most attracted to
        if not Connected then
            nbNodesNotConnected ++;
        end if
    end for
end while
```

Algorithm 6 Potential-based clustering

```
INPUT: Graph (V,E)
OUTPUT: Clusters
for each node $i$ in $V$ do
    for each node $j$ in $V \setminus \{i\}$ do
        calculate attraction force
    end for
end for
for each edge $(i, j)$ in $E$ do
    calculate potential
end for
run Kruskal's algorithm
```

Algorithm 7 Voronoi Clustering

```
INPUT: Graph (V,E)
OUTPUT: Clusters
for each node $i$ in $V$ do
    for each gateway do
        calculate distance to gateway
    end for
end for
associate node $i$ with the gateway $k$ with min distance
Calculate nb Nodes not connected
while Nb Nodes not connected $> 0$ do
    for each node not connected do
        nbNodesNotConnected –;
        check connectivity with other gateway and associate to the closest one if possible
        if not Connected then
            nbNodesNotConnected ++;
        end if
    end for
end while
```

figures). The link capacity is set to 1000 units per second and the traffic sources sent 500 data units per second.

We can see in Fig. 3.15, 3.16, 3.17, 3.18, 3.19 and 3.20 that the algorithms can lead to different clusters depending on the metric being optimized.

In the following section, we investigate the performance of the different algorithms in terms of link utilization (average and maximum) and load balancing (standard deviation of the traffic going through each gateway).

3.6.3 Simulation Results

We evaluated the performance of the heuristics described in the previous section under different scenarios. We primarily focused on the performance of the algorithms in terms of link utilization and load balancing.

Simulation Environment

To solve the linear programs, we used the standard algorithm provided by Matlab based on the simplex method. We assumed that a central entity is responsible for

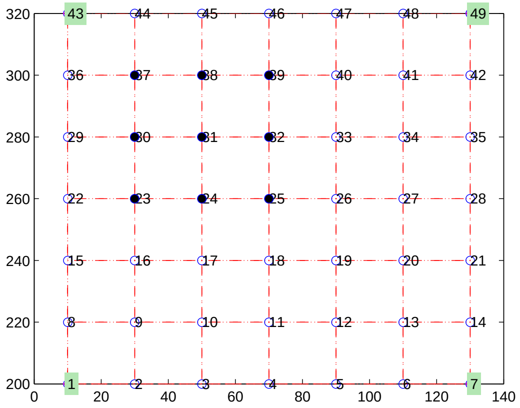


Figure 3.14: Grid topology with 49 routers in total and 4 gateways

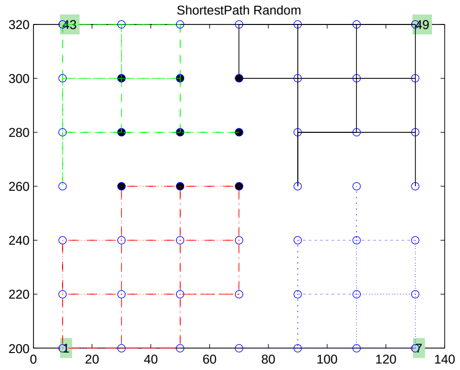


Figure 3.15: Random Shortest Path clustering

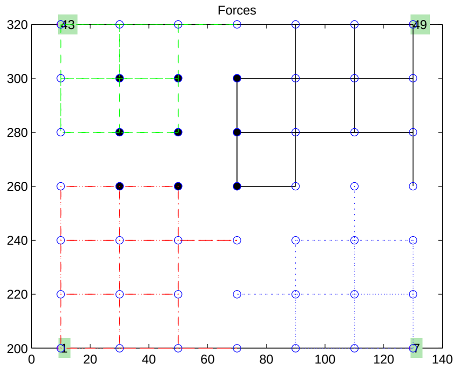


Figure 3.16: Forces-based clustering

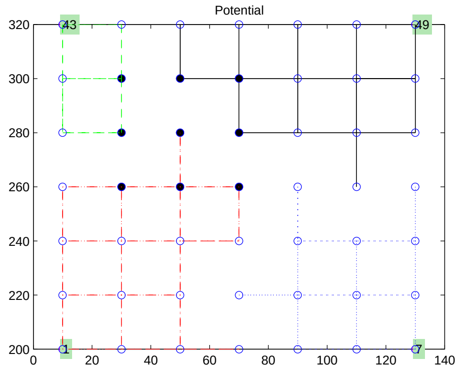


Figure 3.17: Potential-based clustering

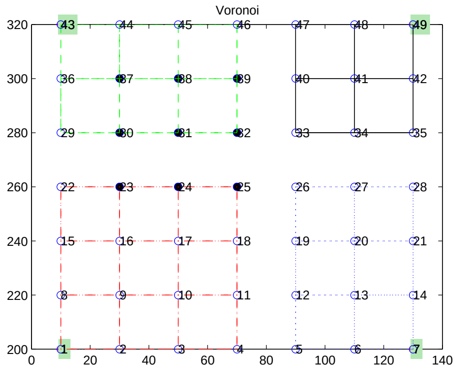


Figure 3.18: Euclidean Voronoi clustering

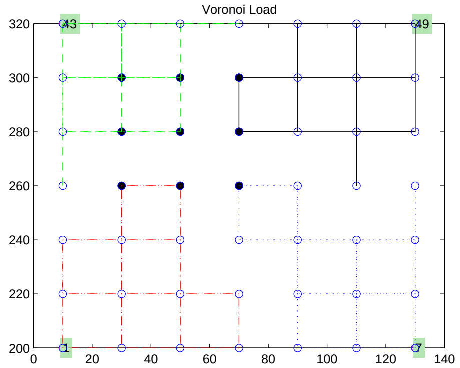


Figure 3.19: Load-adaptive Multiplicatively Weighted Voronoi clustering

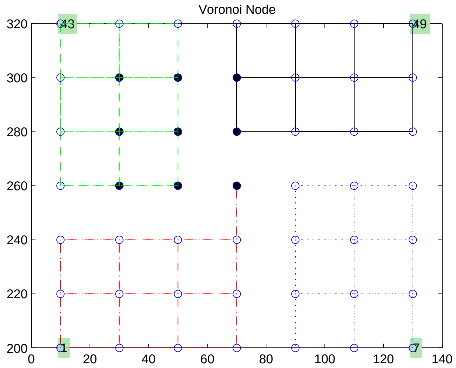


Figure 3.20: Node-adaptive Multiplicatively Weighted Voronoi clustering

the route computation and can efficiently transmit this information to the routers with minimum overhead. We also assumed a 2-hop interference model, i.e. all the nodes at transmission range of the sender and receiver should remain silent for the data transmission to be successful.
We used a 100-node grid network topology and the topology of an existing deployed network from the city of Chaska, Minnesota [94] to evaluate the performance of the algorithms.

Grid topology

We studied the impact of an increasing traffic load on the network utilization on 100-node networks. 4 gateways are located at each corner of the grid network. We increased the number of source routers from 50 to 95, and assigned to each router a traffic demand randomly chosen between 0 and 20 kbit/sec. The link capacity is the same for each router and is set at 1Mbit/sec. We ran 50 tests for each configuration. Fig. 3.23, Fig. 3.24 and Fig. 3.25 depict the results of the simulations.

We can observe that the Forces-based algorithm gives the best performance in terms of maximum link utilization. It also balances the load more evenly among the gateways as shown in Fig. 3.25. The Voronoi-based algorithm and the Shortest-Path algorithm perform relatively poorly as the number of source routers increases due to the fact that they ignore the traffic distribution. The Potential-based approach achieves the worst performance since the links used to route the traffic flows (edges on the graph) are solely chosen based on their weight which can lead to an unbalanced traffic distribution at the gateways.

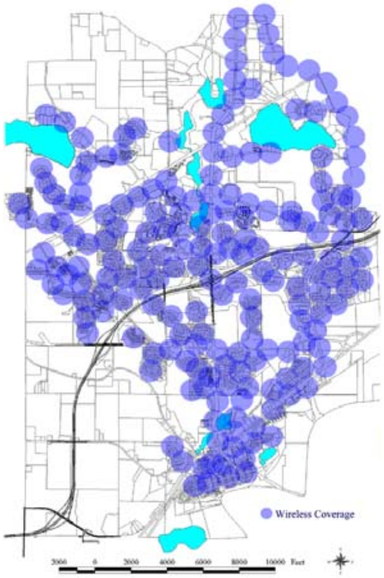


Figure 3.21: Wireless coverage of Chaska and its neighboring communities

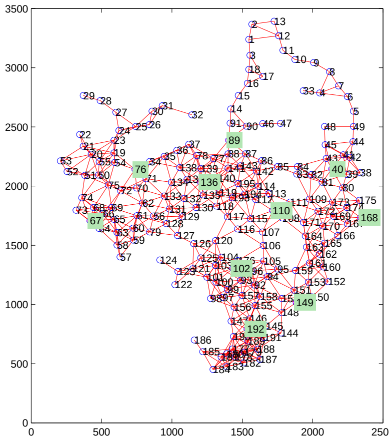


Figure 3.22: Graph representation of the wireless coverage of chaska. The gateways are highlighted in squares.

Chaska network

We further evaluated the algorithms using the wireless network topology of the city of Chaska in our simulations [94] as it exhibits some desirable properties: the network is composed of a large number of nodes (195) which are non-uniformly distributed. As can be observed in Fig. 3.22, there exists a number of holes in the network topology and routers have different degrees of connectivity. As no information on the transmission range and on the actual locations of the network gateways was available, we performed some preliminary analysis and set the transmission to 230m so as to guarantee that the whole network is connected. The gateways have been placed as uniformly as possible with a preference for the densest areas (in terms of number of neighboring routers). Following the guidelines in actual network design, we set the number of gateways to 10 such that one gateway serves on average around 20 routers. We also fixed the link capacities at 1Mbps at the beginning of the simulations.

We can observe in Fig. 3.26, Fig. 3.27 and Fig. 3.28 that the router-to-gateway allocation using the Forces-based algorithm still performs the best overall. The geographic-based approaches based on Euclidian distances are more sensitive to geographical disparities consequently leading to the poorest performance. The Potential-based and the Shortest-path algorithms alleviate this problem by considering the number of hops between routers instead of Euclidean distances. The

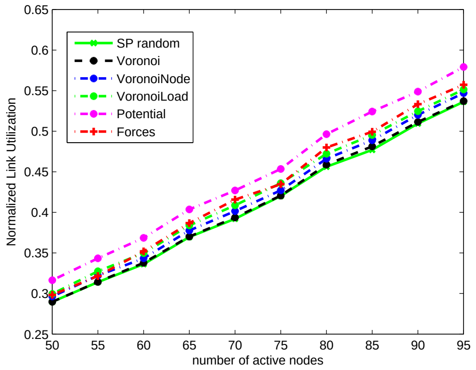


Figure 3.23: Grid Networks: Average Link Utilization at each gateway with Increasing Traffic Load

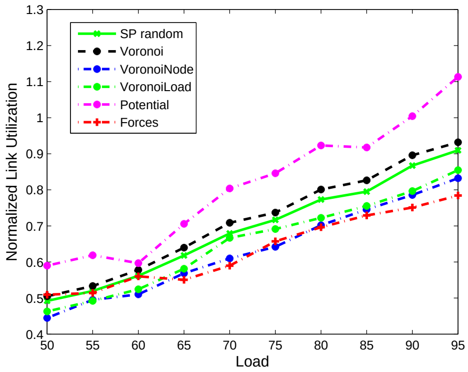


Figure 3.24: Grid Networks: Maximum Link Utilization at each gateway with Increasing Traffic Load

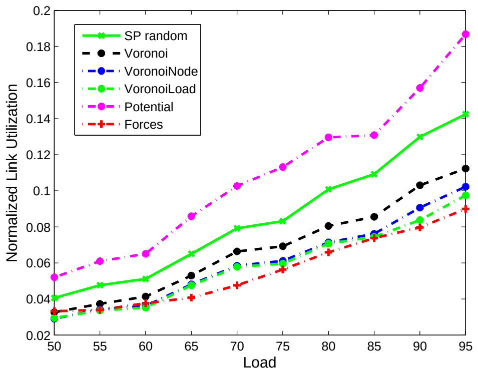


Figure 3.25: Grid Networks: Standard Deviation of the Link Utilization at each gateway with Increasing Traffic Load

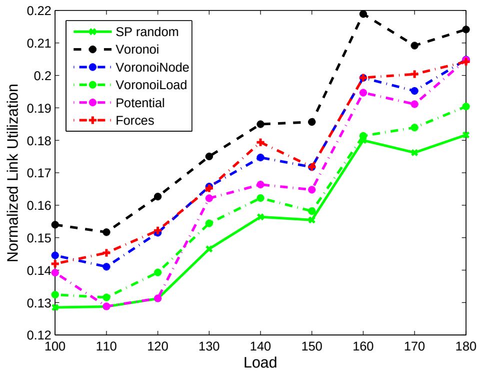


Figure 3.26: Chaska Network: Standard Deviation of the Link Utilization at each gateway with Increasing Traffic Load

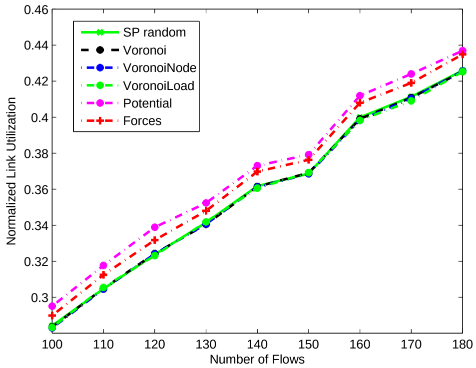


Figure 3.27: Chaska Network: Average Link Utilization at each gateway with Increasing Traffic Load

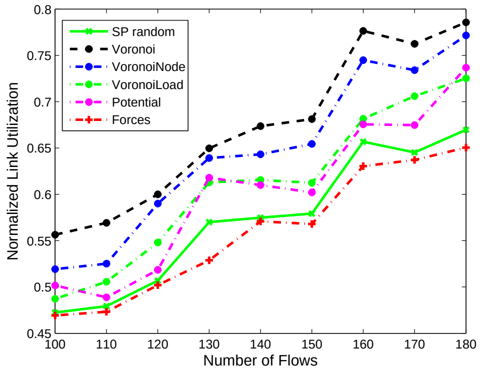


Figure 3.28: Chaska Network: Maximum Link Utilization at each gateway with Increasing Traffic Load

Shortest-path algorithm achieves the best load distribution as a consequence of the uniform distribution of the gateways and source routers.

Another interesting question to address is - once the router to gateway association has been achieved, which routing approach, multipath or single path is preferable. In the next Chapter, we address this problem in a general context, considering a large number of nodes, and multiple sources and destinations.

3.7 Conclusion

By exploiting the properties inherent to wireless mesh networks, we showed that improvements in terms of link utilization and load balancing can be achieved. In particular, the deployment of multiple gateways and the possibility of selecting one (or several) of them to direct the traffic to can greatly improve the network utilization.

Our contributions are the following. We showed that the problem of minimizing the maximum link utilization in wireless mesh networks is NP-hard. In fact, we proved that the solution to this problem is hard to approximate to within a factor of 7/6 (47/46, respectively) for Edge-to-Node (for Edge-to-Edge, respectively) interference models unless $P = NP$. We distinguished the scenario in which one channel is available and proposed a greedy algorithm based on a linear formulation of the problem. When more than 2 channels are available, we designed several heuristics and evaluated them under different constraints. We then showed that depending on the metric evaluated (average link utilization, maximum link utilization, or standard deviation), disparities in terms of performance can occur. Overall the Forces-based algorithm exhibited the best performance in the cases considered.

Chapter 4

Interference-Aware Routing Metric

4.1 Introduction

Recently, the number of proposals for routing metrics tailored to wireless mesh networks has flourished. Through different strategies, the proposals try to evaluate the levels of interference and route the traffic flows around the most congested areas. But so far, none of them has been widely adopted. There are several reasons to explain this:

Level of complexity: Unlike some topological or traffic-related parameters that can be easily obtained, measuring the level of interference is a challenging task. First, the channel quality can be hard to assess as it changes in space and time. A sender and receiver can potentially suffer from different levels of interference, that can lead to a poor quality of communication (with a high packet loss) if the transmission rates are not properly adjusted. Second, the shared nature of the transmission medium makes it difficult to properly evaluate a link utilization as all the nodes in the same neighborhood configured on the same frequency band can freely compete to access the transmission medium. Unless exact information on the traffic characteristics for all the nodes can be maintained and assuming a perfect data scheduling, only a rough approximation of the actual network status can be obtained. Moreover, the exchange of control messages is usually required to propagate link quality measurements. The cost involved in these operations can overshadow the actual improvement obtained by avoiding lossy or congested links.

Lack of comparisons: To the best of our knowledge, no complete evaluation of the existing contributions in this area has been performed. Each proposed metric has been evaluated in a limited number of scenarios, with specific parameters and compared with only a small subset of the existing routing metrics [20].

Lack of insights: The existing evaluations of the different routing metrics for wireless mesh networks have only been conducted for some very contrived scenarios. Insights on the metrics' efficiency in different situations have rarely been provided. It is therefore difficult to extrapolate on the performance of a particular metric if different network settings are considered.

Previous experiments conducted in [35] have shown that currently implemented metrics (Hop Count, Expected Transmission Count, Expected Transmission Time) perform similarly. This suggests that the metrics are essentially equivalent. In fact, only Hop Count, the simplest metric, distinguishes itself in mobile networks, as the other metrics do not adapt quickly enough to topology changes [31].

To deal with the above limitations, we propose a routing metric that evaluates each link's effective share of the medium [118]. The Interference-Aware Routing metric (IAR) MAC-level measurements determine the percentage of time each transmission wastes due to interference from other nodes. This wastage occurs in the form of backoff and waiting time, as well as failed transmissions. Routing using IAR selects links that experience the least interference. We demonstrate through simulations the benefit of IAR compared to some of the most commonly used routing metrics for wireless mesh networks notably Hop Count, Blocking Metric, ETX, mETX, ETT, NAVC and MIC.

4.2 Chapter Organization

The remainder of this chapter is organized as follows. In Section 4.3, we define a set of criteria against which the chosen metrics will be compared. We then discuss the implementation of existing routing metrics in Section 4.4. In Section 4.5, we describe our interference-aware routing metric. The results of the evaluations are presented in Section 4.6. Finally, we conclude this chapter in Section 4.7.

4.3 Route Selection Parameters

Routing in WMNs extends network connectivity to end users through multi-hop relays. Packets can be routed via one or multiple paths, possibly using several different channels. Depending on the application requirements, a routing protocol can focus on optimizing one or more routing metrics. Path length, end-to-end delay or packet loss represent some parameters whose importance varies depending on the level of quality requested by an application. Interference also constitutes an important factor to account for. Indeed, in wireless communications, severe performance degradation can result from interference of concurrent data transmissions. The shared transmission medium constrains all nodes in the interference range of a sender or receiver to inactivity until completion of the ongoing communication. Therefore, when a new flow is to be sent across the network, it is important to realize that the actual expected performance can not simply be estimated without considering the flows already established and without considering the impact of adding this new flow on top of the existing ones. In order to give a clear overview of the focus of the routing metrics considered and before delving into the details of their design, we first define a set of criteria against which we may compare these routing metrics. This list, although not exhaustive, encompasses a set of factors that we consider have the greatest impact on the performance of a wireless mesh network.

Different parameters can enter into the computation of a routing metric. Among them, the ones that can be considered as the most characteristic of wireless networks are the following:

- *Path Length*: The number of hops between a source router and a destination router is an important and the most commonly used comparison criterion as longer paths mean more self-interference (interference among links along the same path) and consequently potentially greater end-to-end delay. The difference in self-interference apply only to paths with length less than 5 hops, since a node can only interfere with nodes 2 hops away. Flows transmitted via a long path also interfere with a greater number of links located geographically close to this path.

- *Bandwidth*: Network links can support different data rates as a result of technical limitations or in the case of wireless networks, environmental noise and signal strength. This difference in capacity affects not only the link considered but also the residual capacity of geographically close links. Indeed, the use of a lower-capacity link not only increases the transmission delay of the flow crossing the link considered, but reduces the achievable rate of neighboring transmissions by increasing their interference level. As current hardware allows rate adaptation depending on the quality of the transmission medium, obtaining and maintaining this information can help improve the network performance.

- *End-to-end Delay*: Delay-sensitive applications require bounded end-to-end delay in order to function properly. Therefore it is important to evaluate the time it takes for a packet to reach its destination, as well as to estimate the variability (jitter) over all data transmissions.
- *Interference*: Owing to the shared nature of the transmission medium, nodes transmitting on the same channel can interfere with each other if they are located in the same geographical area. Integrating interference into the design of the routing metric can therefore help to combat network congestion and increase overall network performance.
- *Packet Loss*: Channel quality can be assessed by estimating the number of retransmissions necessary for a transmission to be successfully performed.
- *Effective Link Share*: As access to the transmission medium is shared among nodes located in the same area, a communication on a particular link is affected by the transmissions on neighboring links. It follows that a node may have to wait for concurrent communications to complete before it is able to send its own data. Obtaining an estimate of the channel occupation (and therefore the congestion level) is a therefore a desirable task.

We will also distinguish the level of complexity of the routing metrics based on some implementation parameters such as:

- *Per-node/Per-link metric*: a per-link metric can potentially allow fine-grained information of each link to be maintained, whereas a per-node metric assumes by default that all the links attached to a node have the same cost. On the downside, a per-link metric might be costly to maintain (e.g. by incurring extra control messages).
- *Knowledge*: a metric can be computed based on different information: packet loss, number of nodes, number of neighbors, traffic characteristics, etc.
- *Interference*: different strategies with different levels of complexity might be implemented to account for the interference.

4.4 Existing Routing Metrics Description

In this section, we present some routing metrics that are currently used in WMNs. They were either specifically tailored for WMNs or previously developed for other types of networks (e.g. ad hoc networks) but adopted for use in WMNs due to the underlying similarities with WMNs. We consider the following metrics: Hop Count, Blocking Metric, Expected Transmission Count (ETX), Expected Transmission Time (ETT), Modified Expected Number of Transmissions (mETX), Network Allocation Vector Count (NAVC) and Metric of Interference and Channel-Switching (MIC).

4.4.1 Hop Count

Hop count is the most commonly used metric in wireless multihop networks. The path selected is the one minimizing the number of links between a given source and destination node. It became very popular in ad hoc networks due to its ease of computation as it only considers the route length as the differentiating criterion. However, on the downside, this routing metric fails to account for the specifics of wireless environments (links may have different transmission rates, loss ratios, etc.) and it does not consider the congestion level resulting from the shared use of the transmission medium.

4.4.2 Blocking Metric

A simple improvement over hop count has been presented in [138] in order to account for the interference along a certain path. In this work, the interference level referred to as the Blocking Value, is defined as the number of neighbors a node is interfering with. Each node is therefore weighted according to this Blocking Value. The Blocking Metric of a path is then defined as the sum of all the blocking values along the path. Paths with minimum cost will consequently be used to carry the traffic flow.

This technique presents the advantage of being simple, without any additional overhead other than to maintain some information on the number of neighbors. However, this metric still does not incorporate any characteristics concerning the traffic flow or link capacity and only superficially addresses the issue of interference. Little improvement over hop count is therefore to be expected.

4.4.3 Expected Transmission Count (ETX)

Expected Transmission Count is defined as the number of transmissions required to successfully deliver a packet over a wireless link [27]. The ETX of a path is then defined as the sum of the ETX of each link along the path. Let p_f and p_r be the packet loss probability in the forward and reverse directions. The probability p of an unsuccessful transmission is:

$$p = 1 - (1 - p_f)(1 - p_r) \tag{4.1}$$

Therefore, the expected number of transmissions to successfully deliver a packet in 1 hop can then be expressed as:

$$ETX = \sum_{k=1}^{\infty} kp^k(1-p)^{k-1} = \frac{1}{1-p} \tag{4.2}$$

The delivery ratios are measured using 134-byte probe packets. One probe packet is sent every τ second (set to 1 sec in the experiments that follow later in the chapter). The packet loss ratio is computed by counting the number of probe packets received over a predetermined period of time (10 seconds in the experiments).

ETX favors paths with higher throughput and lower number of hops as longer paths have lower throughput due to increased self-interference. However, this metric does not consider differences in transmission rates. It does not completely account for the interference on the transmission medium as the sender of a probe packet can defer its transmission if it senses the channel is busy. As the transmission rate of the probe packets is typically low, it does not give a good indication of how busy a link really is. It also does not give any indication of the effective link share.

4.4.4 Expected Transmission Time (ETT)

ETT is an improvement over ETX as it includes the bandwidth in its computation [32]. Let S be the packet size and B the bandwidth of the link considered, then ETT is computed as follows:

$$ETT = ETX\frac{S}{B} \tag{4.3}$$

In a similar fashion to ETX, the expected transmission time of a path is computed according to the sum of the links' ETT along the path.

The authors later improved over ETT by proposing a Weighted Cumulative ETT (WCETT) [32]. This metric was designed to favor channel-diverse paths. For a path p, WCETT is defined as follows:

$$WCETT(p) = (1-\beta) \sum_{\text{link l } \in p} ETT_l + \beta \max_{1 \leq j \leq k} X_j \tag{4.4}$$

where β is a tunable parameter less than 1 and X_j represents the number of times channel j is used along path p.

Nevertheless, this metric still suffers from the same limitations as ETX/ETT by not estimating the effective link share and does not completely capture the inter-flow interference.

4.4.5 Modified Expected Number of Transmissions (mETX)

An enhancement over ETX has been proposed by [74] based on the observation that ETX does not account for the channel variability and only considers the average channel behaviour. The authors therefore defined mETX as follows:

$$mETX = exp(\mu_\Sigma + \frac{1}{2}\sigma_\Sigma^2) \tag{4.5}$$

where μ_Σ and σ_Σ^2 represent the mean and variability of the error probability.

The main challenge in the implementation of this metric is to properly model and quantify the variability of the transmission channel.

4.4.6 Network Allocation Vector Count (NAVC)

NAVC [85] essentially accounts for the interflow interference by averaging the values of the Network Allocation Vector (NAV) experienced by a node along a link for a given observation period. NAV is a virtual carrier sensing mechanism used with wireless network protocols such as IEEE 802.11 and IEEE 802.16 that accounts for the duration needed for the transmission of a frame (specified in the header of the frame). According to the value obtained, a level of congestion is attributed to the node. During the route discovery process, two parameters, *heavy_node_number* and *nav_sum*, are maintained. Upon reception of a ROUTE REQUEST packet, a node has therefore three options depending on the value of the measured NAVC.

1. If $NAVC > 0.65$: increase *heavy_node_number* by 1 and add the square of NAVC to *nav_sum*;

2. If $0.25 \leq NAVC \leq 0.65$: increase *nav_sum* by the square of NAVC;
3. If $NAVC < 0.25$: do nothing.

The cost of a path comprises the sum of the *heavy_node_number* of each node along the path and the sum of the *nav_sum*. Paths are therefore given priority first depending on the *heavy_node_number* and then on the *nav_sum*.

4.4.7 Metric of Interference and Channel-Switching (MIC)

MIC has been designed to improve over WCETT by capturing more information on the effective link share [143]. For a network composed of N nodes and a path p, MIC averages the time to transmit on a particular link over the minimum time to transmit over all the existing links. Similarly to WCETT, MIC adds a term to account for channel diversity called Channel Switching Cost (CSC).

$$MIC(p) = \frac{1}{N \times \min(ETT)} \sum_{\text{link l } \in p} IRU_l + \sum_{\text{node i } \in p} CSC_i \tag{4.6}$$

$\min(ETT)$ represents the smallest ETT in the network and IRU_l represents the interference-aware resource usage defined as:

$$IRU_l = N_l \times ETT_l$$

$$CSC_i = \begin{cases} w_1 & \text{if } CH(prev(i)) \neq CH(i) \\ w_2 & \text{if } CH(prev(i)) = CH(i) \end{cases}$$

$$0 \leq w_1 < w_2$$

N_l is the number of nodes link l is interfering with, ETT_l is the expected transmission time on link l, $CH(i)$ is the channel assignment of node i and $prev(i)$ represents the node before node i along path p. IRU_l can therefore be interpreted as the total channel time consumed by link l. CSC is a weight allocated to a link as a function of the channel used by the link preceding the link considered on a particular path. If both links use the same channel, a greater weight is assigned to the link.

This metric presents some major drawbacks in terms of implementation. First, the overhead required to maintain up-to-date information of the ETT for each link can significantly affect the network performance depending on the traffic load. Second, this metric assumes that all the links located in the collision domain of a particular link contribute to the same level of interference, which does not take into account the difference in traffic load at each node.

4.4.8 Routing Metrics Summary

Table 4.1 summarizes the characteristics of each of the metrics just discussed. In particular, we highlight if the metric is computed on a per-node or or per-link basis, what information is required in the computation (number of nodes, neighbors, packet loss, etc.) and how it handles interference, if applicable.

Table 4.1: Comparison of routing metrics

	Per Node	**Per Link**	**Knowledge**	**Interf. Awareness**
Hop Count	X		None	N/A
Blocking Metric	X		Nb. of neighbors	Nb. of neighbors
ETX		X	Link pkt loss	Per-link pkt loss ratio Averaged over time
ETT		X	Link pkt loss Bandwidth Packet size	Per-link pkt loss ratio Averaged over time
mETX		X	Link pkt loss Channel variability	Per-link pkt loss ratio
NAVC	X		NAV	Node waiting time
MIC		X	Link pkt loss	Per-link pkt loss ratio Avg over time and over neighbors

ETT (and its extension WCETT) satisfies most of the criteria that we identified as important for WMNs but still fails to provide any information on the effective link share. MIC takes into account the number of neighbors for each node but its computation is expensive and only provides an estimation of the actual link utilization. In this paper, we address this issue by proposing a novel routing metric based on the evaluation of the effective link share. We discuss its implementation when a single channel is used and describe how to extend this metric to integrate multiple channels. As our work is solely focused on wireless mesh networks that are characterized by a fixed backbone, we are not concerned with node mobility.

4.5 Interference-Aware Metric

4.5.1 Motivations and Design Choices

The impact of interference on the network performance is a difficult parameter to estimate. However, integrating interference into the design of a WMN routing protocol is of paramount importance. Interference can be considered as a measure of the quality of the transmission channel. If the channel quality is poor, a packet has a high probability of requiring several retransmissions before successfully reaching its destination. Measuring interference also gives an estimation of the network utilization level. If several concurrent transmissions occur in the neighborhood of a source-destination pair, the nodes within transmission distance have to wait for the medium to be cleared before they have access to it. The higher the number of nodes, the greater the probability of collision due to simultaneous transmissions. Consequently, deriving a metric that is able to account for these different states can increase the network performance by avoiding lossy links and congested zones.

Therefore, we believe that a metric best suited for WMNs should incorporate the following characteristics.

- *Low overhead.* Exchange of control messages on the link status can be costly in terms of resource usage. It is therefore preferable to favor a non resource consuming solution based on local monitoring.
- *Interference-Awareness.* Both intra- and inter-flow interference have to be accounted for. This means that it is necessary to account for the waiting time as well as the number of retransmissions due to packet loss.
- *Differentiation on link capacities.* Not all the links have the same transmission rates due to environmental noise or technological limitations. Higher capacity links should be favored when they are not congested.
- *Channel diversity.* If the network nodes are embedded with multiple interfaces, this should be exploited to favor the use of high-quality links (higher transmission rate, less packet loss) and by reducing the interference by spreading the traffic over multiple channels.

4.5.2 IAR: Description

Before we describe the actual computation of our proposed metric, it is important to have a clear view of the different states in which a node can be. There are five states:

- *Idle*: The node does not have any packets of its own to transmit neither does it have any packets to relay. It therefore does not contribute to increasing the interference in the network and should consequently be ignored.
- *Success*: The state refers to the case where a node has successfully received the acknowledgment of the packet it has sent.
- *Collision*: In this state, a node sent a DATA packet but never received an acknowledgement for the packet. Several reasons can explain this situation. The receiver node could be in the range of another transmission and therefore received several packets at the same time. Or the receiving node was itself initiating a communication. It might also happen that a collision occurs between the ACK packet and another DATA or ACK packet.
- *Wait*: As only one communication can occur at the same time in the same geographical area, if a node senses the medium is busy, it has to wait until the ongoing communication is completed before it starts its own.
- *Backoff*: Even though a node has some data to transmit and the medium is free, IEEE802.11 Standard enforces a random waiting period (during which the medium has to remain idle) before it starts sending its data.

The period of time between the moment when a node generates a packet (or receives a packet it then has to relay) and the moment it successfully transmits the packet to the next hop node (possibly the destination of the packet) is a succession of *Success*, *Collision*, *Wait* and *Backoff* states (Fig. 4.1).

Table 4.2: Duration for the 4 channel states

State	**Duration**
Backoff	Time Slot
Wait	*variable*
Collision	DATA+SIFS+ACK+DIFS
Success	DATA+SIFS+ACK+DIFS

We therefore designed a routing metric, *Interference-Aware Routing metric* (IAR), that could address the shortcomings of the existing metrics we previously highlighted. It should reflect more realistically a link usage and includes all possible states a node is in, in particular the waiting period consequent to neighboring nodes' transmissions.

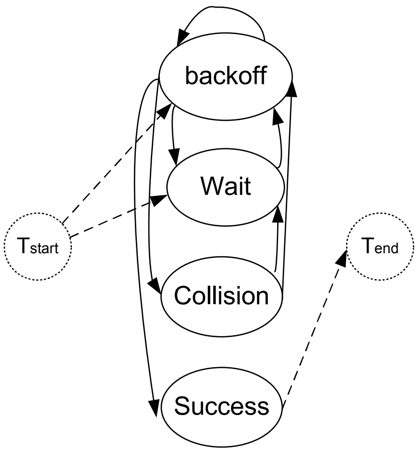


Figure 4.1: 4 of the communication states of a node (IDLE state is not represented)

Let $T_{Success}$, T_{Wait}, $T_{Collision}$ and $T_{Backoff}$ be the time spent respectively in the *Success*, *Wait*, *Collision* and *Backoff* states. The communication cycle is defined as the period between the generation of a packet up to its successful transmission. The duration of each state is summarized in Table 4.2. We omitted the propagation delay in the computation although it is accounted for in the actual implementation since our metric is based on measurements. The Wait state has a variable duration as it depends on other nodes' transmissions.

For each link, we calculate the *unproductive busyness* α_{ub}, that is to say the percentage of time spent in states in which communication on this link is not possible.

$$\alpha_{ub} = \frac{T_{Wait} + T_{Collision} + T_{Backoff}}{T_{Wait} + T_{Collision} + T_{Backoff} + T_{Success}}$$

Therefore, for a link l, IAR is defined as:

$$IAR(l) = \frac{1}{1-\alpha_{ub}} * \frac{S}{B} \tag{4.7}$$

IAR can be interpreted as the time to transmit a packet of size S over a medium of actual bandwidth $(1-\alpha_{ub}) * B$.

The cost of a path p is consequently defined as the sum of the cost of each link along the path.

$$IAR(p) = \sum_{l \in p} IAR(l) \tag{4.8}$$

The amount of time spent in each of these states can be determined by passive measurements using the actual traffic in transmission or by active probing. Similar to ETT, IAR can be modified to handle the multi-channel scenario with the addition of a switching channel cost factor (cf. the computation of WCETT).

4.6 Performance Evaluations

4.6.1 Implementation Details

We compared the performance of the routing metrics through simulations implemented in NS2 [56]. We used the default settings of the simulator for the wireless transmissions: two ray ground propagation mode, 250m transmission range and 550m interference range. The network topologies have been randomly generated in a 2000x2000m^2 area. UDP is used at the transport layer and all flows are sent at a constant bit rate, with a packet size of 512 bytes or 1512 bytes. The source and destination of each flow are randomly chosen in order to avoid the appearance of a single bottleneck. We only performed simulations in a single-channel environment. This decision was motivated by the fact that we wanted to conduct a fair comparison of the performance of the metrics, which is difficult to achieve between single and multi-channel metrics. Besides, it is worth noting that even though some metrics have not been initially designed to handle channel diversity, the addition of a cost factor similarly to what has been done for ETT or MIC can straightforwardly resolve this issue.

For each configuration, we evaluated the end-to-end delay, the path length and the packet loss. We assumed that all links have the same nominal capacity and that the packet size is fixed. In this context, as ETX and ETT necessarily lead to the same results, we only refer at ETX in the remainder of the experimental analysis (although the same results apply for ETT).

The packet loss ratio is determined via periodic transmissions of probing packets (sent every second in the simulations). The routing tables are recomputed periodically. To make the implementation oblivious to the specifics of a particular routing protocol, we assumed the existence of a central entity responsible for computing and keeping the routers updated with the optimal routing tables at any given time.

4.6.2 Simulation Results

Impact of the Network Size

First, we evaluated the impact of the network size on the performance of each routing metric. We increased the size of the network from 10 to 100 nodes with 5 traffic flows of 20 pkt/sec. The results obtained consist of an average of 50 simulations over all the flows. Fig. 4.2, Fig. 4.3, Fig. 4.4, Fig. 4.5 and Fig. 4.6 show the average end-to-end delay, the average number of hops and the average loss probability. We observe that overall NAVC performs poorly in terms of delay and packet loss compared to the other metrics implemented. Incorporating the value of the network allocation vector in the metric computation could theoretically provide some useful information on the effective link share at each node as this parameter indicated the duration of the data transmission on the edge of being initiated. We believe that the bad performance of NAVC results from the way the threshold values for *heavy_node_number* and *nav_sum* are computed. These thresholds are solely based on simulations without being justified by any analysis. Moreover the difference in link capacities is not accounted for, nor are the traffic characteristics. As the network size increases, the performance degrades significantly, eventually leading to a situation in which only flows for which the source and destination are within direct reach of each other can successfully be transmitted. This explains why the average path length is significantly better for NAVC than for the other metrics.

NAVC put aside, we can observe that IAR performs the best in terms of end-to-end delay (Fig. 4.3) and packet loss probability (Fig. 4.5), closely followed by Hop Count. Hop Count favors shortest paths but at the expense of greater end-to-end delay and packet loss probability, whereas IAR avoids highly congested areas, which results in longer routing paths. It is worth noting that the end-to-end delay increases but not significantly since the network size remains fixed. As the number of nodes increases, the probability to choose longer paths increases as well but not significantly given the simulation settings.

In general, routing implemented with Hop Count, Blocking Metric or IAR result in path lengths on average 10 to 15% shorter than with ETX, mETX or MIC.

We also looked at the per-flow performance and computed Jain's fairness index in a 50-node network with 10 traffic flows (Fig. 4.7). We observe a fairer traffic load distribution in the case of IAR, ETX, mETX and MIC than with Blocking and Hop Count. This results from the fact that Blocking and Hop Count can lead

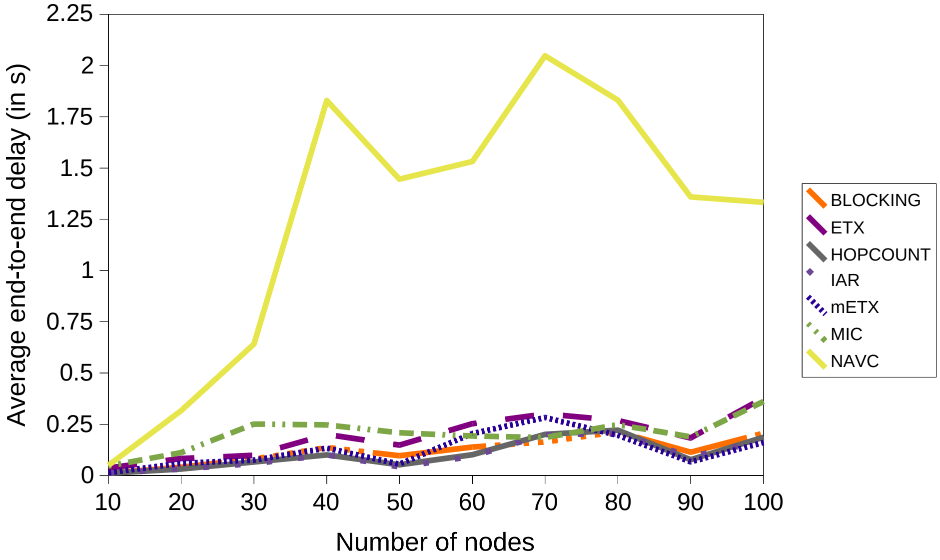


Figure 4.2: End-to-end delay with increasing number of nodes

to the starvation of some flows to the benefit of others. This result is not surprising as IAR, ETX, mETX and MIC favor less congested paths whereas Hop Count and Blocking Metric favor shortest but potentially more congested paths.

This first scenario demonstrates that IAR stands out as the best solution as: 1/ it offers a better or similar level of performance in terms of end-to-end delay and packet loss as Hop Count and Blocking; 2/ it offers a fairer load distribution than Hop Count and is easier to implement than ETX, mETX or MIC.

Impact of the Traffic Load

In the second set of simulations, we studied how the traffic load can impact the network performance by progressively increasing the number of flows between 5 and 30 for a network of 50 nodes uniformly distributed over a 2000x2000m^2 area (Fig. 4.8, Fig. 4.9 and Fig. 4.10). As in the previous case, NAVC performs very poorly compared to the other routing metrics. In terms of end-to-end delay and packet loss, IAR still performs the best followed by Hop Count and Blocking. Similarly to the previous case, Hop Count leads to shorter paths than the other routing metrics but IAR, ETX and MIC lead to a fairer load distribution.

We ran similar experiments while increasing the size of the topologies. We considered networks with 100 and 150 nodes and analyzed the resulting network performance. As the path length increases, with a similar number of flows, the

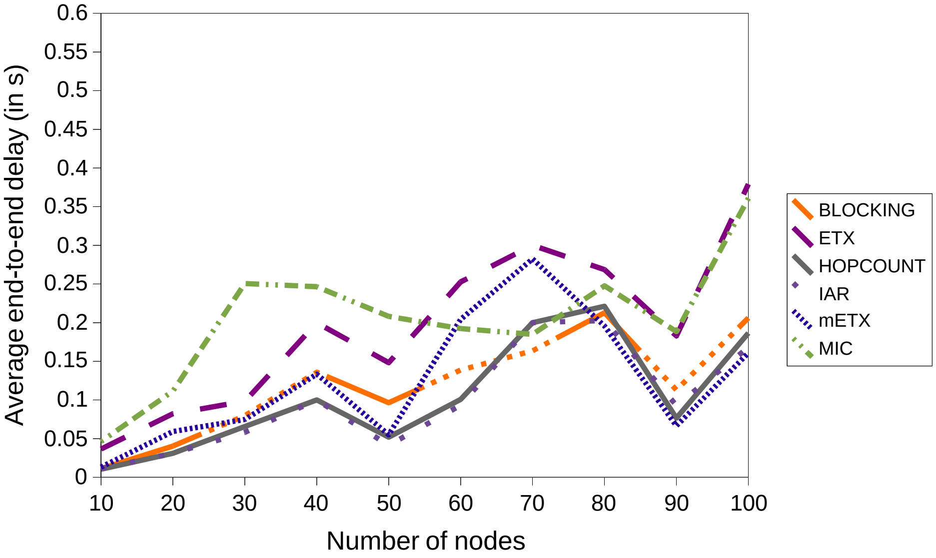


Figure 4.3: Closer look at the end-to-end delay with increasing number of nodes (excluding NAVC)

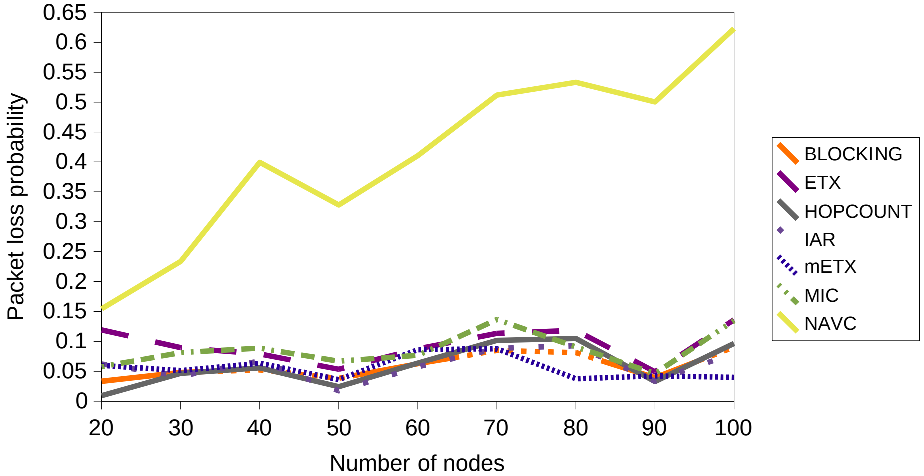


Figure 4.4: Packet loss for all routing metrics with increasing number of nodes

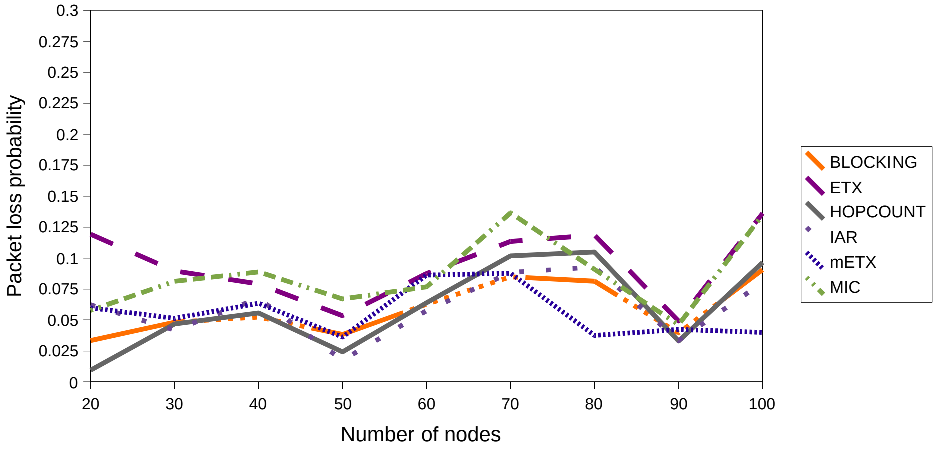


Figure 4.5: Closer look to the packet loss probability for the routing metrics with increasing number of nodes (excluding NAVC)

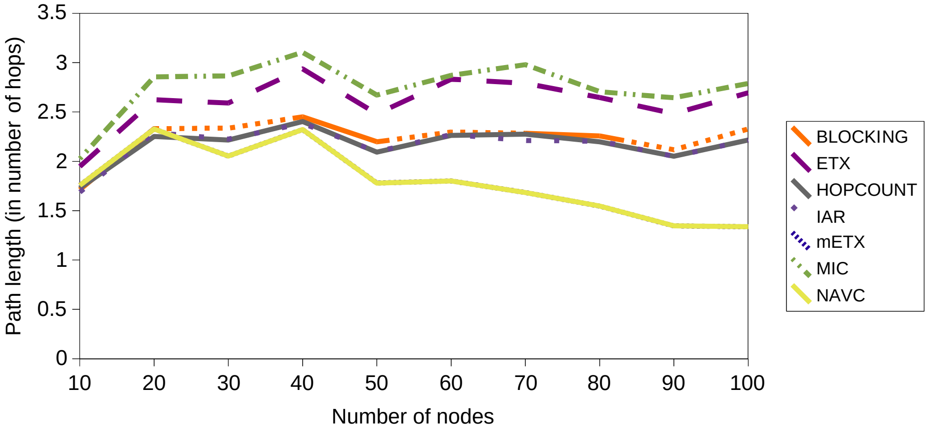


Figure 4.6: Path Length with increasing number of nodes

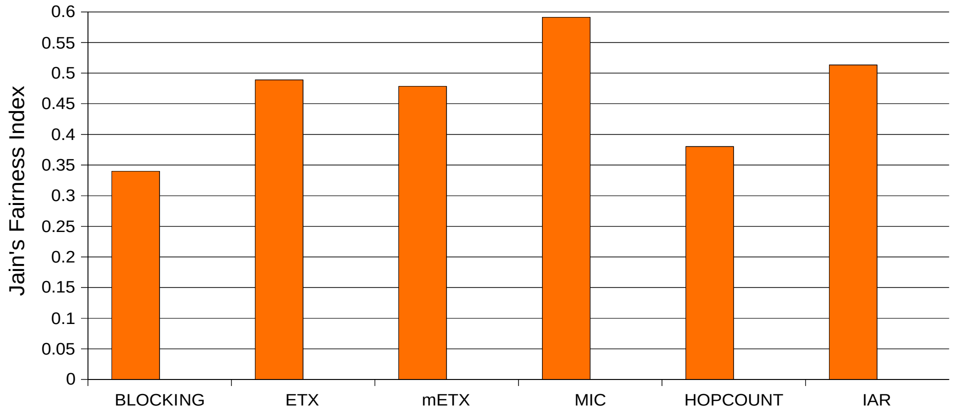


Figure 4.7: Fairness analysis: we compute Jain's fairness index for a 50-node network with 10 traffic flows (1 is the best value).

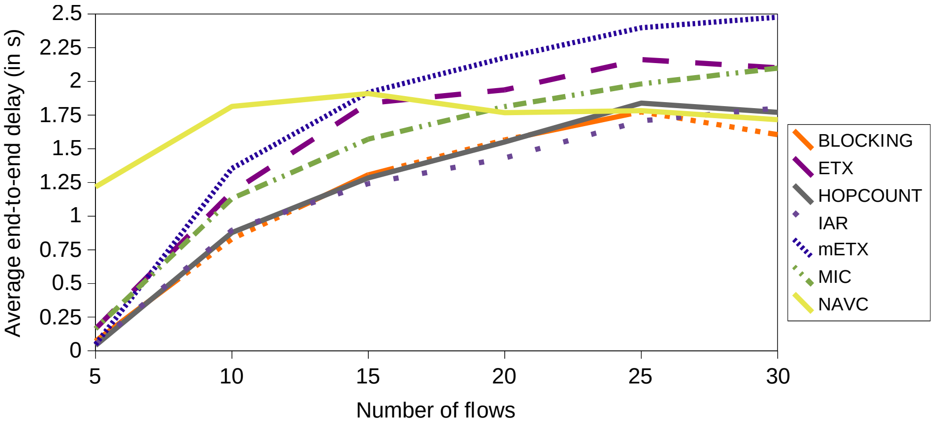


Figure 4.8: End-to-end delay with increasing number of flows for a 50-node network

probability of collision increases. Therefore, flows on shorter paths have a greater chance of being successfully transmitted. Hop Count, IAR and Blocking Metric still perform the best in terms of packet loss whereas ETX, mETX and MIC, although trying to avoid congested areas, lead to a poor network utilization by electing longer paths and therefore contributing even more to the interference level.

We also analyzed the impact of the packet size on the network performance. We ran the same sets of simulations with packets of 1512 bytes. With only 5 flows, given the network characteristics considered, the network gets immediately congested. The packet loss probability is in the order of 70% for 5 traffic flows and goes over 80% with 30 flows. Moreover, if a packet has to be retransmitted due to a collision, a greater packet size will incur some extra time for transmission and consequently an increased end-to-end delay. When the number of flows increases, similarly to the

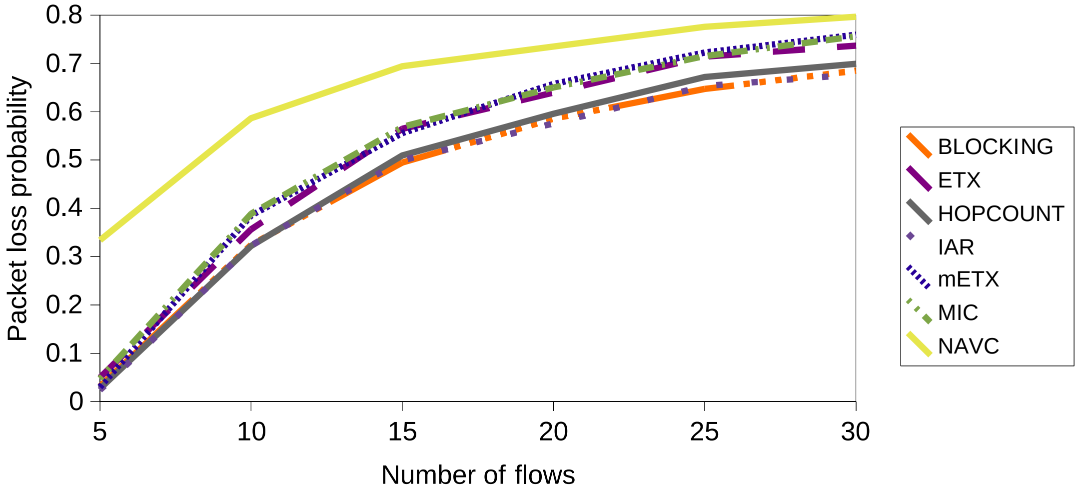


Figure 4.9: Packet loss with increasing number of flows for a 50-node network

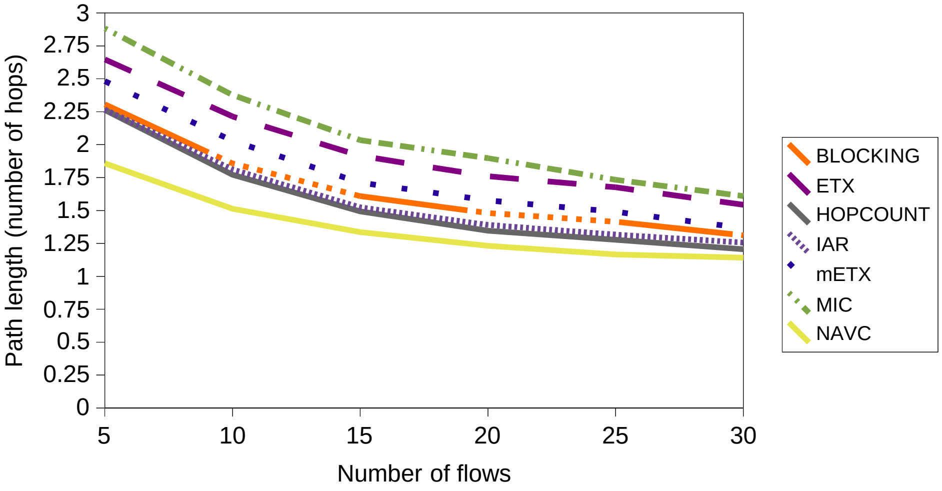


Figure 4.10: Number of hops with increasing number of flows for a 50-node network

previous observation, the flows between the closest source-destination pairs (1 hop away) are favored and starved the other traffic flows. This is a direct consequence of the way the MAC protocol has been designed. As the number of collisions increases, the backoff time (mandatory waiting time before attempting another transmission) exponentially increases as well.

For the packets that succeed in going through, given the packet size, retransmitting a packet due to a collision will take 3 times more compared to the previous experiments.

4.7 Conclusion

As user expectations for ubiquitous connectivity and quality of service increase, wireless mesh networks represent a promising solution. By extending network coverage through the use of multi-hop wireless communication, WMNs offer versatility, along with easy and inexpensive deployment. However, routing in such networks is a challenging research issue with tremendous impact on network performance, particularly when interference is considered. It is important that the routing protocol integrate these effects of both self-interference between hops along the same path, and interference between different paths into the routing decision.

In this chapter, we have studied the abilities of various routing metrics to address interference issues in a WMN. The metrics utilize different types and degrees of network state information. Some are simple (e.g. Hop count, Blocking), others are more sophisticated (e.g mETX or MIC). While the more advanced approaches directly consider interference issues, they also require more complex network state information. This can be costly to obtain and maintain, with control messages competing with data transmissions.

The performance of six popular routing metrics has been studied using simulations. The impact of network size and traffic loads have been evaluated in terms of end-to-end delay, packet loss, and path length. These studies have demonstrated that despite the consideration of interference, the more sophisticated metrics fail to consistently outperform the simpler ones. In fact, in many scenarios, particularly as traffic increases, the performance of the advanced metrics suffers. However, it appeared that the simple approaches are inherently unfair.

Based on these observations, we have proposed a novel Interference-Aware Routing metric (IAR). IAR allows a node to estimate its effective share of the link capacity using local measurements. This approach accounts for intra- and inter-flow interference, as well as packet loss resulting from poor channel quality. The simulation results demonstrate that IAR outperforms hop count in many scenarios, particularly in terms of end-to-end delay. It does so, while maintaining a fair delivery of packets.

The attained results motivate the need for further work into developing an appropriate routing metric for WMNs. IAR demonstrates that such a metric can outperform the simple approaches, despite the additional overhead costs involved in collecting the required information. However, we intend to continue investigating how channel quality can be accurately evaluated and incorporated into the metric. Furthermore, the use of multiple channels and support for channel diversity should be considered in continuing to develop an interference-aware metric.

Chapter 5

Network-Adaptive Multipath Routing

5.1 Introduction

As discussed in Chapter 2, spreading traffic flows over multiple paths can increase the nominal achievable throughput compared to single path routing [80] [102] if the paths are properly chosen. If the data traffic is routed over two (or more) paths that interfere with each other, the overall throughput gain becomes negligible [135]. It is also important to factor into the choice of the routing approach the cost of determining the paths. As the control overhead increases with the number of paths [109], it can void the benefit of multipath routing. Therefore, estimating the probability of finding non-interfering paths for a given network topology can help decide whether multipath routing is an appropriate approach for a particular network, and if it can improve the system performance at all [**?**].

Our contributions in this chapter are as follows. We prove that a restricted version of the problem, i.e. finding two non-interfering paths (that we also refer to as *2-path routing*), is NP-complete. Therefore, an interesting problem is to determine if, for a given network topology, non-interfering multipath routing is appropriate. To address this issue, we determine the probability of finding two non-interfering paths as a function of the network density. Assuming that the network characteristics satisfy the pre-established conditions that render the implementation of a multipath routing protocol suitable, we compute the expected network throughput when traffic flows are split over two non-interfering paths.

5.2 Chapter Organization

The remainder of the chapter is organized as follows. We describe our analysis of the complexity of 2-path routing in Section 5.3. The computation of the probability that two nodes are 2-connected is presented in Section 5.4. The derivation of the probability of finding two non-interfering paths is explained in Section 5.5. We subsequently apply the obtained result to find the throughput per node in Section 5.6. Section 5.7 summarizes our contributions and concludes this chapter.

5.3 Non-Interfering Multipath Routing: Problem Complexity

The goal in this study is to find multiple non-interfering paths between a source-destination pair. To analyze the complexity of this problem, we restrict our analysis to the case in which only two paths are set up between a source and a destination node. We refer to this problem as *2-path routing* and prove its NP-completeness, i.e. that a polynomial time algorithm is currently not known to exist that can find two non-interfering paths.

Definition Given a directed graph $G(V, E)$ and two nodes $(s, t) \in V$, *2-path routing* consists in finding two paths P_1 and P_2 between s and t such that:

1. all the nodes in P_1 and all the nodes in P_2 form a connected graph
2. there exists no edge between a node in P_1 and a node in P_2.

Theorem 5.3.1 *2-path routing is NP-complete.*

Proof To show that 2-path routing belongs to NP, we need to show that a satisfying assignment can be verified in polynomial time. In order to do that, the verifying algorithm needs to check that first, no node in a given path has an edge with any other node on the second path; second, the nodes in each path form a connected graph. By inspection this can easily be done in polynomial time.

To prove that 2-path routing is NP-hard, we show that 3-CNF-SAT is polynomial-time reducible to 2-path routing. Let us assume that the Boolean formula Φ is composed of m clauses $C_1 \wedge .. \wedge C_m$ and has k variables. The reduction maps Φ to a graph $G(V, E)$, creates 3 nodes where each one corresponds to a literal in the clause. Each node in a clause C_i is connected to the nodes in C_{i+1} if there are no contradicting literals in each clause. For each variable, we create a false and true node. Each false and true node of one variable is connected to another false and a true node for another variable. Finally, we need to connect each of these nodes to each node in the triple with a different label (Fig. 5.1). This enforces the situation that for each literal set to true in the clause, the corresponding true/false node created for each variable should be chosen. Otherwise the paths between the source and the destination cannot be disjoint. Thus we construct a graph G with 2k+3m nodes. Again by inspection, the reduction from 3-CNF-SAT to 2-path routing operates in polynomial time.

To solve the 2-path routing problem, pick a true literal in each clause. If the value of a variable is not enforced by the choice of a corresponding literal in one of the clauses, set its value randomly to true or false. The corresponding nodes consequently form 2 paths. If there is no set of variables that would set all the clauses to true, then there is no path between the clauses and there is no solution to Φ.

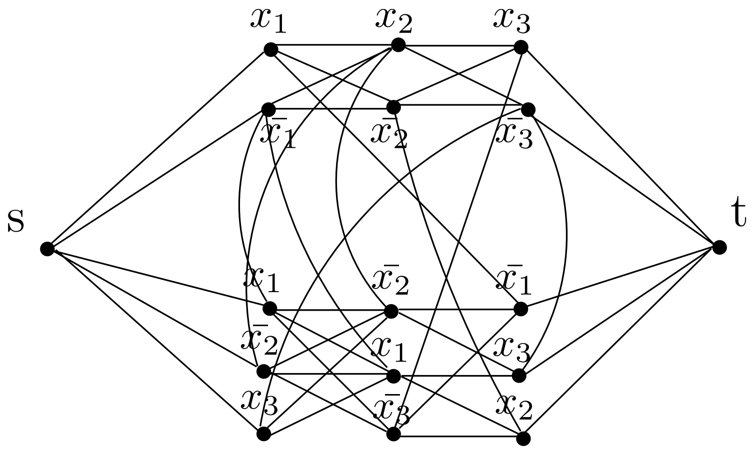


Figure 5.1: Example of reduction of Φ to 2-path routing with $\Phi = (x1 \vee \overline{x2} \vee x3) \wedge (\overline{x2} \vee x1 \vee \overline{x3}) \wedge (\overline{x1} \vee x3 \vee x2)$

Having proved that finding two non-interfering paths for a source and destination is an NP-complete problem in the remainder of this chapter we now introduce a heuristic for the sake of computational efficiency. The heuristic is based on node position to compute the probability of finding two non-interfering paths. We divide the computation into two steps:

1. We derive the probability of finding two paths between a source and destination node (Section 5.4),
2. We compute the probability that two paths do not interfere (Section 5.5) .

5.4 2-connectivity

We first evaluate the condition under which there exists two paths between a given source and destination, or in other words that the graph is two-connected. Let κ be the network connectivity and ξ the minimum vertex degree. Under our network model, the following theorem applies (the proof of the theorem can be found in [107]):

Theorem 5.4.1 *If the number of vertices is high enough, and if one removes all the edges and progressively adds them with increasing length, the resulting graph becomes* $\kappa - connected$ *when the minimum connectivity degree* ξ *reaches* κ*.*

We assume that the nodes are uniformly distributed over an area A with a density ρ. The nodes have a transmission range R and their positions are independent of each other. For a large number of nodes, the probability that k nodes are located in a given area A can be approximated with a Poisson distribution [99]:

$$P(\text{number of nodes} = i) = \frac{(\rho A)^i}{i!} e^{-\rho A} \tag{5.1}$$

Computing the probability that a node degree is greater than κ reduces to determining, for a given node, the probability that it has κ neighbors. This can be further reduced to computing the probability that there is $\kappa + 1$ nodes in the transmission area of a given node. This can be expressed as:

$$P(\text{degree} \geq \kappa) = 1 - \sum_{i=0}^{\kappa} \frac{(\rho \pi R^2)^i}{i!} e^{-\rho \pi R^2} \tag{5.2}$$

If we enforce that the minimum node degree should be greater than κ, then this should be true for each node. We therefore obtain the following equation:

$$P(\text{min degree} \geq \kappa) = (1 - \sum_{i=0}^{\kappa} \frac{(\rho \pi R^2)^i}{i!} e^{-\rho \pi R^2})^{\rho A} \tag{5.3}$$

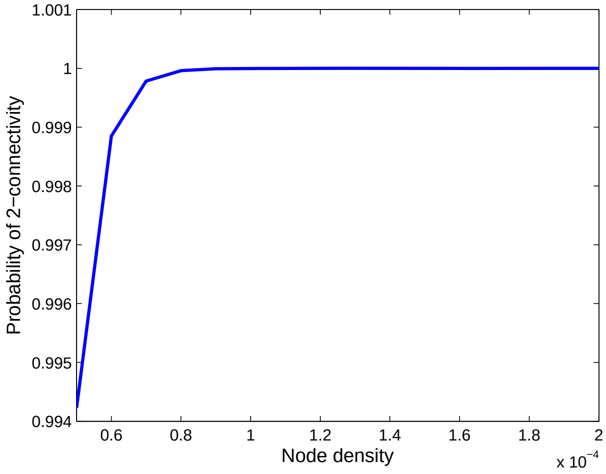


Figure 5.2: Probability of having a 2-connected network

For instance, let us consider a 1000x1000 m^2 network in which each node is assumed to have a transmission range R of 250m. From Fig. 5.2, we can observe that a network density of 0.8e-4 nodes/m^2 is sufficient to guarantee that the network is $2-$*connected* and thus there exists two paths between the source and destination. The next step consists of computing the probability that the two paths are non-interfering.

5.5 Probability of Finding Two Non-interfering Paths

A feasible solution to the problem of finding non-interfering paths should consist of a set of nodes such that the nodes on one path do not interfere with the nodes on the other path (except for the source and destination nodes as depicted in Fig. 5.3).

We therefore need to compute:

1. The probability P_1 of find two non-interfering nodes at the first hop.
2. The probability P_2 that two paths exist after the first hop and before the last hop, with the constraint that the nodes along each path do not interfere with each other.

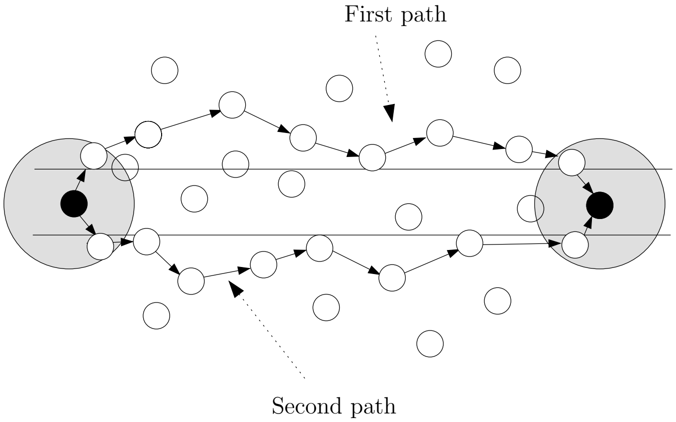


Figure 5.3: Example of 2 non-interfering paths

The probability P_{2paths} that two paths exist between a given source/destination pair can therefore be expressed as:

$$P_{2paths} = \underbrace{P_1}_{1^{st}\text{hop}} \times \underbrace{P_2}_{\text{Intermediary hops}} \tag{5.4}$$

5.5.1 Computation of P_1

The first condition to satisfy is to find two non-interfering nodes in the transmission area of the source. If we consider that no backwards transmission is permitted, this area is limited to the domain located in the same half-space as the destination node (Fig. 5.4).

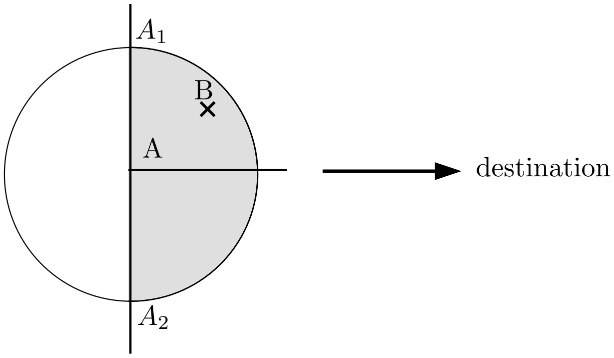


Figure 5.4: Feasible solution domain (gray area)

We need therefore to compute:

1. the probability $P_{11}(k)$ of having k nodes in half a disk;
2. the probability $P_{12}(k)$ that at least two of these k nodes are separated by a distance greater than R (transmission range).

Consequently, P_1 can be determined by:

$$P_1 = \sum_{k=1}^{\infty} P_{11}(k)P_{12}(k) \tag{5.5}$$

The probability $P_{11}(k)$ of having k nodes in half a disk is given by Eq. 5.1. We therefore focus on the computation of $P_{12}(k)$.

Let A be the source node and B a node randomly located in the half-disk centered at A with respective polar coordinates $(0, 0)$ and (r, θ). We refer to the extreme points of the diameter of the half-disk as A_1 and A_2. In order not to interfere with B, a node should satisfy the following conditions:

1. to be within transmission range of A, and
2. not to be within transmission range of B

To find the probability that at least two nodes randomly located in the half a disk do not interfere, we adopt the following method. We choose a point B in the transmission area of node A and determine the probability that there exists at least one node non-interfering with B (therefore located in one of the dashed areas as shown in Fig 5.5 and Fig. 5.6), finally we integrate this for all possible positions of B.

Depending on the position of B, there are two cases:

- **Case 1**: B is located at a distance less than the transmission range R from either A_1 or A_2 (Fig. 5.5). One single solution area exists. This happens when $\cos(\theta) \geq \frac{R}{2r}$.

- **Case 2**: B is located at a distance greater than R from both A_1 and A_2 (Fig. 5.6). Two solution areas exist. This happens when $\cos(\theta) \leq \frac{R}{2r}$.

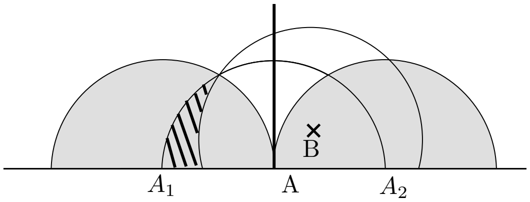


Figure 5.5: Case 1: 1 feasible solution area

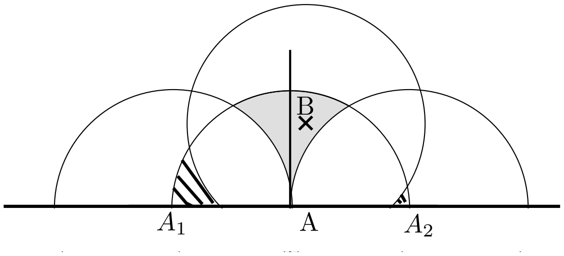


Figure 5.6: Case 2: two feasible solution areas

The non-interfering zones are dashed in Fig. 5.5 and Fig. 5.6.

A general formulation of the probability of finding two nodes distanced by at least R can be expressed as follows.

Theorem 5.5.1 *Let us assume that there are N nodes within the transmission distance of A. The probability P that at least two of these N nodes are at a distance greater than R apart is:*

$$P = 1 - \int_{r=0}^{R} \int_{\theta=0}^{\frac{\pi}{2}} \frac{2}{\pi R}(1 - (\frac{2(A_{inter}(r,\theta))}{\pi R^2})^{n-1}) \partial r \partial \theta \tag{5.6}$$

where $A_{inter}(r,\theta)$ is the interference area of a node with polar coordinates (r,θ) in the solution domain (half-disk).

Proof For conciseness, we only provide a short sketch of the derivation. In order to determine the probability that two nodes are at a distance of at least R, we first need to find the complement of this probability. So basically, we need to evaluate the probability that given a node, the $n-1$ remaining nodes are at a distance less than R. Therefore, none of the $n-1$ nodes should be in $A_{inter}(r,\theta)$ (non dashed area in Fig. 5.5 and Fig. 5.6), with (r,θ) being the coordinates of the initial node considered. This should be done for each node.

In order to determine the actual value of the interference area $A_{inter}(r, \theta)$, we need to break down the computation into the two cases previously described.

Case 1: One feasible region

Let N be the number of nodes in the half-disk area obtained by properly choosing the network density so that the probability of finding at least 2 nodes tends to 1. If we consider one node (Node B) among these N nodes, the probability that at least one of the remaining $N-1$ nodes is at least at a distance R from B can be determined by computing the complement of the probability that all the nodes are at a distance less than R from B.

Let us first calculate the intersection between the coverage areas of A restricted to the half-disk oriented towards the destination node and the coverage of B. The intersection area between the disk centered at A and the disk centered at B forms a lens whose area is referred to as A_{lens}. This area can be computed geometrically as follows:

$$A_{lens} = 2R^2 \arccos(\frac{r}{2R}) - \frac{r}{2}\sqrt{4R^2 - r^2} \tag{5.7}$$

We can also observe that since A and B are within transmission range of each other, these points are necessarily located in the lens whose area has been previously computed. In particular, we can establish the following relation:

$$S_{ACD} = S_{BCD} - S_{ABC}$$

where S_{ACD}, S_{BCD} and S_{ABC} are the areas delimited by the points ACD, BCD and ABC respectively. S_BCD consists of a disk section that can be directly computed as:

$$S_{BCD} = \frac{\widehat{BCD} * R^2}{2} \tag{5.8}$$

To compute $\widehat{BCD}$, let us define $AC = x$. By construction, we have $\widehat{BAC} = \pi - \theta$, $AB = r$ and $BC = R$. Using the law of cosine, we determine x:

$$x = -r\cos(\theta) + \sqrt{R^2 - r^2(\sin(\theta))^2}$$

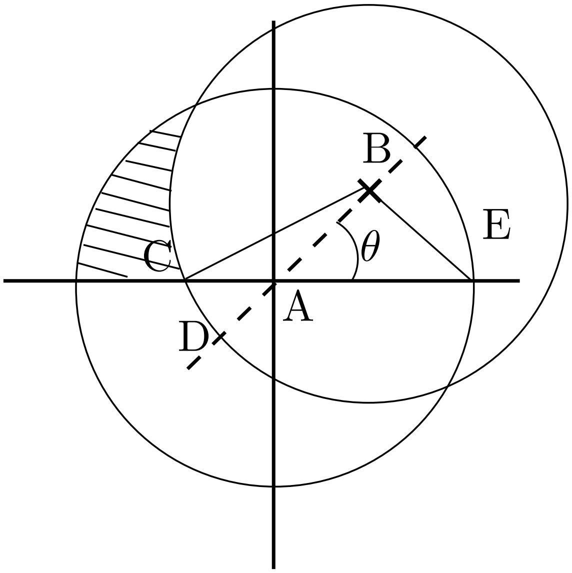


Figure 5.7: Case 1: Computation of the non-interfering zone (dashed)

$\widehat{BCD}$ can therefore be deducted using the same method.

$$\widehat{BCD} = \arccos(\frac{R^2 + r^2 - x^2}{2Rr})$$

To obtain the area of ABC, we apply Heron's formula:

$$S_{ABC} = \sqrt{s(s-r)(s-x)(s-R)} \tag{5.9}$$

where

$$s = \frac{x + r + R}{2}$$

By combining Eq. 5.8 and Eq. 5.9, we obtain:

$$\begin{aligned} S_{ACD} &= \arccos(\frac{R^2 + r^2 - x^2}{2Rr})\frac{R^2}{2} \\ &\quad -\sqrt{s(s-r)(s-x)(s-R)} \end{aligned} \tag{5.10}$$

with $s = \frac{x+r+R}{2}$.

We can therefore compute the intersection area:

$$\begin{aligned} S_{inter}(r,\theta) &= \frac{A_{lens}}{2} - S_{ACD} + R^2\frac{\theta}{2} \\ S_{inter}(r,\theta) &= R^2\arccos(\frac{r}{2R}) - \frac{r}{4}\sqrt{4R^2-r^2} \\ &\quad -\arccos(\frac{R^2+r^2-x^2}{2Rr})\frac{R^2}{2} \\ &\quad +\sqrt{s(s-r)(s-x)(s-R)} \\ &\quad +R^2\frac{\theta}{2} \end{aligned} \tag{5.11}$$

Finally, the probability that at least one of these $N-1$ nodes does not fall in this area is:

$$P_{case1} = 1 - (\frac{S_{inter}(r,\theta)}{\frac{\pi R^2}{2}})^{N-1} \tag{5.12}$$

Case 2: Two feasible regions

In this case, node B is at a distance at least R away from A_1 and A_2. Without loss of generality, let us assume that B is located in the same quarter of disk as A_1 (Fig. 5.8).

The disk centered at B cut the x-axis at two points x_1 and x_2 such that $x_1 < x_2$. Obviously a solution zone exists in this area only if $|x_1| < R$. Let x'_1 be the intersection point with the smallest x-coordinate between the circle centered at A and the circle centered at B.

The solution area is therefore bounded by $A_1x_1x'_1$. Geometrically, we may observe that :

$$S_{A_1x_1x'_1} = S_{ABx'_1A_1} - S_{ABx'_1x_1}$$

By calculating $S_{ABx'_1A_1}$ and $S_{ABx'_1x_1}$, we find the solution area.

First we calculate $S_{ABx'_1x_1}$ as follows:

$$S_{ABx'_1x_1} = S_{Bx'_1x_1} + S_{ABx_1}$$

Straightforwardly, we find $S_{Bx'_1x_1} = \frac{\widehat{x_1Bx'_1}R^2}{2}$.

By applying Heron's formula we obtain S_{ABx_1}:

$$s = \frac{|x_1|+r+R}{2}$$

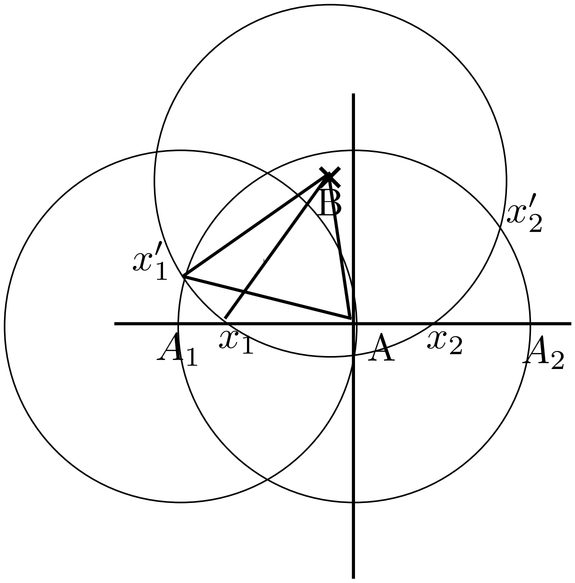


Figure 5.8: Case 2: 2 feasible regions

$$S_{ABx_1} = \sqrt{s(s-r)(s-|x_1|)(s-R)}$$

Finally we get $S_{ABx'_1x_1}$:

$$S_{ABx'_1x_1} = \frac{\widehat{x_1Bx'_1}R^2}{2} + \sqrt{s(s-r)(s-|x_1|)(s-R)} \tag{5.13}$$

with $s = \frac{|x_1|+r+R}{2}$.

Similarly, we find $S_{ABx'_1A_1}$.

$$S_{ABx'_1A_1} = S_{Ax'_1x_1} + S_{ABx'_1}$$

with $S_{Ax'_1A_1} = \frac{\widehat{A_1Ax'_1}R^2}{2}$ and $S_{ABx'1} = \frac{rR}{4}$

We therefore have:

$$S_{ABx'_1A_1} = \frac{\widehat{A_1Ax'_1}R^2}{2} + \frac{rR}{4} \tag{5.14}$$

By combining Eq. 5.13 and Eq. 5.14, we obtain:

$$\begin{aligned} S_{A_1x_1x'_1} &= \frac{\widehat{A_1Ax'_1}R^2}{2} + \frac{rR}{4} - \frac{\widehat{x_1Bx'_1}R^2}{2} \\ &\quad + \sqrt{s(s-r)(s-|x_1|)(s-R)} \end{aligned} \tag{5.15}$$

$S_{A_2x_2x'_2}$ can be determined in a similar way.

Consequently, the probability of finding two non-interfering nodes in this second case is:

$$P_{case2} = 1 - (\frac{\pi R^2}{2} - S_{A_1x_1x'_1} - S_{A_2x_2x'_2})^{N-1} \tag{5.16}$$

Evaluation

To confirm the accuracy of the upper bound produced by our analysis, we compared the results obtained by our derivation with the ones obtained through simulations by computing the distance between two pairs of nodes in a random distribution. We ran the experiments 1000 times for various network densities. The results of the simulations are depicted in Fig. 5.9.

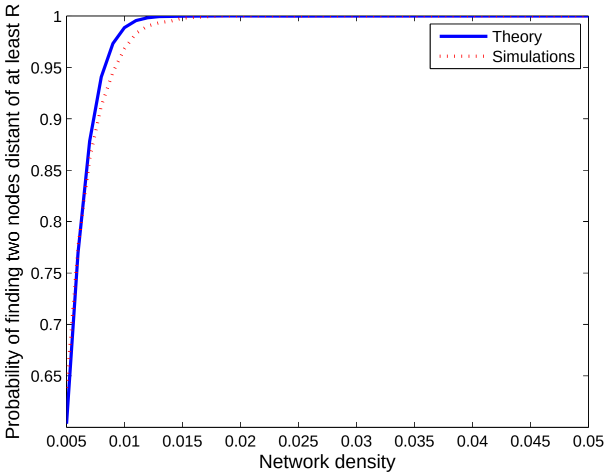


Figure 5.9: Probability of finding two non-interfering nodes. The theoretical estimation of an upper bound on the probability of finding at least 2 non-interfering nodes at the first hop closely matches the results of the simulations.

5.5.2 Computation of P_2

For the subsequent hops along each path, it is sufficient to determine the probability that each node has at least one neighbor towards the destination located in a domain space that guarantees non-interference between each path. Therefore, at each subsequent hop towards the destination, the zone in which the next-hop node can be located can be restricted to a band of width ϵ. ϵ is a parameter tunable depending on network density and transmission range (Eq. 5.17). We can see in Fig. 5.10 that, for a network density of 8e-4 nodes/m^2 and a transmission range of 250m, the probability of finding a node at the next hop with a probability greater than 95% is achievable for a value of epsilon of $15m$.

$$\begin{aligned} P(\text{at least 1 neighbor}) &= 1 - P(\text{no neighbor}) \\ P(\text{at least 1 neighbor}) &= 1 - e^{-\rho R \epsilon} \\ \epsilon &= \frac{-\ln(1 - P(\text{at least 1 neighbor}))}{\rho R} \end{aligned} \tag{5.17}$$

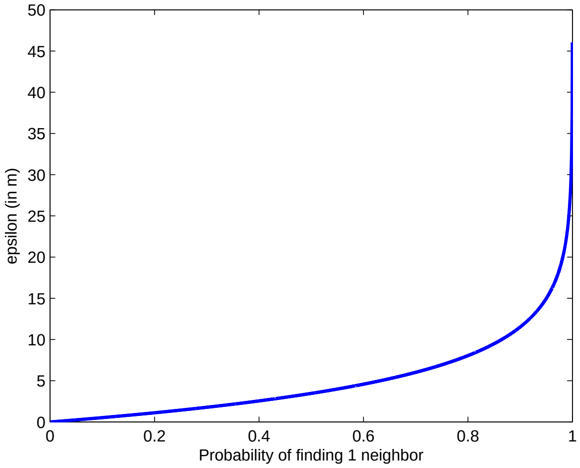


Figure 5.10: Computation of epsilon for a network density of 0.0008 nodes/m^2 and a transmission range of 250m

Let h be the number of hops between the source and the destination, $h \geq 2$. The probability of finding 2 totally-disjoint paths can be expressed as [16]:

$$P_2 = (1 - e^{-\rho R \epsilon})^{2(h-2)} \tag{5.18}$$

Eq. 5.18 is illustrated in Fig. 5.11 for an increasing number of hops. We can see that, as expected, when the number of hops increases, the probability of finding two non-interfering paths decreases but not significantly. We can therefore conclude that depending on an appropriate choice of network density, a multipath routing protocol can be implemented in an advantageous way compared to single path routing. The effect of interference can be alleviated by selecting non-interfering paths, henceforth resulting in a better network utilization.

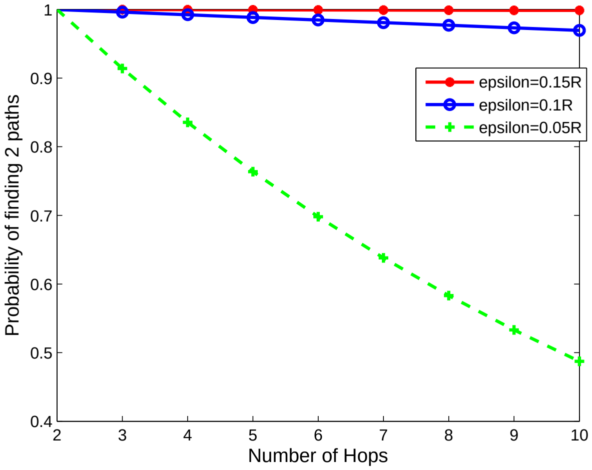


Figure 5.11: Probability of finding 2 paths for a density of 8e-4 nodes/m^2 and a transmission range of 250m

5.6 Throughput Computation

In the previous sections we derived the probability of finding two non-interfering paths given a node distribution. Assuming that these two paths exist between a given source-destination pair, one measure of interest is therefore to evaluate the resulting per-node throughput. We restrict our analysis to networks with a fixed and non-energy constrained wireless backbone in which nodes have potentially enhanced capabilities such as GPS systems. We consider that a network deployed over a circular area of radius R and where nodes are uniformly distributed. We also assume that the network density is high enough so that the probability of finding two non-interfering paths tends to unity. This density can be estimated using the method previously described. In the remainder of this chapter, we focus on how to compute the throughput per node considering that each node can send traffic to any destination.

5.6.1 Throughput Estimation: Methodology

Let A and B be a source-destination pair and F a node on a path between A and B. The evaluation of the throughput at F depends on the traffic generated by F and the traffic needing to be forwarded by F but generated by nodes other then F.

Accordingly, the throughput computation can be broken into two steps:

- Step 1: Determine the maximum number of paths going through node F.

- Step 2: Determine the probability that Node F is participating in a forwarding process. Indeed, a node being geographically located on the trajectory between A and B does not necessarily imply its participation in the forwarding process. For instance, if the communication between node A and node B requires 4 hops, only 3 relay nodes are needed, although more nodes (depending on the network density) can be potential candidates.

5.6.2 Analysis

Relay Traffic

To compute the number of paths going through a particular node F, we need to locate the source and destination nodes that can potentially have a path going through F. The method consists of computing the tangents to the circle centered at F of radius $r/2$. The tangents and their parallel located at ϵ define an area in which the source and destination node should be located (Fig. 5.12).

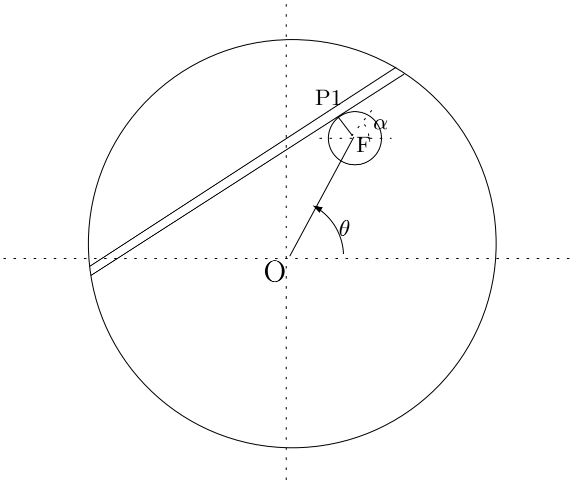


Figure 5.12: Relay traffic: band of width ϵ in which source and destination should be located.

The equation of the circle $\mathcal{C}_F$ centered at F with radius $r/2$ can be straightforwardly derived as:

$$x^2 + y^2 - 2xx_F - 2yy_F + x_F^2 + y_F^2 - (r/2)^2 = 0 \tag{5.19}$$

The equation of the tangent to $\mathcal{C}_F$ at $P_1(x_1, y_1)$ is:

$$xx_1 + yy_1 - x_F(x + x_1) - y_F(y + y_1) + x_F^2 + y_F^2 - (r/2)^2 = 0 \tag{5.20}$$

The coordinates of the intersection points $A(x_A, y_A)$ and $B(x_B, y_B)$ between the tangent and the circle $\mathcal{C}_O$ centered at 0 can be determined from Eq. 5.19 and Eq. 5.20. For each point $P_1 \in \mathcal{C}_F$, we can compute the area where the possible source and destination nodes are located, and consequently the maximum number of paths going through F at P_1. We obtain:

$$\begin{aligned} N_{max_(F,P_1)} &= \sqrt{(x_A - x_1)^2 + (y_A - y_1)^2}\epsilon \\ &\times \sqrt{(x_B - x_1)^2 + (y_B - y_1)^2}\epsilon \times \rho^2 \end{aligned} \tag{5.21}$$

From this, we need to remove the paths whose length is less than r (meaning that the source node and destination node are in direct transmission range of each other). This can be derived by applying Crofton's formula [123]. Let us consider n points $\xi_1, .., \xi_n$ randomly distributed on a domain S, let H be some event dependent on the nodes position. Let δS be a small part of S. Crofton's formula states that:

$$\delta P[H] = n(P[H|\xi_1 \in \delta S] - P[H])S^{-1}\delta S \tag{5.22}$$

We can therefore obtain:

$$P(X > r) = \frac{1}{r}\int_r^{2r} \frac{2r - x}{r} dx$$

$$P(X > r) = \frac{1}{2}$$

The total number of paths to be removed is therefore:

$$N_{rem} = \frac{r^2\epsilon^2}{2} \tag{5.23}$$

Let $\mathcal{N}_F(\alpha_1)$ be the number of paths going through F at P_1. $\mathcal{N}_F(\alpha_1)$ is the result of subtracting Eq. 5.23 to Eq. 5.21.

The next step of the computation consists of determining the total number of paths for all the points located on $\mathcal{C}_F$. We first perform a transformation of P_1's Euclidian coordinates into polar coordinates:

$$\begin{cases} x_1 = & r_F cos\theta_F + \frac{r}{2}cos\alpha \\ y_1 = & r_F sin\theta_F + \frac{r}{2}sin\alpha \end{cases}$$

The maximum number of paths N_{paths} going through F can therefore be obtained by summing all the possible source-destination pairs on the tangents to $\mathcal{C}_F$.

$$N_{paths}(r, \theta) = \int_0^{2\pi} \mathcal{N}_F(\alpha)d\alpha \tag{5.24}$$

This can be evaluated with analytical methods.

Expected Number of Forwarding Nodes

Let us define the expected progress as the distance covered in 1 hop [70]. This parameter is of significant interest in our computation as it is directly related to the number of hops along a path from a source to a destination. The greater the expected progress, the smaller the number of hops. This parameter depends on the network density and the node distribution.

Let z be the maximum expected progress. With a uniform node distribution, the number of nodes follows a Poisson distribution. To have a maximum expected progress z, there should be at least one node in the area located between 0 and z, that is to say the probability p_0 that there is no node between 0 and z should be very small:

$$P(N = 0) = e^{-\rho z \epsilon} = p_0$$

We can thus derive the following equation:

$$\epsilon = \frac{-log(p_0)}{\rho z} \tag{5.25}$$

The expected relay traffic per node $\lambda(r, \theta)$ is therefore:

$$\lambda(r, \theta) = \frac{\lambda}{2} \frac{1}{\rho z \epsilon} N_{paths}(r, \theta) \tag{5.26}$$

5.6.3 Validations

To validate our analysis, we used two methods:

1. We implemented a routing algorithm based on node positioning
2. We computed the total relay traffic in a single path routing strategy and compared it to the total relay traffic in a 2-path routing strategy.

Iterative Position-based Multipath Routing Algorithm

Given the context of our analysis (fixed wireless backbone and the possibility of easily obtaining nodes' position), we propose the following localization-based routing algorithm.

Let V be the set of nodes, S the source node, T the destination node, N_c the current relay node, N the next hop node and N_{orth} the orthogonal projection of N on (S, T). The algorithm consists of iteratively finding the next hop node on each path within the transmission range of the current relay node and satisfying the interference constraints (i.e. the chosen node should be in one of the bands described in Fig. 5.13).

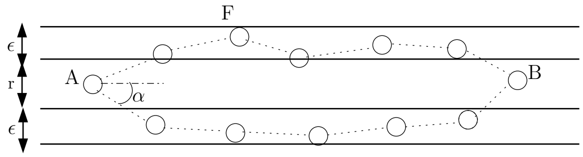


Figure 5.13: 2 non-interfering paths

Algorithm 8 Multipath Routing Algorithm

```
$N_c = S$
$set = V$
$current\_distance = dist(S, T)$
while $set \ = \emptyset$ do
  if $dist(N, N_{orth}) > (r/2)$ && $dist(N, N_{orth}) < (r/2) + \epsilon$ && $dist(N_c, N) < r$ then
    if $dist(N, T) < current\_distance$ then
      $N_c = N$
      $current\_distance = dist(N, T)$
    end if
  end if
  $set = set\{N\}$
  pick $N$ in $set$
end while
```

The algorithm is run for each source-destination pair.

Single path routing

In order to determine the number of nodes involved in the total relay traffic for a single path strategy, we need to compute:

1. the total number of paths
2. the probability that a path length is less than the transmission distance (i.e. the source and destination can communicate directly) in order to exclude these paths from the set of feasible paths

3. the average path length $M(R)$ between two nodes located in a disk of radius R given that the path length exceeds the transmission range

The total number of paths N_{paths} is obtained as:

$$N_{paths} = \rho\pi R^2 * (\rho\pi R^2 - 1) \tag{5.27}$$

The probability density for the distance between two random points located in a circle of radius R can be expressed as [67] [123]:

$$p(x) = \frac{2x}{R^2}(\frac{2}{\pi}\arccos(\frac{x}{2R} - \frac{x}{\pi R}\sqrt(1 - \frac{x^2}{4R^2}))) \tag{5.28}$$

Therefore, the probability that the distance between 2 nodes exceeds the transmission range can be derived as follows:

$$P(x > r) = \int_r^{2R} p(x)dx \tag{5.29}$$

Finally, we need to calculate the mean distance between two nodes randomly dropped in a disk given that the distance between these two nodes is greater than a distance r (the transmission range). Let D be the mean distance between a node A located on the circumference of a circle of radius R and any other node located in the circle whose distance exceeds the transmission radius. D can be expressed as follows:

$$D = \frac{1}{\pi R^2}\int_r^{2R} 2x^2 \arccos(\frac{x}{2R})dx \tag{5.30}$$

$$D = KR$$

with $K = \frac{16}{pi}(-\frac{\alpha}{3}cos^3(\alpha) + \frac{1}{3}sin(\alpha) - \frac{1}{9}sin^3(\alpha))$ and $\alpha = \arccos(\frac{r}{2R})$.

For any two points located in a circle of radius R, the mean distance is:

$$M(R) = \frac{4KR}{5} \tag{5.31}$$

From Eq. 5.27, Eq. 5.29 and Eq. 5.30, we can finally deduce the total relay traffic λ_{tot}:

$$\lambda_{tot} = N_{paths} * P(x > r) * (\lceil\frac{M}{r}\rceil - 1) * \lambda \tag{5.32}$$

The implementation of the validation methods previously described has been realized in Matlab6.4. Both methods necessarily return the same result that is referred to as “theory” in Fig. 5.14. We can observe that both the results obtained with the routing algorithms (”implementation” in Fig. 5.14) and the theoretical formulation match closely.

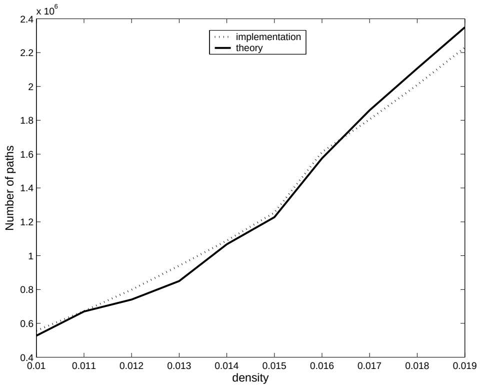


Figure 5.14: Validation of the analytical method

5.7 Conclusion

Multipath routing has been proposed as an alternate solution to single path routing due to its potential for improving the network throughput by balancing the load more evenly. However, to take full advantage of this routing method, interference must be taken into account during the selection of the routing paths.

The contributions of our work are the following. First we studied the complexity of finding two paths between a given source and destination and we proved the NP-completeness of this problem. Then, we analytically derived the probability of finding two non-interfering paths given a certain network density. We finally evaluated the per-node throughput when the nodes are distributed over a circular area. The results obtained are noteworthy as they can be directly applied when deciding the routing strategy. The network density and therefore the probability of finding non-interfering paths can lead to different routing protocols. The results derived in this chapter can consequently enable adaptive routing strategies which depend on the network characteristics.

Chapter 6

Conclusion and Future Works

With the rise of users' expectations of anywhere/anytime connectivity and quality of service guarantees, new wireless technologies are sought after for their versatility, ease of deployment, and low cost. Wireless mesh networks represent a promising solution that can offer extended network coverage through multi-hop communications. WMNs exhibit several prominent characteristics that make them stand apart from traditional wired or wireless networks, and hence call for new resource management techniques.

Routing in multi-hop wireless networks has been and still remains a challenging research topic. Previous work in this area has focused on ad hoc networks. However, the differences between wireless mesh networks and ad hoc networks are significant enough to question the suitability of ad hoc routing protocols for mesh networks. In [135], we discussed the characteristics of wireless mesh networks and compared them to other wireless networks. We established a categorization of existing routing protocols and based on it, we argued that a new routing protocol specifically tailored for WMNs is needed.

In this thesis, we investigated three research problems related to routing in wireless mesh networks: routers-to-gateways association, interference-aware routing metrics and multipath versus single path routing.

To motivate our work, we first started by analyzing how wireless interference affects the nominal capacity [135]. We used known interference models to approximate the achievable throughput for different topologies and traffic flows, and validated them using simulations. The aim of this study was to emphasize the importance of accounting for wireless interference in traffic flow allocation so as to optimize the network performance. We also showed that with carefully chosen paths, multipath routing can result in a better network utilization.

Then, we studied the problem of router-to-gateway association (we considered that each router is equipped with a single network interface). We proved that associating routers to gateways while minimizing the maximum link utilization (an equivalent problem to minimizing the maximum congestion level) is NP-Hard. In single-channel networks, we formulated the problem as a linear program and solved it in a constrained version. We also studied this problem when constraints on paths length and link usage exist. We derived a set of heuristics and experimentally evaluated their performance in different scenarios. In the multi-channel case, we designed several novel heuristics based on path length, traffic load and interference level. We compared their performance in a grid network and using an already-deployed network topology from the city of Chaska, Minnesota. We showed that our forces-based heuristic performs the best and is more adaptive to non-uniform topologies and non-uniform traffic distribution.

We also studied some of the most popular routing metrics currently being used in wireless mesh networks. This analysis allowed us to evaluate the strengthes and weaknesses of these metrics when implemented in a mesh network. We evaluated the relative performance of these metrics by simulations. Based on the results obtained, we designed a novel interference-aware metric (IAR) and demonstrated its advantages over existing metrics.

Finally, we studied the advantages of multipath routing over single path routing. As we highlighted in Chapter 2, multipath routing can result in increased network performance, particularly if non-interfering paths can be used to route the traffic flows between a given source-destination pair. In [135], we studied the performance of multipath routing in multihop wireless networks and demonstrated the importance of properly evaluating the impact of interference in order to enhance network performance. However, setting up and maintaining multiple paths can result in a significant overhead and void the benefit of the load balancing introduced by multipath routing. Consequently we analytically derived the conditions under which two non-interfering paths can be found with high probability. This result is particularly valuable for the implementation of topology-adaptive routing strategies.

In this thesis, we have studied several aspects of routing in wireless mesh networks and proposed solutions for each of them. We have shown that, under the scenarios considered, the mechanisms we proposed can enhance the network performance. We were only concerned in this thesis with a subset of issues related to resource management in wireless mesh networks. Some future research works involve studying the routers-to-gateways association problem when routers are equipped with multiple interfaces. This can be reduced to the study of channel-to-interface assignment algorithms. We have also mainly focused on centralized algorithms. It would be interesting to compare the performance of distributed approaches with centralized approaches, with in particular a focus on the overhead and accuracy of the solutions obtained. In the design of our interference-aware routing metric, we have not considered the cost of the overhead involved in maintaining information on the network status. Passive and active monitoring have both shown advantages and drawbacks that need to be assessed in the context of wireless mesh networks. Finally, we need to extend our analysis of multipath routing to multiple flows scenarios.

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