INTERFERENCE-AWARE ROUTING IN WIRELESS MULTIHOP NETWORKS

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GEORGIOS PARISSIDIS
M.Eng. TUC Greece, DEA Université Paris VI

date of birth
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citizen of
Greece

accepted on the recommendation of
Prof. Dr. Bernhard Plattner, examiner
Prof. Dr. Gunnar Karlsson, co-examiner
Prof. Dr. Peter Steenkiste, co-examiner

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Abstract

Nowadays, wireless multihop networks, providing mesh connectivity emerge as alternative network infrastructure for numerous applications such as shared broadband Internet access, monitoring for emergency, medical and security reasons, distributed backup and multimedia applications. Since these networks are highly decentralized and self-organized, routing becomes a critical factor for their performance and efficiency.

The work in this thesis focuses on interference-aware routing. Interference is an inherent property of wireless networks determining boundaries for spectrum reuse and directly affecting the network capacity as well as protocol performance. Estimating interference in a wireless network and circumventing its effects is not a trivial task. The amount of interference depends on many factors including the radio propagation environment, spatial node distribution, MAC protocol dynamics. Therefore, adding interference-awareness to the routing protocol decisions is challenging.

The first contribution of this thesis is a quantitative comparison of multipath routing protocols proposed for wireless multihop networks. Multipath routing represents a promising alternative to single-path routing in that it enables load balancing and resilience to route failures. We show that multipath routing outperforms single-path in networks with high node density and network load and the use of two, maximum three, paths represents the best
tradeoff between routing overhead and performance. Nevertheless, the requirement for efficient data scheduling remains equally important for both multipath and single-path routing protocols.

The role of interference in that is critical. Therefore, much of our work addresses interference modeling. We derive an analytical model for the probability that a transmission destined to an arbitrary network node is successful in the presence of interference from other nodes in the network. Our analytical expression for the data loss probability is a function of the network density, node transmission probability, radio propagation environment, and network card hardware. We validate our interference model against experiments in a real testbed, set up for this purpose in our indoor office environment, showing good match of the experimental results with the analytical predictions.

Our work concludes with the design of an interference-aware routing metric that explicitly takes interference into account via our analytical derivation. Contrary to measurement-based models, our derivation only requires information that is locally available to the nodes, avoiding all measurement-related pitfalls. We show that its performance compares favorably with those achieved by the state-of-the-art probe-based routing metric.
Kurzfassung


Diese Arbeit schliesst mit der Erstellung einer Routing-Gewichtung mit expliziter Berücksichtigung der Interferenz, wie sie analytisch hergeleitet wurde. Im Gegensatz zu Modellen, die auf Messungen basieren, benötigt unsere Herleitung Informationen, die von jedem Knoten lokal erhältlich sind, und umgeht ausserdem alle Nachteile, die aus Messungen resultieren. Wir zeigen, dass es leistungsfähiger ist als andere moderne Routing-Gewichtungen, die auf Messungen basieren.
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Chapter 1

Introduction

1.1 Motivation

The standardization of wireless communication (IEEE 802.11) [IEE99] for Wireless Local Area Networks (WLANs) enabled the inter-communication of mobile, battery-powered devices and showed the way towards a revolutionary method of communication that extends the well-established wired Internet. But also in static settings, wireless technology has been popular in private households and office environments, since it removes the need for wired infrastructure. Communication between two end nodes in multihop wireless networks is realized through a number of intermediate nodes whose function is to relay information from one point to another.

Whereas radio communication for wireless networks is standardized and many problems have been resolved, networking protocols for wireless intercommunication are still in experimental state. The successful and wide-spread deployment of wireless multihop networks (i.e., mesh, ad hoc) strongly depends on the implementation of robust and efficient network layer protocols.
Efforts of the research community over the last fifteen years resulted in the derivation of numerous routing protocols for wireless multihop networks. The most-well-known are the Dynamic Destination-Sequenced Distance Vector (DSDV) [PB94], Dynamic Source Routing (DSR) [JM96], Ad-hoc On-demand Distance Vector (AODV) [PBRD03], and Optimized Link State Routing Protocol (OLSR) [JMQ98]. The essential design goals of the routing protocols are route discovery and connectivity maintenance. Their specification does not explicitly define how protocols select paths to transfer data over the network most efficiently.

One approach towards improving the routing efficiency in wireless multihop networks involves multipath routing protocols. Multipath routing protocols establish multiple paths from a source to a destination, thereby providing resilience to network failures and allowing for network load balancing. The most popular multipath routing protocols (SMR [LG01], AOMDV [MD01] and AODV_Multipath [YKT03]) are extensions of the aforementioned single-path routing protocols. Whereas separate performance evaluation studies of each protocol has shown that they achieve lower routing overhead and end-to-end delay in comparison with single-path routing, there have been much fewer results regarding how these protocols compare with each other.

To fill this gap, we conducted in early an stage of our research, an extensive performance evaluation of the three aforementioned multipath routing protocols. We studied the advantages and limitations of each protocol under a large set of network properties including mobility, node density, and data load, while having single-path routing as a reference. Our study demonstrates that multipath routing outperforms single-path in networks with high node density and network load. Furthermore, we show that the use of two, maximum three, paths represents the best tradeoff between routing overhead and performance.

Whereas multipath routing has an occasional gain compared to single-path routing, it does not alone answer the question of
efficient scheduling of data over multiple paths. In our evaluation we used a simple scheduling method where in the absence of link-quality information, packets are routed with equal probability over each available path discovered by the routing protocol. Therefore, a fundamental question on the performance of multi-path routing protocol is:

Which path(s) is(are) the best to use?

This question is not directly addressed by the routing protocols; it is rather routing metrics that enable routing protocols to make routing decisions with respect to some optimization objectives such as throughput maximization, delay minimization, robustness, or energy efficiency.

We illustrate the importance of routing metrics by giving a simple example.

Example: Lets assume a simple network of 3 nodes where S is the sender and D the destination node. Node S can communicate either directly to node D (one hop) or through node H (two hops). Let the probability of packet loss over link (hop) S-D in Fig 1.1 be $p_1$ in both directions, $S \rightarrow D$ and $D \rightarrow S$. Likewise, the probability of loss over both hops of path SHD is $p_2$, again in both directions. A packet transmission is considered successful when the data packet is correctly received in the forward direction and an ACK packet is correctly received in the reverse direction, as in the unicast 802.11x transmission mode. What would be the minimum value of loss $p_1$, under which the minimum-hop path

![Figure 1.1: One hop vs. two hop path](image-url)
SD would result in larger delay than the two-hop path SHD? We assume, for simplicity, that the number of retransmissions at the link-layer is infinite.

Given that the propagation delay is small (in the order of \(\mu\text{sec}\)) compared to the transmission delay (in the order of \(m\text{sec}\)), the overall end-to-end delay of the packet is directly proportional to the total number of hop transmissions (including retransmissions) along the path. The number of transmissions over a hop with symmetric packet probability loss, i.e., \(p_f = p_r = p\) (where \(p_f\) is the forwarding loss probability and \(p_r\) is the reverse loss probability), is a geometrically-distributed random variable with parameter \((1-p)^2\); the expected number of transmissions, assuming infinite retransmissions, equals \(1/(1-p)^2\). The normalized end-to-end delays over paths SD and SHD are:

\[
D_{SD} = \frac{1}{(1-p_1)^2}, \quad D_{SHD} = \frac{2}{(1-p_2)^2}
\]

Therefore,

\[
D_{SD} \geq D_{SHD} \Rightarrow \frac{1}{(1-p_1)^2} \geq \frac{2}{(1-p_2)^2} \Rightarrow (1.2)
\]

\[
\frac{1-p_2}{1-p_1} \geq \sqrt{2} \Rightarrow p_1 \geq \frac{\sqrt{2} - 1 + p_2}{\sqrt{2}}
\]

and the minimum required value for \(p_1\) in order to get smaller delay over the two-hop path is

\[
p_{1,\text{min}} = p_1|_{p_2=0} = \frac{\sqrt{2} - 1}{\sqrt{2}} = 0.29.
\]

The message that comes out of this example is that knowledge of the dynamically changing loss probabilities over the network links could support routing decisions in wireless multihop networks. The aforementioned example could have direct use as a routing metric if the probabilities \(p_1, p_2\) were known at node S.
1.1 Motivation

The essential factors that impact the probability of successful packet reception in wireless networks are the radio propagation environment and interference from other transmissions. In the IEEE 802.11x suite of protocols, the distribution coordination function (DCF) is the fundamental mechanism used for wireless medium access based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. While this mechanism enables nodes to communicate over the wireless medium, it introduces additional challenges. Due to the nature of wireless channels that differentiates them from the wired networks, simultaneous transmissions may result in unsuccessful receptions (interfered receptions). Interference impacts significantly the performance of routing protocols as well as network’s efficiency [JPPQ03].

Therefore, a routing metric for wireless multihop networks should account for interference. To address this, we first develop an interference model estimating the probability of successful reception on a wireless link in the presence of interference from simultaneous transmissions of other network nodes. Our model has distinct advantages over proposed methods in the literature that estimate packet loss with active probe measurements [RMR+06] [QZW+07]. It is simple, it does not need seed measurements and the derivation of link loss probability exploits information locally available at a wireless node: spatial node distribution, node transmission probability, radio propagation environment, network card reception sensitivity, and sender-receiver distance. Furthermore, it accommodates mobility as soon as the steady-state spatial node distribution of mobility models is known; e.g., for the random waypoint [BRS03], random walk, and random direction [NTLZ04] models.

Then, with the interference model at hand, we design and implement an interference-aware routing metric for wireless multihop networks. We evaluate its performance against the state-of-the-art routing metric ETX (Expected Transmission Count)
[CABM03] and minimum hop count. The results reveal that our metric performs at least as good as ETX and minimum hop count across a large set of experiments, because it explicitly accounts for interference, the primary cause of performance degradation in wireless multihop networks.

1.2 Research Questions

Wireless multihop networks are challenging in many ways. In this thesis we focus only on a subset of these challenges, i.e., those related to the routing function. In particular, we address the following research questions:

- **Does multipath routing perform better than single-path routing in wireless multihop networks?** The objective is to conduct an extensive performance evaluation study of multipath routing protocols in wireless multihop network under a broad set of network variables including node mobility, node density and data load. There have been much fewer results regarding how multipath routing protocols compare with each other and with single-path routing.

- **How to model interference in wireless multihop networks?** The idea is to model the probability of successful reception in the presence of interference from simultaneous transmissions in the network. However, the complexity of the 802.11x MAC suite of protocols renders a thorough interference characterization. We attempt to strike a good balance between model simplicity and utility with respect to routing.

- **Is it possible to use information locally available (or estimated) at a node to capture the effect of interference?** Our idea is to exploit information locally available at a node –
such as node density, network load, distance of nodes – to estimate the probability of successful reception in the presence of interference. The question is how precise an estimate can be obtained this way and how does it compare with state-of-the-art approaches relying on active probe measurements.

- How can an interference model be used to assist routing in wireless multihop networks? The question is how to design and implement an interference-aware routing metric based on our interference model.

1.3 Contributions

The primary contributions of our work are the development of an interference model for wireless multihop networks and design and implementation of an interference-aware routing metric that draws on this model. Nevertheless, the research path to these two milestones feature further intermediate contributions; we list them all below, in order of appearance in this thesis.

- We survey routing metrics proposed for wireless multihop networks [PKS+07]. Several routing metrics have been proposed to overcome the inefficiencies of minimum hop count. We give a thorough overview of more elaborate metrics that address the additional challenges of wireless multihop networks. In particular, we discuss their optimization goals as well as the type of information required for the metric computation.

- We conduct a quantitative comparison of multipath routing protocols for wireless multihop networks [GLMP06]. We show that multipath routing performs better than single-path routing in dense networks and networks with high traf-
fic load. However, we exhibit the need of a routing metric for efficient scheduling over multiple paths.

- We develop an interference model to capture the effect of interference in wireless multihop networks [PKM+08]. More specifically, we derive an analytical expression for the probability of successful reception in the presence of interference. For the analysis we assume a MAC-agnostic model, which does not take into account the engineering details of real-world protocols (IEEE 802.11x suite of protocols). We then extend our analytical derivation with a simple enhancement to capture the carrier sense function of real-world MAC protocols.

- We set up a 20-node wireless mesh network testbed (TIK-Net) [TIK07]. Since packet-level simulators do not accurately model the wireless physical layer, we set-up an indoor wireless testbed to assess the prediction capacity of our analysis under realistic conditions. The measurements of the experimental evaluation show close match with the analytical predictions of our interference model.

- We demonstrate the usability of our model by designing and evaluating an interference-aware routing metric for wireless multihop networks [PKS+08]. We compare our metric against the ETX and the minimum hop count metrics at the TIK-Net testbed. Our interference-aware routing metric performs at least as good as ETX and minimum hop count in a large set of experiments including intraflow and interflow interference.

1.4 Outline

The present thesis is structured as follows:
• **Chapter 2** discusses related work and it also contains a survey of routing metrics proposed in the literature for wireless multihop networks.

• **Chapter 3** presents a qualitative comparison of multipath routing protocols for wireless multihop networks. This evaluation exhibits the advantages and limitations of multipath routing in wireless multihop networks and distills the main research question treated in the two subsequent chapters, *i.e.*, chapters 4 and 5.

• **Chapter 4** introduces our interference model for wireless multihop networks. We provide a sensitivity analysis of our interference model and evaluate it experimentally at the TIK-Net indoor wireless testbed, which is set-up for this purpose.

• **Chapter 5** demonstrates the utility of our interference model as a routing metric for wireless multihop networks. We design an interference-aware routing metric and we compare its performance against a state-of-the-art routing metric (ETX) in wireless multihop networks and the minimum hop count metric.

• **Chapter 6** concludes this thesis including a discussion on possible weaknesses and future work.
Chapter 2

Related Work

In this chapter, we review related research that influenced our work on routing for wireless multihop networks. First, we summarize the efforts of the research community to develop multipath routing protocols and improve the performance of wireless multihop networks. The summary sketches the background for our comparative study of multipath routing protocols in Chapter 3. Then, we briefly outline the main approaches to interference characterization in wireless multihop networks. Some of the drawbacks of these approaches have actually motivated our model presented in Chapter 4. Finally, we provide a taxonomy of routing metrics for wireless multihop networks. This is a thorough survey that came out of our initial review of metrics at the early stage of our metric design.

2.1 Multipath Routing Protocols

Multipath routing is not a new concept; it has already been proposed and implemented in packet and circuit switched networks. First, in circuit-switched telephone networks, alternate path routing was proposed in order to increase network utilization as well
as reduce the call blocking probability. Later in data networks, a similar concept is present in the Private Network-to-Network Interface (PNNI) signalling protocol [ATM96] proposed for ATM networks. With PNNI, alternate paths are used when the optimal path is over-utilized or has failed. In the Internet, multipath routing is included in the widely used interior gateway routing protocol OSPF [OSP]. OSPF allows multiple paths only if they have equal cost. Multipath routing can alleviate congestion by re-routing data traffic from highly utilized to less utilized links through load balancing. However, the wide deployment of multipath routing is so far hindered by the higher complexity and the additional cost related to storing extra routes in routers.

Wireless multihop networks include many features that differentiate them from conventional wired networks. The non-use of multipath routing in the Internet today does not imply that multipath routing is not an appropriate and promising solution for wireless networks.

The non-reliability of the wireless medium and the dynamic topology resulting from node mobility or failure lead to frequent path breaks, network partitioning, and high delays for path re-establishments. Therefore multipath routing represents a very promising alternative to single-path routing, as it can provide higher resilience to path breaks, especially when paths are node disjoint [TH01], [VKSR03], alleviate network congestion through load balancing [GK04], and reduce end-to-end delay [WSD+01], [PHST00].

More specifically, the effect of the number of multiple paths on routing performance has been studied using an analytical model in [NCD01]. The results show that the performance advantage of multipath is small beyond a few paths and for long path lengths. Simulation results demonstrated that with multipath routing end-to-end delay is higher since alternate paths tend to be longer. However, a radio link layer model is not included in the simulations, thus the effect of interference is not captured.
Analysis and comparison of single-path and multipath routing for wireless mobile ad hoc networks were carried out in [PP03]. As the spatial dimensions of mobile ad hoc networks are finite, network congestion is inherently encountered in the center of the network, since shortest paths mostly traverse the center of the network. Thus, in order to route data packets over non-congested links and maximize overall network throughput, a protocol should target at utilizing the maximum available capacity of the calculated multiple routes. The authors conclude that routing or transport protocols in ad hoc networks should provide appropriate mechanisms to push the traffic further from the center of the network to less congested links.

### 2.1.1 Deployment of Multipath Routing

In addition to the aforementioned theoretical work on multipath routing, multipath routing protocols were developed to support video transport, satisfy reliability requirements or energy conservation, and provide end-to-end transport services.

In [WPLM02], an architecture for video transport over multipath routing and two types of source coding (multiple-description and layered coding) are proposed. Furthermore, a scheme for reliable video transport using multipath routing and layered coding is proposed in [MPLW01]. In this scheme, video is encoded in two layers (base and enhancement) and accordingly packets of each layer are sent over two disjoint paths towards the destination.

A multipath traffic allocation scheme using M-for-N diversity coding for reliable transfer of data is proposed in [TH01]. N+M blocks are allocated over multiple paths and the objective of this scheme is to maximize the probability of losing no more than M blocks in order to satisfy the reliability constraints. In [LLP+01],

\[1\]This is generally true for random traffic patterns and uniform node distribution.
a multipath extension to the DSR protocol attempting to provide end-to-end reliability is proposed. The protocol estimates a reliability factor from the link availability and the probability of reliable transfer along each path. An energy-efficient multipath routing protocol is proposed in [GGSE02]. The objective of the protocol is to minimize the energy consumption of nodes on alternative paths compared to the shortest path. The protocol calculates partially disjoint paths that are shorter than node-disjoint paths and consequently consume less energy resources.

In a different line of work, multipath routing has been investigated in conjunction with transport protocols running on top of it, mainly TCP. In [LXG03], simulation results show that pure multipath routing is detrimental to TCP performance. Thus, a backup-path routing strategy is proposed. Backup-path routing actually uses only one path at a time but maintains some backup paths and can switch from the current path to another alternative path rapidly if the in-use path fails. Duplication of TCP data packets and transmission of a copy over each of the multiple paths is proposed in [CXG04]. However, simulation results show that this solution can improve TCP performance only in very lossy environments. In summary, novel transport protocols or modifications of existing protocols (TCP, UDP, SCTP) exploiting multipath routing represent a challenging research issue.

The most popular multipath routing protocols developed for wireless multihop networks are the AOMDV [MD01], AODV_Multipath [YKT03] and SMR [LG01]. These protocols are multipath extensions/modifications of the popular single-path routing protocols AODV [PBRD03] and DSR [JM96]. In particular, SMR outperforms DSR because multiple routes provide robustness to mobility, AOMDV compared with AODV achieves an improvement in the end-to-end delay (often more than a factor of two) and reduces routing overhead by about 20%, while AODV_Multipath using multiple node-disjoint routes provides potentially some tol-
2.2 Interference in Wireless Networks

Multiple access interference has always been one of the main concerns when building wireless networks. Whereas its impact is quite well understood and addressed in infrastructure-based cellular networks (see, for example, [Lee98] and [TV05]), its characteristics and impact on wireless multihop networks are less well understood.

Jain et al. in [JPPQ03] propose the use of conflict graphs for describing interference between neighboring nodes and links. Contrary to the typical graph semantics, vertices of the graphs are the individual network links (hops) with an edge connecting them when the two links interfere. The authors use this abstraction to derive bounds for the optimal network throughput under ideal routing and scheduling decisions but they do not propose any way to derive the conflict graph. This was addressed in [PAP+05] and [RMR+06]. Padhye et al. in [PAP+05] use broadcast transmissions to derive the Broadcast Interference Ratio (BIR) as a measure of the interaction between two network hops, whereas Reis et al. combine a simplified analytical model for the CSMA/CA function of 802.11 with fewer measurements ($n$ versus $n^2$ in [PAP+05], where $n$ the number of network nodes) to estimate BIR values and determine the graph edges [RMR+06]. Whereas their model is limited to two competing broadcast senders, Qiu et al. develop a general model for interference (GMI) for arbitrary number of senders [QZW+07]. Both models have as starting point RSSI (Received Signal Strength Indicator) measurements that profile the network nodes and become inputs to the analytical model. One major objective of our
The main focus of interference-related research has been on its impact on network capacity and throughput. Gupta and Kumar [GK00] start from the same physical model of interference (SINR) we consider later in Chapter 4, to prove that as the number of nodes \( n \) increases, the throughput per source-destination pair decreases approximately as \( O\left(\frac{1}{\sqrt{n}}\right) \). Grossglauser and Tse in [GT02] show that mobility of nodes can improve the capacity of ad hoc wireless networks. A more explicit model of the carrier sense mechanism of IEEE 802.11 is given by Hekmat and Van Mieghem in [HM04] under restrictive assumptions regarding the mobility of the nodes, which are permitted to occupy positions only along an hexagonal lattice. Their model reveals the existence of a network saturation point, after which the network throughput no longer increases with the number of network nodes. However, the model is not validated with experimentation. In a more empirical work, Li et al in [LBC01] explore via simulations the analytical findings in [GK00], concluding that the relevance of the analytical bounds for network capacity in [GK00] and [GT02] is largely dependent on the locality of traffic patterns. As the traffic becomes more local with neighboring nodes communicating to each other, over paths of fewer hops, the bound becomes more optimistic and the per node throughput can remain intact, i.e., varies as \( O(1) \).

The impact of interference on the performance of wireless ad hoc networks is studied also in [YV06]. They estimate the optimal carrier sense threshold (i.e., the SINR threshold) to maximize the aggregate throughput in wireless ad hoc networks. However, they estimate the interference from simultaneous transmissions taking into consideration only the adjacent nodes of an intended receiver. In our work in Chapter 4, we derive the probability of unsuccessful receptions due to interference taking into consideration all nodes in a network. To estimate the level of interference
in wireless ad hoc networks a grid model is proposed in [HM04]. The expected value of interference is used to estimate the network capacity and the per node throughput. Their work has the limitation of being evaluated in a specific grid topology.

In addition to the analytical work estimating the effect of interference on the network capacity and the aggregated throughput, methods based on measurements on wireless network testbeds were proposed. Focusing more on protocol engineering, there is agreement in the research community that interference should be an input for routing protocols. Several routing metrics have been proposed to overcome the inefficiencies of minimum-hop routing; they rely on estimation of the path round trip time (RTT), expected data transmission count (ETX) [CABM05], and the weighted cumulative expected transmission time (WCETT) [DPZ04b] to drive routing decisions. Since in Chapter 5, we propose our own routing metric, we take a closer look at these metrics and discuss their shortcomings in the following section, in the context of a broader survey on routing metrics.

### 2.3 Metrics for Routing Protocols

In this section we survey routing metrics proposed for wireless multihop networks. First, we discuss the optimization goals of routing metrics, the different methods information required for the metric computation is collected, and the way the route (path) metric relates to individual link metrics. We then argue in favor of more elaborate metrics that can address additional challenges of wireless multihop networks and present the main metrics proposed up-to-date in literature.

#### 2.3.1 Optimization objectives

A routing metric is essentially a value assigned to each route or path, and used by the routing algorithm to select one, or
more, out of a subset of routes discovered by the routing protocol. These values generally reflect the cost of using a particular route with respect to some optimization objective, and could take into account both application and network performance indicators. More specifically, the objective of the routing algorithm and thus the routing metric may be to:

- **Minimize delay.** This is often the canonical objective of the routing function. The network path over which the data can be delivered with minimum delay is selected. If queuing delays, link capacity, and interference are not taken into account, then delay minimization often ends up being equivalent to hop-count minimization.

- **Maximize probability of data delivery.** For non real-time applications, the main requirement is to achieve a low data loss rate along the network route, even at the expense of increased delay. This is equivalent to minimizing the probability of data loss between network end-points.

- **Maximize path throughput.** Here, the aim is the selection of an end-to-end path that consists of links with high capacity.

- **Maximize network throughput.** Contrary to the first three objectives, which are user application-oriented, network throughput is a system objective. The objective may be formulated as the maximization of data flow in the whole network or, implicitly, through the minimization of interference or re-transmissions.

- **Minimize energy consumption.** Energy consumption is rarely an issue in wired networks. However, it becomes a major concern in sensor networks and mobile ad hoc networks, where the battery lifetime constrains the operation of network nodes.
• *Equally distribute traffic load.* This objective is more general. Here, the aim is to ensure that no node or link is disproportionately used, and could be achieved, for example, by minimizing the difference between the maximum and minimum traffic load over the network links. Load balancing may have an indirect effect on other objectives such as battery lifetime, per node throughput, etc.

It is worthwhile to note here that the first three objectives in the list above are concerned with individual application performance, that is, to optimize the performance for a given end-to-end path, while the last three are “system-oriented” objectives that focus on the performance of the network as a whole. Furthermore, routing metrics may consider more than one of the aforementioned objectives. In this case, the multi-dimensional metric combines the different measures, weighting them appropriately to account for the relative prioritization of the objectives.

### 2.3.2 Link and path metrics

The ultimate decision to be made by routing will be about the selected route(s); therefore, the final metric value that will be the subject of comparison will relate to the whole route (path). However, the path metric needs to be derived as a function of the individual metric values estimated for each link in the path. The actual function to be used varies and highly depends on the actual metric in question. The most widely used functions are:

• *Summation.* The link metric values are added to yield the path metric. Examples of additive metrics are the delay or number of retransmissions experienced over a link.

• *Multiplication.* Values estimated over individual links are multiplied to get the overall path metric. The probability of successful delivery is an example of a multiplicative metric.
• *Statistical measures (minimum, maximum, average).* The path metric coincides with the minimum, average, or the maximum of values encountered over the path links. Example of the first case is the path throughput, which is dictated by the minimum link throughput (bottleneck link) over all hops included in a network path.

### 2.3.3 Metric computation method

There are also various ways in which network nodes acquire the information they need for the computation of the routing metric:

• *Reuse of locally available information.* Information required by the metric is available locally at the node, usually as result of the routing protocol operation. Such information may include the number of node interfaces, number of neighbor nodes (degree), length of input and output queues.

• *Passive monitoring.* Information for the metric is gathered by observing the traffic coming in and going out of a node. No active measurements are required. In combination with other measurements, this can be used, for example, to estimate the available bandwidth.

• *Active probing.* Special packets are generated, whose function is to measure the properties of a link/path. This method incurs the highest overhead on the network, which is directly dependent on the frequency of measurements.

• *Piggyback probing.* This method also involves measurements. However, these measurements are now carried out by including probing information into regular traffic or routing protocol packets. With piggyback probing, no additional packets are generated for metric computation purposes, thus reducing the overhead for the network. Piggyback probing is a common method to measure delay.
2.3 Metrics for Routing Protocols

Raw information about a link, acquired from passive or active measurements, usually requires some processing before it can be used to construct efficient and stable link metrics. Measured network parameters (e.g., delay or link loss ratio) are often subject to high variation. It is usually desired that short-term variations do not influence the value of a metric; otherwise, rapid oscillations of the metric value could, depending on the actual metric context, result in the phenomenon of self-interference, quite early observed in Internet applications [KZ89]: once a link is recognized as good, it is chosen by the routing protocol and starts getting used until it is overloaded and is assigned a worse metric value. As traffic starts to route around this link, its metric value increases again and the effects starts anew. Therefore, metric measurements are subject to some filtering over time. Different metrics apply to different types of filtering:

- **Dynamic history window**: an average is computed over a number of previous measurement samples, which varies depending on the current transmission rate.

- **Fixed history interval**: an average is computed over a fixed number of previous measurement samples.

- **Exponential weighting moving average (EWMA)**: measurement samples are weighted so that the impact of past samples on the current value of the metric decays exponentially with the sample age. Every time a new sample $d_{sample}$ is obtained, the value of the metric is updated as: $d_{new} = \alpha \cdot d_{old} + (1 - \alpha) \cdot d_{sample}$ with $\alpha \in [0, 1]$ being the weighting factor, and $d_{old}$ the current metric value.

2.3.4 Active probing based metrics

Inferring the probabilities of data loss in the network links via the signal strength values is one possibility, however this method
is not very promising \[\text{ABB}^+04\]. The alternative approach is to carry out active measurements and use probe packets to directly estimate those probabilities.

Probing introduces various challenges. One concern with it is that it should be treated as normal traffic in the network, e.g., the packet sizes of probes should be equal to the actual traffic data so that what probes measure is as close to the target as possible. Likewise, probe packets should not be prioritized or treated preferentially in the network. On the other hand, if the probing packets are interlaced with the regular traffic (so-called intrusive or in-band measurement), the probes themselves influence the amount of traffic. Ferguson and Huston [FH98] compare this effect with the Heisenberg Uncertainty Principle. Lundgren et al. [LNT02] and later Zhang et al. [ZAS06] observed that the different properties of unicast and broadcast communication in IEEE 802.11 systems may lead to similar effects. Probes that are sent using the broadcast mechanism will report neighbors that are not reachable using unicast communication. Both papers call this phenomenon the grey-zone problem.

Of even more concern, in particular when wireless links are involved, is the overhead related to probe messages. The actual probing period is a tradeoff between measurement accuracy and signaling overhead. Nevertheless, probing based approaches have proved promising in the context of wireless multihop networks. They measure directly the quantity of interest, rather than inferring it from indirect measurements, and do not rely on analytical assumptions. This is why these metrics have been particularly popular in the last five years. The main novelty came with the Expected Transmission Count (ETX) metric [CABM03]; then a whole family of metrics has emerged out of it that attempts to optimize routing performance under various assumptions for the link rates and the channels used in the network.
2.3.5 Per-hop Round Trip Time (RTT)

The per-hop Round-Trip Time metric reflects the bidirectional delay on a link [ABP+04]. In order to measure the RTT, a probe carrying a timestamp is sent periodically to each neighboring node. Then each neighbor node returns the probe immediately. This probe response enables the sending node to calculate the RTT value. The path RTT metric is simply the addition of the link RTTs estimated over all links in the route. The RTT metric is a load-dependent metric, since it comprises queuing, channel contention, as well as 802.11 MAC retransmission delays. Besides the probe-related overhead, the disadvantage of RTT is that it can lead to route instability (phenomenon of self-interference).

2.3.6 Per-hop packet pair delay (PktPair)

The PktPair delay involves the periodic transmission of two probe packets back-to-back, one small and one large, from each node. The neighbor node then measures the inter-probe arrival delay and reports it back to the sender. This technique is designed to overcome the problem of distortion of RTT measurements due to queuing delays. The PktPair metric is less susceptible to self-interference than the RTT metric, but it is not completely immune, as probe packets in multihop scenario contend for the wireless channel with data packets. To understand this, consider three nodes A, B and C in a chain where A sends data to C via B. Data packets sent to node B contend with probe packets of B destined to C. This increases the PktPair metric between B and C and consequently increases the metric along the path from A to C. Performance evaluation on an indoor wireless testbed showed that RTT performed 3 to 6 times worse than the minimum hop count, Packet Pair or ETX metrics in terms of TCP throughput [DPZ04a]. As RTT is more sensitive to load, it performs worse than PktPair.
Both the RTT and PktPair metrics measure delay directly, hence they are load-dependent and prone to the self-interference phenomenon. Moreover, the measurement overhead they introduce is $O(n^2)$, where $n$ is the number of nodes. On the contrary, the metrics presented below are not load-independent and the overhead they introduce is $O(n)$.

### 2.3.7 Expected Transmission Count (ETX)

The Expected Transmission Count (ETX) is one of the first routing metrics based on active probing measurements specifically designed for MANETs. Starting with the observation that minimum hop count is not optimal for wireless networks, De Couto et al. [CABM03] proposed a metric that centers on bidirectional loss ratios. ETX estimates the number of transmissions (including retransmissions) required to send a packet over a link. Minimizing the number of transmissions does not only optimize the overall throughput, it does also minimize the total consumed energy if we assume constant transmission power levels, as well as the resulting interference in the network [KB06]. Let $d_f$ be the expected forward delivery ratio and $d_r$ be the reverse delivery ratio, i.e., the probability that the acknowledgment packet is transmitted successfully. Then, the probability that a packet arrives and is acknowledged correctly is $d_r \cdot d_f$. Assuming that each attempt to transmit a packet is statistically independent from the precedent attempt, each transmission attempt can be considered a Bernoulli trial and the number of attempts till the packet is successfully received a geometrically-distributed variable, $\text{Geom}(d_r \cdot d_f)$; therefore, the expected number of transmissions is:

$$
ETX = \frac{1}{d_r \cdot d_f}
$$

(2.1)

The delivery ratios are measured using link-layer broadcast probes, which are not acknowledged at the 802.11 MAC layer.
Each node broadcasts a probe packet every second including in its probes the number of probes received from each neighboring node over the last \( w \) seconds (\( w = 10 \) in their implementation). Each neighbor of a sender node A can then calculate the \( d_r \) value to A each time it receives a probe from node B, as the ratio of the reported count over the maximum possible count \( w \). The whole process is summarized in Fig 2.1.

Node B reports with the latest broadcast probe the number of probes \( x \) received over the previous time window \( w \). Node A estimates the probability that a data packet will be successfully transmitted to B in a single attempt. It also counts the number of probes \( y \) received from node B over the same time and gets the ETX value for the link. The ETX along a path is defined as the sum of the metric values of the links that form this path.

The main advantages of the ETX metric are its independence from link load and its account for asymmetric links. In other words, ETX does not try to route around congested links and
therefore it is immune to the phenomenon of self-interference. Measurements conducted on a static test-bed network show that ETX achieves up to two times higher throughput than minimal hop-count for long links. ETX is one of the few non hop-count metrics that has been implemented in practice in MANETs, e.g., as part of the OLSR protocol daemon (OLSRD) over multiple platforms [Lop04].

The main disadvantage of the ETX metric, as already mentioned earlier, is the overhead injected in the network from the probe packets. Furthermore, since broadcast packets are small and are sent at the lowest possible rate, the estimated packet loss may not be equal to the actual packet loss of larger data packets sent at higher rates. Moreover, it does not directly account for the link transmission rate; two links with different transmission rates, hence different transmission delays, may have the same packet loss rate.

2.3.8 Extensions of the ETX metric

Draves et al. [DPZ04b] observe that ETX does not perform optimally under certain circumstances. For example, ETX prefers heavily congested links to unloaded links, if the link-layer loss rate of congested links is smaller than on the unloaded links. Therefore, they address this by proposing the Expected Transmission Time (ETT) metric incorporating the throughput into its calculation. Let $S$ be the size of the probing packet and $B$ the measured bandwidth of a link, then the ETT of this link is defined as $ETT = ETX \cdot \frac{S}{B}$. They go one step further in their work to suggest computing the path metric as something more than just the sum of the metric values of the individual links in this path. Pure summation of link metrics does not take into account the fact that concatenated links interfere with each other, if they use the same channel. As many wireless technologies, including 802.11a/b/g, provide multiple non-overlapping channels,
they propose an adaptation of the ETT metric accounting for the use of multiple channels, namely the Weighted Cumulative ETT (WCETT). As the total path throughput will be dominated by the bottleneck channel, they propose to use a weighted average between the maximum value and the sum of all ETTs. In their static test-bed implementation they showed that WCETT outperformed ETX by a factor of two and minimal hop count by a factor of four, when two non-interfering radio channels were used. The main disadvantage of the WCETT metric is that it is not immediately clear if there is an algorithm that can compute the path with the lowest weight in polynomial or less time.

Draves et al. propose to use packet pairing techniques (see Section 2.3.6) to measure the transmission rate on each link at the expense of additional measurement overhead. On the contrary, Awerbuch et al. recommend the use of inter-layer communication, so that the routing layer can have access to relevant information and statistics maintained by the physical and MAC layer. This would require some standard interface that, at least for the moment, is not available on most wireless network adapter cards.

The Metric of Interference and Channel switching (MIC) [KV06] improves WCETT by addressing the problem of intraflow (simultaneous transmissions of the same path) and interflow (simultaneous transmissions of other paths) interference. The two components of MIC, IRU (Interference-aware Resource Usage) and CSC (Channel Switching Cost). The IRU component accounts for the interflow interference and corresponds to the aggregate channel time consumed (or the amount of bandwidth resource consumed) on a link. In other words, this component includes the expected transmission time for an intended sender as well as the time neighbor nodes defer (not transmit) in CSMA/CA MAC protocols and favors a path that consumes less channel time at its neighboring nodes. The CSC component represents the intraflow interference, favoring paths with more diversified channel assign-
ments and penalizing paths with consecutive links using the same channel. The MIC metric provides better performance because it considers intra/interflow interference and channel diversity. The disadvantage of the metric is the high overhead needed to estimate the per path MIC($p$) value. Each node should be aware of the total number of nodes in the network; this in large networks may become very expensive. In Table 2.1 a summary of the routing metrics including the pros and cons of each metric is presented.

2.4 Summary

Summarizing, in this section we presented the efforts of the research community that influenced our work on routing for wireless multihop networks. Whereas each multipath protocol is developed to satisfy specific requirements, a quantitative comparison of their performance is missing. We fill this gap in Chapter 3, by conducting an extensive performance evaluation study of three multipath routing protocols in a broad set of network variables including mobility, node density and data load.

Whereas multipath routing represents a promising alternative to single-path routing, efficient scheduling over multiple paths is an open issue; simultaneous transmissions over disjoint paths may interfere with each other. In Chapter 4 we present an interference model to capture the impact of interference on wireless multihop networks. Finally, in Chapter 5 we present an interference-aware routing metric assisting network layer protocols to select high throughput paths.
### Table 2.1: A summary of metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Pros:</th>
<th>Cons:</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTT</td>
<td>-Measure delay directly.</td>
<td>-Route instability (phenomenon of self-interference)</td>
</tr>
<tr>
<td>PktPair</td>
<td>-Measure delay directly.</td>
<td>-Load dependent.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Route instability (phenomenon of self-interference).</td>
</tr>
<tr>
<td>ETX</td>
<td>-Explicitly takes loss rate into account.</td>
<td>-Overhead from probe packets.</td>
</tr>
<tr>
<td></td>
<td>-Implicitly takes interference into account.</td>
<td>-PHY-layer loss rate of broadcast probe packets is different than PHY-layer loss rate of data packets.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Does not take into account data rate and link load.</td>
</tr>
<tr>
<td>ETT</td>
<td>-It takes into account data rate and link load.</td>
<td>-Overhead from probe packets.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-PHY-layer loss rate of broadcast probe packets is different than PHY-layer loss rate of data packets.</td>
</tr>
<tr>
<td>WCETT</td>
<td>-Extension of ETT to exploit multiple channels.</td>
<td>-No algorithm to compute lowest weight path in polynomial or less time.</td>
</tr>
<tr>
<td>MIC</td>
<td>-Considers intraflow and interflow interference.</td>
<td>-High overhead to estimate the per path $p$ MIC($p$) value.</td>
</tr>
<tr>
<td></td>
<td>-Channel diversity.</td>
<td>-Not scalable.</td>
</tr>
</tbody>
</table>
Chapter 3

Multipath Routing in Wireless Multihop Networks

This chapter presents a quantitative comparison of multipath routing protocols proposed for wireless multihop (mesh, mobile, ad hoc) networks. We first describe the routing protocols and the methodology used in the performance evaluation. Then we present the results of the quantitative comparison of multipath routing protocols. Finally we discuss the advantages and the limitations of multipath routing protocols and we present two open questions that are addressed in this thesis.

3.1 A Quantitative Comparison of Multipath Routing Protocols for Wireless Multihop Networks

Single-path routing protocols have been heavily discussed and examined in the literature. A more recent research topic for wireless
multihop networks are multipath routing protocols. Multipath routing protocols establish multiple disjoint paths from a source to a destination thereby improving resilience to network failures and allowing for network load balancing. These effects are particularly interesting in networks with high node density (and the corresponding larger choice of disjoint paths) and high network load (due to the ability to balance the traffic load around congested links). A comparison of multipath protocols is therefore particularly interesting in scenarios of highly congested and dense networks.

In this section, we present an extensive performance evaluation and comparison of three multipath routing protocols proposed for wireless multihop networks, namely SMR [LG01], and two modifications of AODV [PBRD03]: AOMDV [MD01] and AODV_Multipath [YKT03]. With the help of the ns-2 simulator, we examine the protocol performance under a set of network properties including mobility, node density and data load. The comparison focuses on the following metrics: data delivery ratio, routing overhead, routing latency, sustainability of multiple paths, end-to-end delay of data packets and load balancing. In addition, the AODV protocol is included as a reference single-path routing protocol to enable a more generic comparison of multipath with single-path routing.

With the quantitative comparison of multipath routing protocols i) we show in that: AODV_Multipath performs best in static networks with high node density and high load; AOMDV outperforms the other protocols in highly mobile networks; SMR offers best load balancing in low density, low load scenarios; ii) we demonstrate that multipath routing is only advantageous in networks with high node density or high network load; and iii) we confirm that multipath routing protocols create less routing overhead (except SMR) compared to single-path routing protocols.
3.2 Multipath Routing Protocols

In the performance evaluation we consider multipath routing protocols with the following fundamental properties: (i) The routing protocol provides multiple, loop-free, and preferably node-disjoint paths to destinations, (ii) the multiple paths can be used simultaneously for data transport and (iii) multiple routes are known at the source. Multipath routing protocols that have been proposed for wireless multihop networks and satisfy the above-mentioned requirements are:

1. **SMR** (Split Multipath Routing) [LG01].
   SMR is based on DSR [JM96]. This protocol attempts to discover maximally disjoint paths. The routes are discovered on demand in the same way as with DSR. The sender floods a Route REQuest (RREQ) message in the entire network. The main difference with DSR is that intermediate nodes do not reply even if they know a route to the destination. From the received RREQs, the destination identifies multiple disjoint paths and sends a Route REPlay (RREP) packet back to the source for each individual route. According to the original proposal of SMR, we configure our implementation to establish at maximum two link disjoint (SMR_LINK) or at maximum two node disjoint (SMR_NODE) paths between a source and a destination.

2. **AOMDV** (Ad hoc On demand Multipath Distance Vector routing) [MD01].
   AOMDV extends AODV to provide multiple paths. In AOMDV each RREQ and respectively RREP defines an alternative path to the source or destination. Multiple paths are maintained in routing entries in each node. The routing entries contain a list of next-hops along with corresponding
hop counts for each destination. To ensure loop-free paths 
AOMDV introduces the `advertised_hop_count` value at node 
$i$ for destination $d$. This value represents the maximum hop-
count for destination $d$ available at node $i$. Consequently,
alternate paths at node $i$ for destination $d$ are accepted 
only with lower hop-count than the `advertised_hop_count` 
value. Node-disjointness is achieved by suppressing duplica-
cate RREQ at intermediate nodes.

In our simulations we consider four alternative configura-
tions of the AOMDV protocol depending on the type (link 
or node disjoint) and the maximum number of multiple 
paths the protocol is configured to provide:

(a) $AOMDV\_LINK\_2paths$: Maximum two link-disjoint paths.
(b) $AOMDV\_LINK\_5paths$: Maximum five link-disjoint paths.
(c) $AOMDV\_NODE\_2paths$: Maximum two node-disjoint 
paths.
(d) $AOMDV\_NODE\_5paths$: Maximum five node-disjoint 
paths.

To avoid the discovery of very long paths between each 
source-destination pair the hop difference between the short-
est path and the alternative paths is set to five for all 
AOMDV protocol configurations.

3. $AODV\_Multipath$ (Ad hoc On-demand Distance Vector Mul-
tipath) [YKT03].

AODV_Multipath is an extension of the AODV protocol 
designed to find multiple node-disjoint paths. Intermediate 
nodes are forwarding RREQ packets towards the destina-
tion. Duplicate RREQ for the same source-destination pair 
are not discarded and recorded in the RREQ table. The 
destination accordingly replies to all route requests target-
ing at maximizing the number of calculated multiple paths.
3.3 Methodology

RREP packets are forwarded to the source via the inverse route traversed by the RREQ. To ensure node-disjointness, when intermediate nodes overhear broadcasting of a RREP message from neighbor nodes, they delete the corresponding entry of the transmitting node from their RREQ table. In AODV_Multipath, node-disjoint paths are established during the forwarding of the route reply messages towards the source, while in AOMDV node-disjointness is achieved at the route request procedure.

4. AODV (Ad hoc On demand Distance Vector) [PBRD03].

We use the AODV as a reference on demand single-path routing protocol. AODV is used as a benchmark to reveal the strengths and the limitations of multipath versus single-path routing.

Summarizing the presentation of the routing protocols, we list the essential properties of the multipath protocols:

- SMR: The protocol calculates link and node disjoint paths. The maximum number of paths is set to two. The source is aware of the complete path towards the destination.

- AOMDV: The maximum number of paths can be configured, as well as the hop difference between the shortest path and an alternative path. The protocol calculates link and node disjoint paths.

- AODV_Multipath: The protocol establishes only node disjoint paths. There is no limitation on the maximum number of paths.

3.3 Methodology

We next describe the methodology we used to compare the different routing protocols.
Simulation environment: We use a detailed simulation model based on ns-2 [nNS]. The distributed coordination function (DCF) of IEEE 802.11 [IEE99] for wireless LANs is used at the MAC layer. The nominal bit-rate is set to 2 Mb/s and the communication range to 250 meters; we also apply an error-free (zero bit error rate) wireless channel model.

Mobility model: We use the random waypoint model [BMJ+98] to model node movements. The random waypoint movement model is widely used in simulations in spite of its known limitations [BRS03]. The simulation time is 900 seconds while the pause time of fixed length varies from 0 seconds (continuous motion) to 900 seconds (no mobility) [0,30,60,120,300,600,900 seconds]. Nodes move with a speed, uniformly distributed in the range [0,10 m/s].

Network size and communication model: We consider 4 network sizes with 30, 50, 70, and 100 nodes uniformly distributed in a rectangular field of size 1000m × 300m. We vary the number of nodes to compare the protocol performance for low and high node density. Traffic patterns are determined by 10, respectively 20 CBR/UDP connections, with a sending rate of 4 packets per second between randomly chosen source-destination pairs. Connections begin at random times during the simulations and are active till the end of each simulation. We use identical traffic and mobility patterns for the different routing protocols. Simulation results are averaged values of 20 scenarios with different seeds. Data packets have a fixed size of 512 bytes and the network interface queue size for routing and data packets is set to 64 packets.

Scheduling of data packets: A sender uses all available paths to a destination simultaneously. Data packets are sent over each individual path with equal probability. When one path breaks, the source stops using that path but does not directly initiates a new route request. Only when all available paths are broken a
new route request is initiated. Furthermore, a sender schedules
data packets as soon as the first route reply (RREP) has arrived.

**Protocol implementation:** The original source code of AOMDV
[MD01] and AODV_Multipath [YKT03] protocols in ns-2 is used
in our performance evaluation. The implementation of SMR in
ns-2 is adopted from [WZ04].

**Metrics:** We use the following five metrics to compare the
performance of the multipath routing protocols.

1. *Routing overhead.* The routing overhead is measured as the
   average total number of control packets transmitted at each
   node for each seed. Each hop is counted as one separate
   transmission.

2. *Routing latency.* The routing latency is measured as the
time until routes are known at the source for each route
request.

3. *Sustainability of multiple paths.* The sustainability of mul-
tiple paths is the ratio of the time that more than one paths
are available per source-destination pair to the total con-
nection time.

4. *Average number of paths.* The average number of paths is
   the amount of paths that are discovered per route request.

5. *Data packet delivery ratio.* The data packet delivery ratio
   is the ratio of the total number of delivered data packets at
   the destination to the total number of data packets sent.

6. *Average end-to-end delay of data packets.* The average end-
to-end delay is the transmission delay of data packets that
are delivered successfully. This delay consists of propagation
delays, queueing delays at interfaces, retransmission
delays at the MAC layer, as well as buffering delays during
route discovery. Note here, that, due to the priority queuing
of routing messages, queueing delays for data traffic packets can be higher than the normal maximum queuing delay of a 64 packet queue.

7. **Load balancing.** Load balancing is the ability of a routing protocol to distribute traffic equally among the nodes. We capture this property by calculating the deviation from the optimal traffic distribution.

### 3.4 Performance Evaluation

We present in this section the simulation results comparing the multipath routing protocols. In addition, we compare the results with the results obtained with AODV to emphasize the benefits of multipath versus single-path routing. The results are presented individually per routing metric. We summarize the main findings of the comparison at the end of this section.

#### 3.4.1 Routing Overhead

In general, SMR produces more control overhead than the AODV-based multipath routing protocols. This is caused by the fact that SMR rebroadcasts the same RREQ packets it receives from multiple neighbors. In the following, we discuss in detail the routing overhead for each individual scenario.

*Low density, low load:* The routing overhead in networks with low node density and low traffic load is shown in Figure 3.1. We clearly observe the higher overhead of SMR compared to the AODV-based routing protocols. Interestingly, the version of SMR which computes link disjoint paths (SMR\_LINK) produces more overhead than the variation which determines node disjoint paths (SMR\_NODE). The reason is that the source waits until all existing paths break before sending a new route request, and the
probability that two paths break is lower if they are node-disjoint than otherwise.

When comparing AODV, AOMDV, and AODV Multipath, we see that all three protocols have similar control overhead, only the overhead of AODV is slightly larger. Indeed, multipath routing protocols require less control messages for routes to destination nodes that have been previously requested. Therefore, the saving in terms of overhead originates from connections with the same destination node.

High density, low load: In Figure 3.2, we plot the routing overhead for a higher node density (100 nodes on a square of the same size as before). The absolute number of control packets at each node is higher than with 30 nodes. However, the relative performances remain the same.

Varying density, low load: The effect of node density on the routing overhead in a scenario with moderate mobility is illus-
The routing overhead increases slightly with increasing node density for the AODV-based protocols. However, the routing overhead of SMR starts to decrease when the number of nodes exceeds 50. The reason is that for more than 50 nodes, the network becomes congested and many control packets are dropped. We will see later that for such networks, the delivery ratio of data packets is below 10%.

### 3.4.2 Average Number of Paths

We next look at the ability of the different routing protocols to find multiple paths. For this, we measured the average number of discovered routes per route request. The result is plotted for the low density and low load scenario in Figure 3.4 and for the high density and high load scenario in Figure 3.5. AODV_Multipath is clearly the protocol which finds the most paths. However, as
3.4 Performance Evaluation

**Figure 3.3:** Routing overhead: Varying density, low load

we will see later when looking at the packet delivery ratio, many discovered paths are not usable when the nodes are very mobile. Note that AOMDV and SMR tend to find on average significantly less paths than their upper limit. AOMDV configured to find a maximum of 5 paths (node-disjoint or link-disjoint) finds approximately on average at most 2 paths. AOMDV and SMR when configured to find a maximum of 2 paths find on average 1.4 paths.

### 3.4.3 Routing latency

The multipath routing latency corresponds to the total amount of time a route request (RREQ) is sent till the last route reply is received back at the sender. However, the way that latency is measured differs for each protocol. In SMR multipath routing latency corresponds to the total time that maximum 2 paths
are known at the sender and in AOMDV corresponds to maximum 2 or 5 paths according to the protocol configuration. In both cases, additional routes are not taken into consideration. In AODV Multipath, as there is no limitation on the maximum number of multiple paths, routing latency is measured till the last route reply has arrived at the sender.

Low density, high load: The effect of node mobility on the routing latency in a scenario of low density and low mobility is illustrated in Figure 3.6. As it is shown in section 4.2, AODV Multipath finds the most of the paths. However the ability of the protocol to find maximum node disjoint paths is ”penalized” with high routing latency especially in scenarios with high node mobility. The total time that all calculated paths are known at the sender is on average 7 seconds in high mobility scenarios. Intermediate nodes are cashing route replies and attempt to forward them recursively in order to find a neighboring node that can potentially
forward them further towards the source. Latency decreases in lower mobility scenarios and drops to 1 second in the static scenario.

Latency in SMR is in general high and independent of mobility. This is due to the immense routing overhead in high load scenarios.Routing packets are experiencing high buffering delays resulting in high routing latency. AOMDV has the lower latency among the protocols as the protocol overhead is in general low.

High density, high load: In high node density scenarios, routing latency for AOMDV and SMR is increased comparing with the low density scenarios as illustrated in Figure 3.7. Routing latency for AOMDV_Multipath is high in mobile scenarios (pause time 0-300 sec) and decreases rapidly in low mobility reaching the performance of AOMDV in a static scenario. AODV_Multipath in general is performing better in low mobility scenarios.

Figure 3.5: Average number of paths: High density, high load

![Average number of Paths](image-url)
Figure 3.6: Routing latency: Low density, low load

Varying density, high load: In Figure 3.8 the effect of node density on routing latency in moderate mobility scenarios is presented. For AODV_Multipath latency is constant approximately 7 seconds. Node density do not affect the total time that the protocol requires to find multiple routes. On the contrary, routing latency increases with node density for SMR and AOMDV respectively.

3.4.4 Sustainability of multiple paths

The sustainability of multiple paths represents the percentage of time to the total connection time in which multiple paths (more than one paths) are available at the sender. This metric captures the “capability” of a multipath routing protocol to provide and maintain multiple routes. The AODV protocol as single-path protocol is not included in the metric.
3.4 Performance Evaluation

**Figure 3.7:** Routing latency: High density, high load

Low density, low load: The effect of mobility on the sustainability factor in the low density low load scenario is illustrated in Figure 3.9. Surprisingly, in high mobility scenarios the sustainability of multiple paths is equivalent or higher (in case of AODV_Multipath) than in the static scenario. This is due to the fact that routes break with higher probability in high mobility resulting in more frequent route requests and consequently in reestablishment of new multiple routes. In low mobility scenarios as the lifetime of the more robust route is longer, the frequency of new route requests is effectively lower. AODV_Multipath maintains multiple paths on average 80% of the total time in high mobility scenarios. On the contrary, in the static case the sustainability factor drops to 65%.

High density, high load: Higher node density do not affect the high sustainability factor values of the AODV_Multipath in high mobility scenarios. However, in low mobility scenarios the sus-
Figure 3.8: Routing latency: Varying density, high load

Sustainability factor drops to 50% (Figure 3.10). The sustainability of multiple paths for the AOMDV protocol is consistent compared with low density scenarios. On the contrary, SMR does not manage to provide multiple paths at the source more than 10% of the total connection time.

**Varying density, low load:** In Figure 3.11 the effect of node density on the sustainability of multiple paths in a static scenario is illustrated. AODV Multipath maintains multiple routes approximately 70% of the total connection time in low and moderate node density scenarios. However, in higher node density, sustainability decreases to 45%. AOMDV configured to find maximum 5 paths (AOMDV_LINK_5paths and AOMDV_NODE_5paths) maintain multiple routes more than the 50% of the total time independent of nodes density. This confirms the robustness of the protocol. On the contrary, SMR does not manage to maintain
3.4 Performance Evaluation

Figure 3.9: Sustainability of multiple paths: Low density, low load

multiple paths more than 20% of the total connection time. In high node density the sustainability factor drops at 10%.

3.4.5 Data Packet Delivery Ratio

The data packet delivery ratio is now presented for the three different scenarios.

Low density, low load: As expected, in sparse networks with low traffic load, multipath routing does not improve the performance compared to single-path routing in terms of successful packet delivery. As we see in Figure 3.12, the packet delivery ratio in this scenario is equal for AODV and all variants of AOMDV independent of the node mobility.

Surprisingly, the performance of SMR and AODV_Multipath is even worse compared to single-path routing. AODV_Multipath
severely suffers from packet losses when the network becomes dynamic. This is mainly because the protocol finds much more paths than the other protocols (see Figure 3.4) and a source tries to use all of them until all become stale. Detecting that a route is stale is time-consuming since with 802.11, a broken link is only detected by retransmitting a packet at the MAC layer multiple times without receiving an acknowledgment. SMR overloads the network with control messages and data packets are dropped at full buffers of intermediate nodes. Even in the static case (900 seconds pause time), SMR and AODV_Multipath have a packet delivery ratio which is approximately 10% below the ratio of AODV.

High density, high load: Figure 3.13 shows the benefits of multipath routing versus single-path for dense networks with high traffic load. In this case, both AODV_Multipath and AOMDV clearly outperform AODV. Comparing AODV_Multipath and AOMDV,
Figure 3.11: Sustainability of multiple paths: Varying density, low load

the performance strongly depends on the node mobility in the network. When the network is static, AODV_Multipath achieves the best performance (almost 80% delivery ratio). When the network is highly mobile (pause time less than 400 seconds), AOMDV has a higher delivery ratio.

Apparently, SMR has a very poor performance in this scenario (below 5% delivery ratio). This is easy to understand when we consider the routing overhead of SMR (see Figures 3.1, 3.2). SMR produces a large amount of control packets which overloads the network dramatically. The network is so congested that only routing packets are queued and most of the data packets are dropped.

Varying density, high load: In Figure 3.14, we also plot the packet delivery ratio versus the node density for a network with a large amount of traffic. We fixed the pause time to 120 sec-
Figure 3.12: Data packet delivery ratio: Low density, low load.

onds (moderate mobility) which is in favor of AOMDV as we have seen in the previous Figure. By increasing the network density, we see that the performance of AOMDV and SMR decreases whereas the performance of the AODV_Multipath remains stable. We conclude that the performance of AOMDV_Multipath is independent of the network density when the amount of traffic is high.

3.4.6 Average End-to-End Delay of Data Packets

We have just seen that multipath routing outperforms single-path routing in terms of delivered data packets when the traffic load in the network is high. We now compare the average end-to-end delay of the multipath routing protocols in these scenarios. We differentiate between three cases: high node mobility with a pause time of 0 seconds (see Figure 3.15), moderate node mobility with
a pause time of 120 sec (Figure 3.16) and no node mobility (900 seconds pause time, see Figure 3.17).

End-to-end delay for the SMR protocol is higher than all protocols. In low mobility and low node density scenarios end-to-end delay is approximately 650ms, while in higher mobility and node density the end-to-end delay augments to 1200ms. The high routing overhead of SMR penalizes data packets, therefore high buffering delays contribute to high end-to-end delay.

AODV_Multipath is an exception in low mobility scenarios (in bold in Figures 3.15, 3.16, 3.17). In high mobility, end-to-end delay is approximately 900 ms, while in moderate mobility and no mobility, the delay decreases to 750 ms and 200 ms respectively.

AOMDV achieves the smallest end-to-end delay compared to the other protocols, including the AODV, in high and moderate mobility. The average number of hops a data packet travels with multipath routing is higher than with single-path routing.
Figure 3.14: Data packet delivery ratio: Varying density, high load

packets are equally distributed among all available paths independent of hop difference between the shortest and an alternative path towards the same destination. However, in a congested network, multipath routing AOMDV manages to distribute the traffic on less congested links and data packets experience smaller buffering delay on intermediate nodes.

AOMDV_LINK_5paths and AOMDV_NODE_5paths, achieve in general lower end-to-end delay than AOMDV_LINK_2paths, AOMDV_NODE_2paths, AODV, AODV_Multipath and SMR with regard to node density and mobility. Taking into consideration Figure 3.5 that presents the average number of paths that are available at each sender for high node density and data load versus mobility we observe that multipath routing is beneficial if the number of multiple paths is between 2 and 3. The high number of multiple routes that AODV_Multipath calculates is not awarded
with better performance as many paths break with higher probability. Therefore multipath routing becomes beneficial if it provides one or two additional link or node disjoint paths.

### 3.4.7 Load Balancing

Load balancing is the ability of a routing protocol to equally distribute the traffic among all nodes. Load balancing is for example useful to maximize the network lifetime when the networked devices are battery-powered. It is also helpful to distribute the traffic equally to avoid single bottlenecks in the network where most traffic is passing through. We first look at load balancing in sparse networks with low load and then consider networks with increased node density.
Figure 3.16: Average end-to-end delay of data packets: Moderate mobility, high load.

Low density, low load: In Figure 3.18 load balancing with low node density, low data load, and moderate mobility (120s pause time) is presented. We sorted the nodes according to the number of data packets they forwarded on the x-axis and plot the percentage of data packets each node has forwarded on the y-axis. Since there are 30 nodes in the network, an optimal load balancing would result in 3.33%. We see that SMR and AOMDV achieve a better distribution of the traffic between the different nodes.

We also plot the results in the low density and low data load case for different pause times in Figure 3.19. Instead of plotting the percentage of forwarded packets, we plot the standard deviation from the average value. Thus, a value of 0 results in optimal load balancing. SMR and AOMDV have lower standard deviation than AODV_Multipath independent of node mobility. Fur-
thermore, increased mobility results in better load balancing of the data traffic among the nodes. However, this result is intuitive as mobility contributes towards data traffic dispersion.

Varying density, low load: To circumvent the effect of mobility, we illustrate the standard deviation of the total forwarded data packets from the optimum value in static scenarios versus node density in Figure 3.20. AOMDV and SMR disseminate data across all nodes better than AODV_Multipath.

3.4.8 Advantages and Limitations of Multipath Routing Protocols

In Table 3.1, we summarize the performance of each multipath routing protocol for the different metrics. We differentiate three network regimes: (a) low density and low load, (b) high density,
high load and low mobility, and (c) high density, high load, and high mobility. Recapitulating the performance evaluation of multipath routing protocols, we present the essential results regarding protocol performance, multipath routing in general as well as in comparison with single-path routing.

*Comparison of multipath routing protocols:*

- AOMDV achieves the best performance in scenarios with high node mobility.

- AODV_Multipath performs best in relatively static scenarios.

- The performance of SMR is poor in dense networks and networks with high traffic load because of the immense control traffic generated.

*Figure 3.18: Load balancing: Low density, low load, 120 seconds pause time.*
3.4 Performance Evaluation

**Figure 3.19:** Load balancing: Low density, low load.

**General multipath routing findings:**

- Maintenance of many routes is very difficult and results in performance degradation.

- The number of multiple paths affects the performance of multipath routing protocols. Two or three paths are more beneficial than many paths.

- Routing overhead should be taken into consideration when designing a multipath routing protocol.

**Multipath vs single-path routing:**

- Multipath routing generally achieves better performance than single-path routing in dense networks and networks with high traffic load.
Despite the higher per route routing overhead, the total routing overhead is lower (not for SMR). Multipath routing is more robust to route failures.

Even though multiple disjoint paths are longer than shortest path, end-to-end delay is lower in higher density scenarios. Multipath routing manages to distribute the traffic to uncongested links and packets experience lower buffering delay.

3.5 Open Questions

In this chapter we have shown that multipath routing protocols have advantages as well as limitations. In the performance evaluation we used a simple scheduling method, i.e. the paths are
Table 3.1: Comparison of multipath routing protocols. 
(;++: very good, +: good, 0: neutral, -:poor). AODV_M corresponds to AODV_Multipath.

(a) Low density, low load

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<td>Routing latency</td>
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<td>Sustainability</td>
<td>+</td>
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<tr>
<td>Packet delivery ratio</td>
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<td>Average end-to-end delay</td>
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<td>Load balancing</td>
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(b) High density, high load, low mobility

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(c) High density, high load, high mobility

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selected with equal probability. The load is equally distributed on all paths without taking into consideration the “quality” of each path, such as the end-to-end throughput, delay, capacity, packet loss, number of hops etc. Therefore, improving the performance of multipath routing protocols is only possible with the knowledge of link or path quality.
Another issue that impacts the performance of multipath routing protocols in wireless multihop networks is the interflow and intraflow interference. In wired networks node disjoint paths are not associated to each other in intermediate hops and therefore packet forwarding is independent. However, this is not the case in wireless networks due to the broadcast nature of the wireless medium and the 802.11 MAC protocol mechanisms. Nodes defer from transmission if the medium is sensed busy and simultaneous transmissions may result in unsuccessful packet reception due to interference.

Therefore, we restate the question posed at the beginning of the thesis and we add the abovementioned issue:

1. For a more sophisticated routing decision that would eventually result in better performance of routing protocols, we need a routing metric that can find paths with high throughput.

2. Interference is an essential factor that impacts the performance and the efficiency of wireless multihop networks. How can we estimate the effect of interference on routing performance?

In the subsequent chapters we address these problems. More specifically, in chapter 4 we develop an interference model that captures the effect of interference in wireless multihop networks. Then, in chapter 5 we reply to the first question proposing an interference-aware routing metric which main goal is to find paths with high throughput.

### 3.6 Conclusion and Discussion

The objective of this chapter is to provide a quantitative comparison of multipath routing protocols for wireless multihop (mesh,
mobile, ad hoc) networks. At the same time, we examine and validate the advantages and the limitations of multipath versus single-path routing in general. Our study shows that the AOMDV protocol is more robust and performs better in most of the simulated scenarios. The AODV-Multipath protocol achieves best performance in scenarios with low mobility and higher node density. SMR performs best in networks with low node density, however the immense routing overhead generated in high node density degrades protocol’s performance.

In addition, we demonstrate that the establishment and maintenance of multiple routes result in protocol performance degradation. The use of two, maximum three, paths offers the best tradeoff between overhead and performance. Furthermore, protocols with high routing overhead perform badly since the routing messages fill the queues and generate data packet losses. This could be demonstrated by varying the queue length for different traffic levels and protocols. Compared to single-path routing, our results validate the better performance of multipath routing in networks with high node density.

Furthermore, we identify two open issues that impact the performance of multipath routing: i) interference in wireless networks and ii) path(s) selection. We address these two issues in the subsequent chapters.
Chapter 4

Interference in Wireless Multihop Networks

In this chapter we present our interference model for wireless multihop networks. We first derive an analytical expression for the probability of successful reception in the presence of interference. Then, we conduct a numerical analysis of the parameters that influence this probability. Finally, we assess the prediction capability of our interference model with an experimental evaluation on a testbed.

4.1 Introduction

The IEEE 802.11 ad hoc mode [IEE99] enables a new communication paradigm where messages are routed (relayed) over multiple wireless (mesh) hops to reach their destination. Within this paradigm, interference has a major impact on the network efficiency. Due to the broadcast nature of the medium and the complexity of wireless propagation phenomena, it is exceedingly difficult to spatially partition the wireless medium into clearly disjoint links as in the case of wired networks. This, combined
with the random access nature (implemented by a carrier sense
function) of the 802.11 MAC protocol gives rise to nodes that
do transmit while they ultimately should not (hidden nodes) but
also nodes that do not transmit while they could (exposed nodes).
Both phenomena result in significant reduction of the information
delivery capacity of the network.

Adding interference-awareness to routing decisions can there-
fore significantly enhance the network performance. Jain et al.
in [JPPQ03] show that under ideal interference-aware routing,
the data delivery capability of the network can be significantly
improved with respect to shortest-path routing, even under non-
optimal MAC scheduling. Nevertheless, almost all routing met-
rics proposed in the literature as alternatives to minimum-hop
metrics do not explicitly account for interference (see, for exam-
ple, [CABM05] and [DPZ04b]). They rather use measurement-
estimates of higher-level metrics of network performance,
such as delay or number of transmissions. These measurement
estimates depend partly on interference and capture its effect
indirectly.

Measurement-based approaches have two major disadvantages.
The first is the data overhead they impose on the network. The
second has to do with the achievable accuracy and reliability of
the measurements.

These considerations motivated us to take a different ap-
proach. We would like to answer the following question: how well
can we estimate interference and predict the success probabil-
ity of transmitting a message over a link without resorting to
measurements and probing, but rather by exploiting information
that is locally available to the node? In other words, we would like
to come up with a simple yet accurate analytical metric for the
probability of successful transmission over each link, that can be
used by an interference-aware routing protocol to choose routing
paths that maximize throughput.
To this end, we develop an analytical model to estimate the probability \( P(x_j) \) that a transmission destined to node \( x_j \) is successful in the presence of interference from other nodes in the network. Starting from the simple physical (SINR) model [GK00], we introduce the concepts of *interference areas* and *interference zones* with respect to the intended data recipient node; with these zones we aim at quantifying the effect of cumulative interference by concurrently transmitting nodes outside the immediate neighborhood of a node controlled by the carrier sense function. Furthermore, to also capture the carrier sense function of many MAC protocols we include in our model a very simple and generic MAC model, which ensures that nodes within range of the transmitting source defer from transmitting a message themselves. Accounting for both of these effects, we derive an analytical expression for the probability \( P(x_j) \) as a function of the network density, node transmission probability, radio propagation environment, and network card reception sensitivity.

Compared to probe-based approaches, the advantage of this derivation is that all model inputs can be available (or estimated) locally to the node; for example, information regarding a node’s degree can be extracted from the routing layer at no additional cost in terms of communication overhead. Compared to other, more complex analytical models of wireless interference [RMR+06, QZW+07], our model does not require prior measurements and can scale up to large number of nodes. Interestingly, its simplicity comes without significant loss in prediction accuracy, as our evaluation of the model suggests.

Nevertheless, our analytical model does not capture the exact working details of a realistic 802.11 protocol (*e.g.*, Distributed Coordination Function of 802.11 [IEE99]), and also unavoidably makes some assumptions with respect to real propagation phenomena, in order to ensure that it remains simple enough to be utilized as a practicable routing metric. To evaluate the effect of our assumptions in a real world setting, we validate our model
against experiments in a testbed, set up for this purpose in our indoor office environment. Despite the generic nature of the model, the experimental results from our IEEE 802.11 testbed show good match with the analytical predictions, and confirm the model’s utility for real-world MAC protocols and realistic radio propagation conditions.

We find that our model predictions follow closely those of more elaborate analytical model such as the GMI (General Model for Interference) [QZW+07], which is viewed as state-of-the-art in the community. Finally, to demonstrate the real utility of our model, we have implemented on our testbed a routing metric that explicitly takes interference into account via our derivation. The throughput of the resulting routes compare favorably with those achieved by a well-known probe-based routing metric [CABM05].

This chapter is organized as follows. In Section 4.2, we present our analytical derivation for the probability of successful reception in the presence of interference. We devote Section 4.3 to numerical results showing the model sensitivity to its parameters and their independencies. The model validation against testbed experiments is carried out in Section 4.4. In the same section we compare our model predictions with those made by other models and present its utility as a routing metric. We conclude the chapter with a discussion in Section 4.5.

### 4.2 Analytical model

Our analytical model formulation proceeds as follows. First, we derive the probability of successful reception $P(x_j)$ at a receiver node $x_j$ in the presence of cumulative interference for a “MAC-agnostic” model, where nodes do not sense the medium before transmitting. Then, we include a simple enhancement into our model that aims at capturing the effect of carrier sense and calculate $P(x_j)$ for the complete model. Central to our derivation is
the concept of *interference zone*, which aims at quantifying the effect of cumulative interference by multiple concurrently transmitting nodes at various “distance zones” away from the receiver. Finally, we show how this probability can be expressed as a function of radio and propagation parameters, node degree, and network load.

### 4.2.1 Physical model and assumptions

In our analysis, the network comprises a set of nodes \( X = \{x_1, .., x_n\} \) located in the Euclidean plane. The reference physical model that determines whether a packet is received successfully or not is the Signal-to-Interference-Noise-Ratio (SINR) model (see, for example [GK00]). Under the SINR model, the transmission success depends on the received signal strength, the interference caused by simultaneously transmitting nodes, and the environmental thermal noise level. Let \( P_{w,i} \) be the transmit power of node \( i \), and \( T \) the set of nodes transmitting at that instant (\( T \subseteq X \)). A transmission from node \( x_i, i \in T \), is successfully received by node \( x_j \) if

\[
\frac{P_{w,i}}{|x_i - x_j|^{\alpha}} N^{+\sum_{k \in T, k \neq i} \frac{P_{w,k}}{|x_k - x_j|^{\alpha}}} \geq \beta. \tag{4.1}
\]

In (4.1) \(|x_i - x_j|\) denotes the Euclidean distance between nodes \( x_i \) and \( x_j \) and \( N \) is the ambient noise power level. The parameter \( \alpha \) is the path loss exponent, which depends on the environment and typically ranges from 2 to 5. The SINR model implies that a minimum signal-to-interference ratio of \( \beta \) is necessary for successful reception. The actual value of \( \beta \) primarily relates to the specific physical layer design, such as the deployed modulation, interleaving, and channel coding schemes.

For the sake of analytical tractability, we make the following minimal set of assumptions:
A summary of key notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Path loss exponent</td>
</tr>
<tr>
<td>$\beta$</td>
<td>SINR threshold</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Transmission probability</td>
</tr>
<tr>
<td>$r$</td>
<td>Euclidean distance between sender $x_i$ and receiver $x_j$</td>
</tr>
<tr>
<td>$r_{\text{max}}$</td>
<td>The maximum distance for successful signal reception</td>
</tr>
<tr>
<td>$P_w$</td>
<td>Transmit power</td>
</tr>
<tr>
<td>$N$</td>
<td>Thermal noise</td>
</tr>
<tr>
<td>$P(x_j)$</td>
<td>Probability of successful delivery at node $x_j$</td>
</tr>
<tr>
<td>$C_{j,m}$</td>
<td>$m^{th}$ interference area with respect to recipient node $x_j$</td>
</tr>
<tr>
<td>$r_{j,m}$</td>
<td>Radius of $m^{th}$ interference area $C_{j,m}$</td>
</tr>
<tr>
<td>$A_{j,m}$</td>
<td>$m^{th}$ interference zone with respect to recipient node $x_j$</td>
</tr>
<tr>
<td>$M$</td>
<td>Maximum number of interference zones</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Node density</td>
</tr>
</tbody>
</table>

A.1 All nodes have similar receiver chain characteristics: omni-directional antenna, the same transmit power and noise floor, and similar physical layer performance, i.e., $P_{w,i} = P_{w,j} = P_w$ and $\beta_i = \beta_j = \beta \ \forall i \neq j$. This is called the uniform node assumption. Given this, the maximum distance $r_{\text{max}}$ for successful signal reception is given from

$$r_{\text{max}} = |x_i - x_j|_{\text{max}} = \sqrt[\alpha]{\frac{P_w}{N \beta}}. \quad (4.2)$$

A.2 We assume a slotted operation and Bernoulli traffic model. Nodes transmit with equal probability $\gamma$ (uniform load assumption). The probability $\gamma$ reflects the uniform network load [Bia00], [KAMG05].

In Table 4.1 we summarize our notation.
4.2 Analytical model

4.2.2 Interference ("MAC-agnostic") Model

We first assume that all nodes access the medium without previously checking to see if any other node is already transmitting nearby, and evaluate the effect of cumulative interference on message reception for an arbitrary sender-receiver pair. This simple model, sometimes referred to as physical model [GK00], has often been used in studies of network throughput for ad hoc networks. Here, in order to better quantify the additive effect of interfering nodes at different distances from the intended receiver, we introduce the concept of interference zones.

**DEFINITION 1.** An interference zone $A_{j,m}$ with respect to a receiver node $x_j$ is the area in which a minimum of $m$ simultaneous transmissions result in unsuccessful reception at node $x_j$.

**Lemma 1.** Assuming that a node $x_i$ transmits to another node $x_j$ at distance $r$. Then, a third node $x_k$ lies in the interference zone $A_{j,m}$ of $x_j, m \in \{1,2,3\ldots\}$, if its Euclidean distance to the intended recipient node $x_j$ is

$$\alpha \sqrt{(m-1)\beta} \cdot r < |x_k - x_j| \leq \alpha \sqrt{m\beta} \cdot r, \quad m \in \{1,2,3\ldots\}$$

(4.3)

**Proof.** From (4.1) and assumption A.1, the simultaneous transmission of $m$ nodes will not result in unsuccessful reception due to interference at node $x_j$, as long as

$$\frac{\sum_{k=1,k\neq i}^m P_w}{N + \sum_{k=1,k\neq i}^m \frac{P_w}{|x_k - x_j|^\alpha}} \geq \beta.$$

Assuming that noise $N$ is sufficiently small comparing to the interference induced from the simultaneous transmissions $^1$, it follows that

$$\frac{P_w}{r^\alpha} > (\sum_{k=1,k\neq i}^m \frac{P_w}{|x_k - x_j|^\alpha})\beta.$$

$^1$Thermal noise $N$ for a 2.4GHz channel as used in wireless networks is very small compared to the interference.
The sum on the right hand side is maximized when the distance 
\[ |x_k - x_j|, \forall x_k \in A_{j,m} \] is minimized. Requiring that

\[
\frac{P_w}{r^\alpha} > \left( \sum_{k=1,k\neq i}^{m} \frac{P_w}{|x_k - x_j|^{\alpha \min}} \right) \beta
\]

we get

\[
\frac{P_w}{r^\alpha} > \frac{mP_w}{|x_k - x_j|^{\alpha \min}} \beta.
\]

Therefore,

\[
|x_k - x_j|^{\alpha \min} > m \beta \cdot r^\alpha
\]

\[
|x_k - x_j|_{\min} > \sqrt[\alpha]{m \beta} \cdot r \equiv r_{j,m}.
\]

In other words, the simultaneous transmission of \( m \) nodes will not result in unsuccessful reception due to interference at node \( x_j \), if all \( m \) nodes lie at distance greater than \( \sqrt[\alpha]{m \beta} \cdot r \) and vice versa.

We use the notation \( C_{j,m} \) for the area within the circle of radius \( \sqrt[\alpha]{m \beta} \cdot r \), hereafter called interference area; then, \( \overline{C_{j,m}} \) denotes the area outside that circle. At least \( m + 1 \) nodes are required in \( \overline{C_{j,m}} \), even when all of them are placed at the minimum possible distance \( r_{j,m} \) from the receiving node, to prevent the successful delivery of the packet. Then, the interference zone \( A_{j,m} \) is the intersection of interference area \( C_{j,m} \) with the complement of interference area \( C_{j,m-1}, C_{j,m} \cap \overline{C_{j,m-1}} \), as shown in Fig. 4.1. For example, a node \( x_k \) is located in the interference zone \( A_{j,2} \) if its Euclidean distance to node \( x_j \) is \( \sqrt[\alpha]{\beta} \cdot r < |x_k - x_j| \leq \sqrt[\alpha]{2\beta} \cdot r \).

We now estimate \( P(x_j) \), the conditional probability that a transmission from node \( x_i \) to node \( x_j \) is successful despite interference from any other nodes in the network.
4.2 Analytical model

Figure 4.1: Interference zones $A_{j,m}$ with respect to recipient node $x_j$

**Theorem 1.** Under the assumptions A.1-A.2, the probability $P(x_j)$ is given by

$$P(x_j) = (1 - \gamma)^{n(A_{j,1})} \sum_{i_2=0}^{1} \binom{n(A_{j,2})}{i_2} \gamma^{i_2} (1 - \gamma)^{n(A_{j,3}) - i_2}$$

$$+ \sum_{i_3=0}^{2-i_2} \binom{n(A_{j,3})}{i_3} \gamma^{i_3} (1 - \gamma)^{n(A_{j,4}) - i_3}$$

$$+ \cdots$$

$$+ \sum_{i_M=0}^{M-1} \sum_{n=1}^{M-1} \binom{n(A_{j,M})}{i_M} \gamma^{i_M} (1 - \gamma)^{n(A_{j,M}) - i_M}$$

(4.4)

where $\gamma$ is the probability that a node is transmitting at the MAC layer, $n(A_{j,m})$ are the number of nodes in interference zone $A_{j,m}$ and $M$ corresponds to the number of interference zones $A_{j,m}$ $m \in \{1,2,3,...\}$ that are taken into account.

**Proof.** In the light of Definition 2, to avoid destructive interference at the receiver node $x_j$, the number of nodes in each interference area $C_{j,m}$ $m \in \{1,2,..M\}$ should not exceed $m - 1$. The allowed number of transmissions within each interference zone
is strongly dependent on the ongoing transmissions in the other interference zones. Apparently there is an area, the first interference zone $A_{j,1}$, which coincides with $C_{j,1}$, where no transmission should happen. Likewise, up to one transmission can be tolerated in interference zone $A_{j,2}$, whereas the transmissions $i_3$ in zone $A_{j,3}$ should not definitely exceed two but could be further restricted to one, if there is simultaneous transmission in zone $A_{j,2}$. Iterative application of the same argument results in (4.4).

The number $M$ of interference zones that are taken into account in this equation is dependent on the node spatial distribution. In paragraph 4.2.4 we get numerical values for $M$ when nodes are uniformly distributed in space.

The node transmission probability $\gamma$ is a measure of the traffic load input to the network. Note that $\gamma$ represents the per-node traffic load that appears at the wireless medium after the MAC protocol shaping, rather than the higher-layer packet transmission rate. In general, the parameter $\gamma$ and the number of nodes competing for the medium are coupled each other, i.e., they do not vary independently. Their exact coupling relationship differs according to the details of the specific MAC protocol. In the IEEE 802.11x suite of protocols, for example, it is well known that the actual allowed values of the transmission probability $\gamma$ depend on many parameters such as the number of contending nodes, the back-off algorithm, and the bandwidth of the wireless medium (see [Bia00] and [KAMG05]). In section 4.5 we discuss how we can estimate the parameter $\gamma$ in an IEEE 802.11x protocol and then use it in (4.4).

### 4.2.3 Interference-cum-MAC Model

In this section we extend our model to capture essential properties of CSMA MAC protocols. The “MAC-agnostic” interference model overestimates the cumulative interference because it as-
4.2 Analytical model

Assumes that nodes can transmit independently. However, in CSMA MAC protocols nodes defer when they sense the medium busy (when the reception energy is over the *Clear Channel Assessment* threshold, $CCA_{thr}$) and schedule a transmission based on an exponential backoff algorithm. This mechanism partially solves the problem of interfering transmissions as often nodes within the interference range of the receiver are outside the carrier sense range of the sender (hidden nodes problem). To keep our model simple, rather than incorporating the full complexity of CSMA MAC protocols, we include in our model a simple generic MAC that takes into account the physical carrier sense property ($CCA_{thr}$) for the nodes located in the first interference zone $A_{j,1}$. In other words, all nodes within carrier sense range from the transmitter and inside the first interference zone of the receiver defer from transmitting. Whereas this is only an approximation, our evaluation shows that this enhancement already has sufficient power to predict the successful packet reception probability under unsaturated demand.

In Figure 4.2, $r_1 = \alpha/\beta \cdot r$ denotes the radius of interference zone $A_{j,1}$ and $r_2 = \alpha/\sqrt{10^{CCA_{thr}/10}} = (1 + \varepsilon) \cdot r_1$ is the sender’s physical carrier sense range. Hidden nodes can still exist in the area $R_H$, given by

$$S_{RH} = \pi r_1^2 - B$$

(4.5)

where $B$ is the surface of the intersection between $A_{j,1}$ and sender’s physical carrier sensing area, given by

$$B = r_1^2 \cos^{-1} \left( \frac{r_1^2 + r_2^2 - r_2^2}{2 \cdot r \cdot r_1} \right) + r_2^2 \cos^{-1} \left( \frac{r_2^2 + r_1^2 - r_1^2}{2 \cdot r \cdot r_2} \right)$$

$$- \frac{1}{2} \sqrt{(r_1 + r_2 - r)(r_1 + r_2 + r)(r_1 - r_2 + r)(r_2 - r_1 + r)}$$

(4.6)

The probability of successful reception $P(x_j)$ for the complete model results from (4.4) when replacing $n(A_{j,1})$ with $n(R_H)$
Figure 4.2: Hidden nodes area $R_H$ in the first interference zone $A_{j,1}$

$$P(x_j) = (1 - \gamma)^{n(R_H)} \sum_{i_2=0}^{1} \binom{n(A_{j,2})}{i_2} \gamma^{i_2} (1 - \gamma)^{n(A_{j,2}) - i_2}$$

$$\sum_{i_3=0}^{2-i_2} \binom{n(A_{j,3})}{i_3} \gamma^{i_3} (1 - \gamma)^{n(A_{j,3}) - i_3} \ldots$$

$$\sum_{i_M=0}^{M-1} \binom{n(A_{j,M})}{i_M} \gamma^{i_M} (1 - \gamma)^{n(A_{j,M}) - i_M}$$

(4.7)

In the rest of the chapter we use the probability of successful reception $P(x_j)$ obtained from the Interference-cum-MAC model.

4.2.4 Probability of Successful Reception under Uniform Node Distribution

The probability of successful reception at a node $x_j$, is a function of the network load ($\gamma$), number of network nodes $n(A_{j,m})$ in each interference zone $A_{j,m}$, $\forall m \in \{1, 2, 3 \ldots\}$, propagation environment ($\alpha$), and hardware equipment ($\beta$).
4.2 Analytical model

For each node $x_i$ it is possible to define its node degree and transmission range.

**DEFINITION 2.** The node degree $d(x_i)$ of a node $x_i$ is

$$d(x_i) = \left| \left\{ x_j \bigg| \frac{n_x}{|x_i-x_j|^4} \geq \beta, x_j \in X \backslash \{x_i\} \right\} \right|. \quad (4.8)$$

In other words, the degree of the node $x_i$ equals the number of network nodes from which $x_i$ can successfully receive a signal in the absence of any interference from other nodes. In the case of uniform node distribution with node density equal to $\rho$, it is easy to see that

$$d(x_i) = \rho \pi (r_{max})^2. \quad (4.9)$$

For the uniform node assumption, we consider a topology where in total $n$ nodes are positioned randomly and uniformly in a finite area $A$. Assuming that the area $A$ consists of $i$ equal sized subareas $A_i$ and each node is placed in a specific location with independent probability $p = \frac{1}{i}$, the probability $p(n_i)$ that a subarea $i$ has $n_i$ of $n$ nodes is given by the binomial distribution:

$$p(n_i) = \binom{n}{n_i} p^{n_i} (1 - p)^{n-n_i}. \quad \text{For } n \gg 1, A_i \ll A \text{ and large } A,$$}

we can approximate $p(n_i)$ with a Poisson distribution with parameter $\lambda = \frac{A_i n}{A}$. Thus, the probability $p(n_i)$ that $n_i$ nodes are located in an subarea $A_i$ is:

$$p(n_i) = \frac{(\frac{A_i n}{A})^{n_i} e^{-\frac{A_i n}{A}}}{n_i!}$$

with mean $E(A_i) = \frac{A_i n}{A}$.

Under the uniform node assumption, the expected number of nodes in an interference zone $A_{j,m}$ will be proportional to its surface

$$E[n(A_{j,m})] = \frac{\pi \frac{\sqrt{(m\beta)^2 - r^2}}{\sqrt{A}} n - \frac{\pi \frac{\sqrt{(m-1)^2 - r^2}}{A}}{\sqrt{A}} n}{\sqrt{A}} \quad (4.10)$$
where \( r = |x_i - x_j| \) is the transmitter-receiver distance. The latter is always a function of the maximum communication range \( r_{max} \)

\[
r = c \cdot r_{max}.
\]  

(4.11)

where \( 0 < c < 1 \) is a scale factor that depends on the node distribution but also on the routing protocol. For example, minimum-hop routing protocols tend to select nodes at the edge of coverage as next-hop, implying a value of \( c \) close to unity. On the contrary, protocols that favor reliable over shortest paths will yield smaller values of \( c \).

\[
E[n(A_{j,m})] \text{ can now be written as a function of the node degree } d(x_j)
\]

\[
E[n(A_{j,m})] = c^2 \cdot \left( \sqrt{a((m-1)\beta)^2} - \sqrt{(m\beta)^2} \right) \cdot d(x_j)
\]  

(4.12)

We can then write the probability \( P(x_j) \) as a function of the node degree \( d(x_j) \), if we replace \( n(A_{j,m}) \) in (4.4) with \( E[n(A_{j,m})] \), rounded to the closest integer, for the expected number of nodes in interference zone \( A_{j,m} \).

Throughout the rest of the chapter, we are going to assume that the node degree is manipulated *independently of other parameters* by changing the corresponding node density.

**Interference zone number estimation**

The number of nodes in all circles \( C_{j,m}, m \in \{1,2,..M\} \) should be greater than the number of potential senders. This is expressed by function \( G(m) \) as

\[
G(m) = \sum_{i=1}^{m} E[n(A_{j,m})] - m \geq 0
\]  

(4.13)

Given (4.12), \( G(m) \) is written

\[
G(m) = \sum_{i=1}^{m} c^2 \cdot \left( \sqrt{(m\beta)^2} - \sqrt{((i-1)\beta)^2} \right) \cdot d(x_j) - m
\]

\[
= c^2 \cdot \sqrt{(m\beta)^2} \cdot d(x_j) - m,
\]  

(4.14)
where $2 \leq \alpha \leq 5$, $\beta > 0$, $d(x_j) > 0$. Then the number $M$ of interference zones can be defined as

$$M = \max\{m | G(m) \geq 0, \ m \in \{1,2,3,...\} \} \quad (4.15)$$

The parameter $M$ can be computed only numerically for given $\alpha, \beta, c$, and $d(x_j)$. In Fig. 4.3, 4.4, $G(m)$ is illustrated for $\beta = 2.5$, $c = 0.3$, $d(x_j) = 10$ and $d(x_j) = 15$ respectively. For example, when $d(x_j) = 15$, $M = 15$ for $\alpha = 3$, $M = 4$ for $\alpha = 4$, and $M = 3$ for $\alpha = 5$, as shown in Fig. 4.4.

**Interference Model Applicability under Node Mobility**

An interesting property of our interference model is that it can address both static and certain mobile networks, in contrast with other models that apply only to static networks [RMR+06] [QZW+07].
Figure 4.4: $G(m)$ as a function of the number $m$ of interference areas/zones for given $\alpha$ and $\beta = 2.5$, $c = 0.3$, and $d(x_j) = 15$

The probability of successful reception in Eq. 4.4 allow for arbitrary node distributions in space. Different mobility models can be accommodated as long as steady-state spatial node distributions exist for their mobility patterns.

For example, our derivation under the assumption that nodes are uniformly distributed applies directly for mobility models widely used in the literature, such as the random walk and random direction. For these two models it has been proved that if users are uniformly distributed in their movement space, they remain so for arbitrary movement patterns [NTLZ04].

In addition, the more generic derivation in Eq. 4.4 still hold when the node mobility patterns do not give rise to uniform node distribution assumption. Bettstetter et al., for example, have analytically derived the spatial node distribution over a bounded rectangular area for the random waypoint (RWP) mobility model.
in [BRS03]. Though less straightforward, their result could be directly used to derive the number of nodes per interference zone, \( n(A_j,m) \), whenever the RWP model is deemed a valid assumption for the node mobility. Only now the resulting distribution of nodes amongst interference zones is strongly related to the actual position of the transmitter and receiving nodes, rather than simply their distance.

### 4.2.5 Model Input Parameters

The estimation of the successful reception \( P(x_j) \) at node \( x_j \) for the uniform node assumption depends on five parameters that can be estimated locally at a node.

- **Node degree** \( d(x_j) \). The node degree represents the node density and can be easily retrieved from any conventional routing protocol. Routing protocols have a mechanism to estimate the number of neighbors of a node, i.e., the nodes with whom can directly communicate. In our implementation, the node degree is obtained from the DSDV routing protocol.

- **Transmission probability** \( \gamma \). The transmission probability in our model is the per-node traffic load in the network. For unsaturated traffic demands this probability is approximated as the percentage of time during which the medium is sensed busy due to transmission. To estimate it, we use the open source Madwifi wireless adapter drivers [ww], similar to [DL05], and we measure the busy time per sender receiver pair. For saturated traffic demands the transmission probability can be approximated as a function of the number of nodes [Bia00].

- **Path loss exponent** \( \alpha \). The path loss exponent for a specific area (within a building, an urban area) can be measured in
advance and used directly in the model. For heterogeneous environments (i.e., with different path loss exponent), our model can not be directly applied.

- **Reception threshold** \( \beta \). The reception threshold (or the SINR threshold) is either given on wireless adapters specifications or it can be estimated with measurements similar to Section 4.4.1.

- **Sender-receiver distance scale factor** \( c \). The estimation of the sender-receiver distance \( c \) assumes positioning capabilities at the wireless nodes. This is not a problem as nowadays more and more devices are equipped with such capabilities (see, for example, [ZBR02]). In our experiment, as the nodes are static, we measure their distance in advance.

In our implementation, the first two parameters (node degree \( d(x_j) \) and transmission probability \( \gamma \)) are estimated in real time at each node. The values of the other three are calculated in advance as they do not change during an experiment.

### 4.3 Numerical Results

In this section we provide numerical results for the impact of the five parameters \( \alpha, \beta, \gamma, c, \) and \( d(x_j) \) on the probability of successful reception \( P(x_j) \) (4.1). In the case of the node degree \( d(x_j) \), it is important to note that we manipulate it by changing the respective node density \( \rho \) (see (4.9)). Of course, for a fixed number of network nodes, \( d(x_j) \) is dependent on the card reception threshold \( \beta \) and path loss exponent, \( \alpha \). Yet, since from the MAC perspective it is the number of node neighbors that is more relevant, we choose to depict the various plots as a function of node degree, even though it is always implied that the respective degree is determined by choosing the node density accordingly.
4.3 Numerical Results

Figure 4.5: Probability of successful reception versus node degree (i.e., node density $\rho$) for variable $\gamma$, $\alpha = 4$, $\beta = 2.5$, $c = 0.5$.

4.3.1 Model sensitivity to transmission probability, $\gamma$

For fixed $\alpha$, $\beta$, the communication range is also fixed. As long as $c$ remains fixed, the radii of the interference areas and the sizes of interference zones do not change. Nevertheless, the number of nodes in each zone, under uniform node distribution in space, increases linearly with the node density, and thus with the node degree also (ref. (4.12)). For a given node degree value, increasing $\gamma$ implies more communication-active nodes. Higher values of both node degree and transmission probability result in higher loss probability, as intuitively expected.

Figure 4.5 plots the successful reception probability $P(x_j)$ as a function of the node degree for various values of the transmission
Figure 4.6: Probability of successful reception versus node degree (i.e., node density $\rho$) for variable $\alpha$, $\beta = 2.5$, $\gamma = 0.04$, $c = 0.5$.

probability $\gamma$. All other parameters are kept constant; the specific values, i.e., $\alpha = 3.84$, $\beta = 2.5$, $c = 0.5$, were chosen so that they match the values measured in the testbed and reported in Section 4.4. The decrease of successful reception probability is more dramatic for higher node degree values, since the number of potentially interfering nodes is then higher. One order size increase of $\gamma$, from 0.005 to 0.05 reduces $P(x_j)$ by approximately 13% for $d(x_j) = 30$, versus less than 4% for $d(x_j) = 10$. As a final note, $\gamma$ in these examples corresponds to an unsaturated network (see discussion in Section 4.2.2).
4.3 Numerical Results

4.3.2 Model sensitivity to path loss exponent, $\alpha$

The path loss exponent $\alpha$ models the reduction of the radio signal power as a function of distance from the transmitting source. Its values depend strongly on the radio propagation environment [Rap01].

Combining (4.2) and (4.3) we could write for the radius $r_{j,m}$ of interference area $C_{j,m}$

$$r_{j,m} = \sqrt{m \cdot \beta \cdot \sqrt{\frac{P_w}{N \cdot \beta}}} = \sqrt{m \cdot \frac{P_w}{N}} \tag{4.16}$$

As $\alpha$ increases, the signal attenuation with distance is higher and the radii of the interference zones decrease. Nodes can be placed closer to the receiver without interfering with the intended signal. The impact of the parameter $\alpha$ on $P(x_j)$ is plotted in Fig. 4.6. As with Fig. 4.5, higher node degree values amplify the variation of $P(x_j)$ with $\alpha$.

4.3.3 Model sensitivity to reception threshold, $\beta$

The reception threshold $\beta$ determines when a MAC frame is successfully received. It depends on the transmission rate, frequency, and sensitivity of the network card/chipset; higher rates and lower-quality network cards require higher $\beta$ value for achieving a given frame error rate. Typical values for $\beta$, as reported in network card specifications, are 2.5 to 25 [aWCBAd].

Increasing the reception threshold value at a given environment reduces the communication range, after (4.2), increases the widths of interference zones, as (4.3) suggests, and for given $c$ results in higher concentration of nodes at the first interference zones, see (4.10). The result is increased interference, as shown in Fig. 4.7. The relative reduction on the successful reception probability increases with higher node density, where the concentration of interfering nodes at the first zones becomes more visible.
Figure 4.7: Probability of successful reception versus node degree (i.e., node density $\rho$) for variable $\beta$, $\alpha = 4$, $\gamma = 0.02$, $c = 0.5$.

4.3.4 Model sensitivity to the sender-receiver distance scale factor, $c$

In our analytical derivation, we express the distance between the sender and receiver nodes as a ratio of the maximum communication range, $c \cdot r_{max}$. The impact of the sender-receiver distance on the probability of the successful reception is plotted in Fig. 4.8. We vary the node degree, while letting all other parameters constant. As with $\alpha$ and $\beta$, higher network densities magnify the effect of $c$. Only the latter is more dramatic in absolute terms than the one $\alpha$ and $\beta$ have on the probability of successful reception.

Finally, Fig. 4.8 directly points to the well known inefficiencies of minimum-hop routing. Minimum-hop routing tends to se-
4.4 Model validation via testbed experimentation

Figure 4.8: Probability of successful reception versus node degree (i.e., node density $\rho$) and sender receiver distance $c$; $\beta = 2.5$, $\alpha = 3.84$, $\gamma = 0.02$

lect few but distant hops when selecting network routes. This trend results in more noisy but also, as Fig. 4.8 suggests, more interference-prone links. Of course, “shorter” links may also imply a large number of hops, which can also be detrimental to throughput [GK00]. Interference-aware routing has benefits in this context and, as explained in Section 5.2, it is an area where our model can find direct application.
4.4 Model validation via testbed experimentation

The analysis in Section 4.2 is carried out for a generic MAC-interference model. Yet, real-world MAC protocols bear a large number of finer engineering details, which cannot be easily captured into a simple analytical model without making a much larger number of restrictive assumptions. Therefore, we resort to experimentation to get a better understanding of the strengths and limitations of our analysis in a real wireless network using a real MAC protocol such as the IEEE 802.11b. In what follows, we first present our experimental testbed and describe the experiment configuration. We then present the experimental results obtained and compare them against the predictions made using our analytical model. Finally, we demonstrate how our model could be used as a metric in an interference-aware routing protocol, and compare the resulting performance against a well-known probe-based routing scheme [CABM03].
4.4 Model validation via testbed experimentation

![Signal strength measurement](image)

**Figure 4.10:** Signal strength $P_{ij}[dBm]$ as a function of the distance $d_{ij}$.

### 4.4.1 Testbed description

The testbed consists of 23 stationary Linux PC nodes equipped with 802.11a/b/g Atheros cards. The nodes are located at the second floor of the ETZ building, as illustrated in Fig. 4.9. All nodes in our testbed communicate using the IEEE 802.11b protocol operating in ad hoc mode. The RTS/CTS handshake mechanism is disabled in line with the default behavior for most wireless cards [KXB04]. The cards are configured to send at 1Mbps with 31.62mW (15dBm) of transmit power.

**Path loss exponent $\alpha$ estimation**

The dependence of path loss on $\alpha$ is approximated by the log-distance path loss model (e.g., [Rap01]):

$$P_{ij}[dBm] = P_{d_o}[dBm] - 10 \cdot \alpha \cdot \log_{10} \left( \frac{d_{ij}}{d_o} \right)$$  \hspace{1cm} (4.17)
where \(d_0\) is a reference distance, \(d_{ij}\) is the distance between the sender \(i\) and the receiver \(j\), \(\overline{P_{ij}}[dBm]\) is the mean received signal power in \(dBm\) and \(\overline{P_{d_0}}[dBm]\) is the mean received power at a reference distance \(d_0\). We used two nodes to measure the signal strength as a function of distance in our indoor office environment. The signal strength is derived by the RSS (Received Signal Strength) values reported by the cards at various distances. Setting \(d_0 = 4m\) and carrying out a least-square fit computation, we estimated \(P_{d_0} = -51.12\) dBm, \(\alpha = 3.84\). The measured values and the least-square fit curve are plotted in Fig. 4.10.

**SINR threshold \(\beta\) estimation**

The CMU wireless channel emulator [JS05] was used to estimate the SINR threshold \(\beta\) of our Atheros wireless cards. In our experiment, two Atheros cards similar to the ones in our testbed, were connected to the hardware emulator; one card was sending
5000 802.11 broadcast packets at 1Mbps and the other was receiving them. Note that 802.11 broadcast packets are not subject to MAC retransmissions. Varying the attenuation of the radio signal through the emulator in increments of 1dB, we estimated $\beta$ by measuring the ratio of the correctly delivered packets as a function of the received signal strength (RSS). The results are plotted in Fig. 4.11. Since the noise floor of our Atheros cards is -96dBm, the knee $^2$ of the delivery ratio curve at $RSS = -92$dBm means that the threshold value $\beta$ equals 4dB or 2.5.

4.4.2 Experimentation methodology

The communication range in our testbed for 15dBm of transmit power was measured approximately to be 25 m. The sender-receiver pair used in our experimental evaluation are nodes 4 and 23, respectively. Their Euclidean distance is $r = 12.5m$, which corresponds to a distance scale factor value of $c = 0.5$.

Distribution of nodes

For the $\alpha$ and $\beta$ values estimated earlier in Section 4.4.1, the radii of interference areas for the receiver node 23 using lemma 1 are: $r_{23,1} = 15.8m$, $r_{23,2} = 19m$, $r_{23,3} = 21.1m$, $r_{23,4} = 22.8m$, and $r_{23,5} = 24.1m$. Equations (4.14)-(4.15) provide the number of interference areas that have to be considered and (4.12) yields the expected number of nodes $E(A_{j,m}) \forall m = 1, 2, 3...M$ in each interference zone as a function of the degree of the receiver node 23. We vary the network density by letting the node degree $d(x_j)$ take values in the interval $[5, 15]$ nodes. This is done by activating the nodes for each scenario listed in Table 4.2.

$^2$The knee corresponds to the receiver’s sensitivity for 8% error rate. The receiver’s sensitivity is a measure of wireless cards ability to discern low-level signals.
Table 4.2: Number of nodes in each interference area $A_{j,m} \forall m = 1, 2\ldots 5$.

<table>
<thead>
<tr>
<th>$d(x_j)$</th>
<th>$n(A_{j,1})$</th>
<th>$n(A_{j,2})$</th>
<th>$n(A_{j,3})$</th>
<th>$n(A_{j,4})$</th>
<th>$n(A_{j,5})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3, 16</td>
<td>12</td>
<td>1</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>11, 16</td>
<td>12</td>
<td>1</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>3, 10, 16</td>
<td>12</td>
<td>1</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>8</td>
<td>3, 10, 16</td>
<td>5, 12</td>
<td>1</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>9</td>
<td>3, 10, 16, 17</td>
<td>5, 12</td>
<td>1</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>10</td>
<td>3, 10, 11, 16</td>
<td>5, 12</td>
<td>1</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>11</td>
<td>3, 10, 11, 16</td>
<td>5, 12</td>
<td>1, 22</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>12</td>
<td>3, 10, 11, 16, 17</td>
<td>5, 12</td>
<td>1, 22</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>13</td>
<td>3, 10, 11, 16, 17</td>
<td>5, 12, 21</td>
<td>1, 22</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>14</td>
<td>2, 3, 10, 11, 16, 17</td>
<td>5, 12, 21</td>
<td>1, 22</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>15</td>
<td>2, 3, 10, 11, 16, 17</td>
<td>5, 12, 21</td>
<td>1, 22</td>
<td>14, 13</td>
<td>18</td>
</tr>
</tbody>
</table>

Traffic model description

All nodes in each experimental scenario send IEEE 802.11 broadcast packets, since they involve no retransmissions or link-layer acknowledgments. This is a common practice in related work [PAP$^+$05, RMR$^+$06, QZW$^+$07]. We estimate the successful reception probability under simultaneous interfering transmissions measuring the ratio of the successfully received packets over the total number of broadcast packets sent. All experiments were done during the night to circumvent interference induced from external energy sources $^3$. Having estimated the parameters $\alpha$, $\beta$ and $c$ for our experimental evaluation, we conduct experiments for different network loads.
4.4 Model validation via testbed experimentation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>packet payload</td>
<td>128 bits</td>
</tr>
<tr>
<td>UDP header</td>
<td>64 bits</td>
</tr>
<tr>
<td>IP header</td>
<td>160 bits</td>
</tr>
<tr>
<td>LLC+MAC header</td>
<td>192 bits</td>
</tr>
<tr>
<td>PHY header</td>
<td>192 bits</td>
</tr>
<tr>
<td>Channel bit rate</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Propagation delay</td>
<td>1 $\mu$s</td>
</tr>
<tr>
<td>DIFS</td>
<td>50 $\mu$s</td>
</tr>
<tr>
<td>Expected mandatory back-off time $E(b)$</td>
<td>310 $\mu$s</td>
</tr>
</tbody>
</table>

### Node transmission probability $\gamma$ estimation

The node transmission probability $\gamma$ in the analysis of Section 4.2 does not have a direct equivalent in the IEEE 802.11 MAC. To get the equivalent packet send rate for our experiments, we approximate the transmission probability $\gamma$ of each node as the ratio of the time taken by a successful packet transmission over a large time interval $T$. Table 4.3 lists the parameter values used for the basic DCF access mode. Let $H = PHY + MAC + IP + UDP$ be the packet header, $Pkt$ the packet payload and $t_{prop}$ the propagation delay. In the basic access mode, the duration of a successful transmission $T_s$ is

$$T_s = \frac{H + Pkt}{\text{channel bit rate}} + DIFS + E(b) + t_{prop}$$

Let $n_{total}$ the total transmitted packets in time $T$, then the parameter $\gamma$ is approximated as

$$\gamma \approx \frac{n_{total} \cdot T_s}{T}$$  \hspace{1cm} (4.18)

---

3External interference was only from the management frames broadcasts (beacons) of the wireless AP’s (Access Points) installed in the building, which is negligible comparing with the traffic generated from our experiments.
4.4.3 Experimentation results

In this section, we present our experimental results. All captured traces of this evaluation are available in [ENL]. We plot the average values of the successful packet receptions for each experiment along with their 90% confidence intervals.

The model predictions are compared against the experimental results in Fig. 4.12-4.14. We quantify the accuracy of our model by computing the root mean square error (RMSE), defined over the total number $k$ of predictions (experiment repetitions) as \[ \sqrt{\frac{\sum_{i=1}^{k}(\text{est}_i - \text{actual}_i)^2}{k}}. \] There is close match between the two curves in all

\[ \text{Figure 4.12: Analytical model vs. testbed experimentation results for } \gamma = 0.005 \ (\alpha = 3.84, \beta = 2.5, c = 0.5), \ RMSE=0.025. \]
three figures, the analytical one obtained from the Interference-cum-MAC model and the one from the testbed. The analytical predictions for the probability of successful reception match the monotonic change of $P(x_j)$ with the node degree throughout the $[5..15]$ range of node degree values for different $\gamma$. This is also reflected in the RMSE values. For $\gamma = 0.005$, the RMSE is 0.025 and for higher $\gamma = 0.05$ the RMSE equals 0.029.

Furthermore, we compare our model with the general model for interference (GMI) proposed in [QZW+07]. The model, which reflects the state-of-the-art in interference modelling, uses measurements to create RF-profiles of network nodes and links and then inputs those profiles to MAC models for the analytical deriva-
Figure 4.14: Analytical model vs. testbed experimentation results for $\gamma = 0.05$ ($\alpha = 3.84, \beta = 2.5, c = 0.5$), $RMSE=0.029$.

The GMI evaluation in [QZW+07] was limited to five simultaneous broadcast senders. Here, we compare the predictions of our model and GMI in scenarios of Table 4.2 involving up to nine simultaneous broadcast senders under unsaturated traffic demands. Note here that the computational time required for the GMI model predictions does not scale with high number of nodes. $^5$

Table 4.4 illustrates the relative error in prediction $\delta$,

$$\delta = \frac{\text{abs}(\text{est}_i - \text{actual}_i)}{\text{actual}_i}$$  \hspace{1cm} (4.19)

$^5$The model requires to compute $2^N$ states and $2^N \times 2^N$ state transitions for $N$ senders.
for node degree $d(x_j) = [5..8]$. In these scenarios, both models yield high accuracy in predicting the measured probability of successful delivery. Interestingly, our model appears to even outperform GMI for higher values of $\gamma$ (i.e. $\gamma = 0.05$). Moreover our model features distinct advantages over GMI; it is simple, it does not require seed measurements (RF profiling) and is directly applicable to routing, as discussed below.

### 4.4.4 Impact of Packet Size

A final note on the experimental results concerns the impact of packet size. The analytical derivation for $P(x_j)$ is not packet size aware; namely, it does not take into account the packet size transmitted over the medium. We investigated the impact of packet size with a set of experiments. For the given $\alpha, \beta,$ and $c$ values of our testbed set-up, we simultaneously varied the packet size and packet transmission rate, so that they yield the same equivalent node transmission probability $\gamma$, as estimated in Section 4.4.2. For example, the ($pkt\_size$, $rate$) pairs estimated for $\gamma = 0.04$ are (128 bytes, 20 pkts/second), (256 bytes, 15 pkts/second), (512 bytes, 8 pkts/second), and (1024 bytes, 4.5 pkts/second). Figure 4.15(a) plots $P(x_j)$ for all four scenarios. The deviation between the four combinations increases with node degree, but remains overall below 0.06. In fact, the deviation between the
Figure 4.15: Impact of packet size on $P(x_j)$. 

(a) $P(x_j)$ vs packet size. 

(b) Scatter plot of $P(x_j)$. 

Packet size 256 bytes, rate 15pkts/sec, Packet size 512 bytes, rate 8pkts/sec.
curves are comparable to the confidence intervals for the measured results, suggesting that there is no significant change of \( P(x_j) \) with packet size. Another way to see this is at Fig. 4.15(b). Each point plots the \( P(x_j) \) values for two scenarios of different packet size (256 and 512 bytes). Absolute coincidence of the measured values in the two cases would align the two-dimensional points along the 45°-slope line.

\[ \text{4.5 Conclusion and Discussion} \]

This chapter addresses interference in ad hoc wireless networks. Starting from the SINR model, we derive an analytical expression for the data loss probability as a function of the network density, load, propagation environment, and network card hardware. The analysis is carried out assuming a MAC-agnostic model, which does not take into account the engineering details of real-world protocols, such as the IEEE 802.11x suite of protocols. We then extend our analytical derivation with a simple enhancement to capture the carrier sense function of real-world MAC protocols. To assess the prediction capacity of our analysis under realistic conditions, we have set up a wireless mesh network testbed. Measurements obtained from the testbed show close match between the analytical predictions and experimental results.

Where and how could this analytical derivation be useful? Interference-aware routing is one profound area. The analytical derivation could eventually evolve to a routing metric used by routing protocols to route packets in the network. This is indeed promising, since it results in significant control data overhead savings over state-of-the-art measurement-based approaches in the literature. In general, an interference-aware routing metric using our analytical model can be refined and tailored according to the specific objectives of the routing algorithm, such as robustness, scalability, low latency, high throughput, or energy efficiency.
Chapter 5

Interference-aware Routing

This section presents the performance evaluation of the interference-aware routing metric. Note here, that our goal is not a new routing metric definition but to exhibit the usability of our interference model as an input to a routing metric. For this, we borrow the essential design properties of the state-of-the-art routing metric for wireless multihop networks (e.g., ETX).

5.1 Motivation

Routing in wireless multihop networks has been a highly popular research topic during the last decade. Whereas many routing function objectives are the same as in wired networks and the Internet, wireless multihop networks add several new dimensions that make the problem less straightforward and more interesting at the same time. As a result, although experience and wisdom gained by wired networks have guided the first steps in the wireless domain, in many cases there has been need for novel approaches and solutions.
In the Internet changes in connectivity may happen but are not frequent. As a result, routing protocols for wired networks pro-actively maintain routes from all nodes to every other node, by propagating the occasional topology update as soon as it occurs. However, the topology of wireless multihop networks changes much more dynamically than in wired networks. This is due to node mobility on the one hand, e.g., in mobile ad hoc networks or hybrid networks with both mobile and static nodes, and the impairments of wireless links due to propagation phenomena, on the other hand. These two phenomena result in wireless networks being often only intermittently connected, which makes the use of proactive routing protocols and the overhead related to route maintenance less attractive. We summarize here the additional challenges related to wireless multihop networks:

- **Node mobility.** Wireless nodes may move. As a result, links may break and network topology may change frequently; in graph-theoretic terms, the connectivity graph varies more quickly with time. This makes route maintenance much more complex than in wired networks.

- **Wireless propagation phenomena.** In the wireless environment, node transmissions are physically broadcast and subject to radio propagation dynamics, such as shadowing, fading, etc. This makes even static link quality fluctuate over time, and can also result in the emergence of grey zones in the network; although links have bad quality and are not good for data communication, may still allow some successful transmissions as for instance routing packets. Situations like these trigger frequent route re-establishments.

- **Energy constraints.** In many cases, energy preservation and battery lifetime extension may become the primary objectives for network operation. Advances in battery technology are significantly slower than those in nanotechnology and
electronics. Thus, the available power will continue to be a performance bottleneck for handheld, low-end devices and sensors, in scenarios where nodes move and operate for long periods without access to mains power.

- **Lack of centralized control.** One of the most attractive features of wireless multihop networks is self-organization. Various functions, such as medium access control and routing, are carried out in a fully distributed manner with minimal human intervention. They are not subject to any centralized network management processes of the kind practiced in wired networks. However, the drawback is that most decisions are made by individual nodes having primarily knowledge about their local environment only. This leaves little margin for network optimizations that require global knowledge of the network state. More critically, the network operation itself assumes the cooperation of all nodes, rendering the network more vulnerable to node misbehavior.

The need to think differently when it comes to wireless multihop networks is also reflected in the large variety of routing metrics that have been proposed along with routing protocols, in order to enable efficient data delivery in the wireless context. Besides minimum hop count (shortest path first), which is the alma mater of metrics, the literature is quite rich in other metrics that have either been more “intelligent” in pursuing minimum delivery delay or have prioritized other aspects of network performance [AGKT98].

The overall goal of a routing metric is to find routes with high end-to-end throughput. Furthermore, load balancing, fault-tolerance and low jitter rank highly on the list of goals determining the costs of links and paths in the network. Whereas these objectives remain relevant in wireless multihop networks, there
are additional concerns that may complement or overshadow traditional objectives. In particular, in wireless networks a routing metric should also account for

- interference from simultaneous transmissions of neighboring nodes
- interference between successive hops of multihop paths
- asymmetric links (asymmetric loss rates).

Our routing metric accounts for the aforementioned objectives as our interference model estimates explicitly the effect of interference on packet receptions. We discuss this in detail in the next section, presenting the design of the interference-aware routing metric. The performance evaluation of routing given our metric versus the minimum hop count and the ETX metrics is presented in the subsequent section.

5.2 Interference-aware Routing Metric

The essential advantage of our analytical derivation (see Section 4.2) is that the probability of successful reception depends on parameters that are known or can be estimated locally at each node. The path loss exponent $\alpha$ depends on the environment, while the SINR threshold $\beta$ relates directly to the receiving sensitivity of the wireless adapter. The node degree $d(x_j)$ can be known from the state of conventional routing protocols, whereas the network load parameter $\gamma$ can be estimated by sensing the wireless channel. Modern wireless adapter drivers, such as the madwifi ones [ww], permit access to information about the time intervals during which the wireless medium is sensed busy. Finally, the distance $r$ of any sender-receiver pair in the network can be made available through GPS [ZBR02] or other positioning methods. Thus, our analytical expression for the probability
of successful reception can directly be used for the computation of an interference metric, circumventing the need for additional measurements (\textit{i.e.}, probing).

In our routing metric implementation, each node distributes its own local estimate of the probability of successful reception $P(x_j)$ (see sections 4.2.2 and 4.2.3). To avoid additional overhead in the network, the metric information is encapsulated in the routing packets sent periodically to maintain the routing tables at each node. Then, similar to ETX, each sender node $x_i$ estimates the expected number of transmissions (including retransmissions) to a potential receiver neighbor node $x_j$ as a function of $P(x_j)$ and its local estimate $P(x_i)$. The routing protocol select paths with the lowest number of transmissions.

From an implementation perspective, a routing metric is a component (add-in) of a routing protocol. For this, in our evaluation we used the Click toolkit [MKJK99] and the Click-based implementation of the DSDV [PB94] routing protocol. In the next section we discuss the main elements of the DSDV-based implementation of the interference-aware routing metric. First we give an overview of the DSDV protocol and then we present the changes needed to adopt our metric in the routing scheme.

5.2.1 Overview of the DSDV protocol

DSDV is a distance-vector protocol using sequence numbers to ensure fresh route table information (freshness of routes). Every node maintains a routing table entry for each destination. The route entry contains four fields: the destination’s identifier (IP address), the next-hop node on the route towards the destination, the latest sequence number heard for each destination and the value of the metric (Table 5.1). Packets are forwarded according to the current contents of the routing table. The original DSDV protocol uses the minimum hop count as metric. In our evaluation
Table 5.1: \textit{DSDV routing entry}

we used the implementation of the ETX metric included in the Click toolkit.

DSDV has several mechanisms for the setup, maintenance and update of the routing entries. The first is that each node broadcasts periodically a routing update of its complete routing table (full update). Each node maintains a sequence number (for each route) which it increments in every full update that it originates (own routing table entry). When a node receives a routing update, it checks the sequence number of the advertised routes for each destination. If the sequence number is newer than the sequence number in its current entry, or the sequence number is equal and the metric is better, it replaces its current entry with the new route. Otherwise a node ignores the advertised route. Furthermore, if a node has no entry for a destination, it accepts the new route.

In addition to full updates, triggered updates are used to quickly propagate good routes through the network. When a node receives or locally estimates a better route towards a destination, it sends a triggered update to its neighbors containing only the changed information. In order to prevent an explosion of updates whenever a route changes, triggered updates are not sent until at least $2xWST$ time (Weighted Settling Time) has passed since the first hearing of the current sequence number of a route.

Changes to DSDV

In this section we discuss the changes we made to enable the DSDV protocol to use the interference-aware routing metric. In contrast with ETX that uses probe packets to estimate the delivery ratio, the probability of successful delivery at the receiver
5.2 Interference-aware Routing Metric

| IP header | Next hop | Seq_num | Metric | $P_{x_i}(x_j)$ |

Table 5.2: Extension of the DSDV routing entry to include the $P_{x_i}(x_j)$ value.

Node $x_j$ is derived from theorem 4.4 using only locally retrieved information. Generalizing for all links, each node $x_j$ maintains a table of delivery probabilities $P_{x_i}(x_j)$ for each potential sender (neighbor) node $x_i \forall i \in d(x_j)$. The interference-aware metric $I(x_i, x_j)$ is calculated as in ETX, converting the delivery ratios in both directions to expected number of transmissions:

$$I(x_i, x_j) = \frac{1}{P_{x_i}(x_j) \cdot P_{x_j}(x_i)} \quad (5.1)$$

To derive $I(x_i, x_j)$, each node $x_j$ advertises its local estimation of $P_{x_i}(x_j)$ for all its neighboring nodes $x_i$. To avoid additional routing overhead, these messages can be encapsulated into the DSDV routing updates. For this, we extended the DSDV routing table entry (as illustrated in Table 5.2), to include a field for the probability $P_{x_i}(x_j)$.

As route decisions are taken by the sender node $x_i$, the question that arises now is how $x_i$ estimates the metric value $I(x_i, x_j)$. While the reverse probability of successful reception at node $x_i$ ($P_{x_j}(x_i)$) from $x_j$ is estimated locally at $x_i$, the forward probability of successful reception $P_{x_i}(x_j)$ needs to be communicated to $x_i$ from $x_j$. For this, we use triggered updates to disseminate the extended DSDV routing entry with the forward probability of successful reception.

We implemented the interference-aware routing metric at the Click toolkit. In the following section we discuss how the model inputs are obtained to calculate the probability of successful reception.
5.2.2 Obtaining Model Inputs

The required inputs for the calculation of successful delivery are the parameters $\alpha, \beta$ and $\gamma$. In Section 4.4.1, we discuss how the path loss exponent parameter $\alpha$ can be estimated through measurements. Likewise, vendors of modern wireless adapters usually provide information about the adapter’s SINR threshold in their specifications. If this information is not available, the SINR threshold can be estimated with similar measurements we present in Section 4.4.1. The Euclidean distance $r$ between the transmitter and receiver nodes can become available through GPS [ZBR02] or other positioning methods. In our testbed we measure the distance of nodes and the values are statically given to the routing protocol.

Whereas the estimation of the aforementioned parameters is straightforward, the estimation of the transmission probability parameter $\gamma$ in real time represents a challenging task.

Estimation of transmission probability $\gamma$

As discussed in Section 4.2, the transmission probability $\gamma$ is a measure of the input network traffic load. In Section 4.4.1 we describe how the parameter $\gamma$ is estimated for given traffic load (unsaturated traffic demands). In the experimental validation of the model, we calculate a priori the value of $\gamma$ for a given data rate. While this is a good approximation in the specific settings of the experiment, in reality a node should measure the traffic load in real time.

To achieve this, we used the open source Madwifi wireless adapter drivers [ww]. We modified the source code of the drivers similar to [DL05] to measure the time the wireless medium is sensed busy. The percentage of the busy time $b(t)_{total}$ ($0 \leq b(t)_{total} \leq 1$) is reported in a one-second time window to the interference-aware routing metric process. More specifically the busy time
5.2 Interference-aware Routing Metric

report includes the percentage of time $b(t)_{x_i}$ during which the medium is sensed busy due to transmissions of sender $x_i$. This information is useful to estimate the traffic load induced from interferer nodes to each sender-receiver pair.

In the next Section we describe how the interference-aware metric is calculated for uniform node distribution (see also Section 4.2.4).

**Interference-aware metric under uniform node distribution**

In the interference model we assume that all nodes send with probability $\gamma$ (uniform network load). However this is not the case in most application scenarios. Therefore, we approximate the transmission probability $\gamma_{x_i,x_j}$ for a sender-receiver pair $x_i,x_j$ as:

$$\gamma_{x_i,x_j} = \frac{b(t)_{total} - b(t)_{x_i}}{d(x_j)} \quad (5.2)$$

where $d(x_j)$ is the degree of the receiver node $x_j$. The probability $\gamma_{x_i,x_j}$ here, denotes the percentage of busy time resulting from the total busy time at receiver node $x_j$ from all nodes ($b(t)_{total}$) except the sender’s $x_i$ percentage of busy time, calculated for the uniform node distribution ($d(x_j)$). The node degree $d(x_j)$ is retrieved directly from the DSDV routing protocol. The busy time calculation is an approximation of the transmission probability used in the model. It actually corresponds to the network load after the effect of the MAC protocol.

Now, the last parameters required to estimate the probability $P(x_j)$ under uniform node distribution is the number of interference zones $M$ given from 4.15 and the expected number of nodes per interference zone, given from 4.10. Note here, that in the evaluation of the interference-aware metric, the probability of successful reception $P(x_j)$ is calculated for the uniform node dis-
Algorithm 1 Estimation of the interference-aware routing metric value $I(x_i, x_j)$ at node $i$.

Upon packet reception $p$

if $p ==$ data packet from neighbor $j$ then

Update variables $b(t)_{x_i}, b(t)_{total}$ and calculate $\gamma_{x_i, x_j}$ (5.2)

else

if $p ==$ routing packet from neighbor $i$ then

1. Get the probability of successful reception $P_{x_j, x_i}$ and estimate the metric $I(x_i, x_j)$ (4.4), (4.6), (5.1)

2. Update the routing table. The routing protocol then maintains the routing tables updated

else

Packet not used in the algorithm

end if

end if

5.3 Routing Metric Performance Evaluation

In this section we present the results of the interference-aware routing metric performance evaluation against the ETX metric and the minimum hop count. The ETX metric represents the state-of-the-art of routing metrics for wireless multihop networks and the hop count is the default metric used from commodity routing protocols. Our goal is to exhibit the usability of our interference model as a routing metric and to assess its performance in a different set of experiments.
5.3 Routing Metric Performance Evaluation

5.3.1 Methodology

We evaluate the performance of the interference-aware metric versus the ETX and minimum hop count (Hop Count) metrics in our indoor real-world TIK-Net testbed (a comprehensive description of the testbed is given in section A.1). For this, we installed the Click Toolkit $^1$ on all 20 nodes of the testbed and we used the Click-based implementation of the DSDV protocol. The minimum hop count is the default metric for the DSDV protocol whereas the ETX implementation is included in the Click toolkit. We implemented our interference-aware routing metric according to the design discussed in Section 5.2 as a Click module.

The 802.11b cards in the experimental evaluation are set to “ad-hoc” mode $^2$, RTS/CTS is turned off and rate adaptation mechanism is inactive. We evaluate the three routing metrics in two set of experiments varying the transmission rate, the transmit power $P_w$, and the packet size as illustrated in Table 5.3. We did also experiments for 0dBm of transmit power, however for these settings the network is very loosely connected. We discuss this further in Section 5.4. We did not perform experiments with higher rate (e.g., 54 Mb/s) because the network is loosely connected and partitioned due to the very small node communication range. Now, regarding the packet size used in our experiments, small packets correspond to real-time traffic applications (VoIP), whereas large packets to file sharing or peer-to-peer applications. All experiments are carried out during weekends or nights to minimize interference from external sources $^3$.

---

$^1$Installation and configuration details of the Click toolkit can be found in www.read.cs.ucla.edu/click/.

$^2$More specifically we used the “ahdemo” mode, which is a Madwifi driver specific “ad-hoc” mode. In “ahdemo” mode no management packets are sent to maintain connectivity.

$^3$External interference was only from the management frames broadcasts (beacons) of the wireless AP’s (Access Points) installed in the building, which is negligible comparing with the traffic generated from our experiments.
Table 5.3: Parameters used for the routing metric’s performance evaluation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pkt_size</td>
<td>Packet size (bytes)</td>
<td>128, 1024</td>
</tr>
<tr>
<td>Bit_rate</td>
<td>Channel bit rate (Mb/s)</td>
<td>1, 11</td>
</tr>
<tr>
<td>$P_w$</td>
<td>Transmit power (dBm)</td>
<td>10, 18</td>
</tr>
</tbody>
</table>

Experiment Sets

Two main sets of experiments are conducted in the experimental evaluation:

- **Set A**: One node pair is active at a time for all pairs in the TIK-Net testbed, resulting in a total of 20x19=380 sender-receiver pairs.

- **Set B**: Ten node pairs transmit simultaneously. We select the 10 extreme (in distance) node pairs in our testbed. The pairs used in this set of experiments are illustrated in Table 5.4. Nodes 1 to 10 are senders and nodes 11-20 act as receivers, respectively. The node ids of the pairs are $i \rightarrow 20 - (i - 1)$ and represent the most challenging transmissions patterns (this scenario results in many multihop paths with much cross traffic).

In the first set of experiments (set A) we evaluate the performance of each metric to find high throughput paths in absence of interflow interference, *i.e.*, interference from other flows. Thus, in this specific set of experiments interference is mainly due to simultaneous transmissions of multihop forwarding (intraflow interference). In every experiment each node sends UDP packets at maximum rate (maximum channel capacity) for 30 seconds. Each round is followed by 20 seconds of pause to let routing entries converge to the initial state (no traffic/boot phase). Thus, the total duration of the first set of experiments (set A) is $380 \times 50 \times 3$ seconds or 15.9 hours testing all three metrics under a single tuple
Table 5.4: Node pairs used for the second set of experiments (Set B)

<table>
<thead>
<tr>
<th>Node pair</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1→20</td>
</tr>
<tr>
<td>2</td>
<td>2→19</td>
</tr>
<tr>
<td>3</td>
<td>3→18</td>
</tr>
<tr>
<td>4</td>
<td>4→17</td>
</tr>
<tr>
<td>5</td>
<td>5→16</td>
</tr>
<tr>
<td>6</td>
<td>6→15</td>
</tr>
<tr>
<td>7</td>
<td>7→14</td>
</tr>
<tr>
<td>8</td>
<td>8→13</td>
</tr>
<tr>
<td>9</td>
<td>9→12</td>
</tr>
<tr>
<td>10</td>
<td>10→11</td>
</tr>
</tbody>
</table>

of \((\text{Bit}_\text{rate}, P_w, \text{Pkt}_\text{size})\) values and approximately 130 hours for all tuples.

The goal in the second set of experiments (set B) is to evaluate the metrics in a more challenging scenario with many simultaneous data flows. We selected node pairs with the largest possible distance at our testbed. Within an experiment round each sender node is configured to send 5000 UDP packets at a rate of 10 packets per second. The duration of each round is 500 seconds followed by 100 seconds of pause time, thus in total 600 seconds. We repeat each round 20 times, resulting in \(600 \times 20 \times 3\) seconds or 36 hours for the three metrics under a single tuple of \((\text{Bit}_\text{rate}, P_w, \text{Pkt}_\text{size})\). In the results that follow, we present the mean values as well as the 95% confidence intervals.

## 5.4 Experimentation Results

In both experimental scenarios we evaluate the performance of the three metrics varying the transmission rate, the transmit power \(P_w\), and the packet size as illustrated in Table 5.3. The
graphs below do not include error bars, but are representative of the many runs we have performed.

5.4.1 One Node Pair Active

Figure 5.1(a) compares the throughput CDFs (in packets per second) of paths found by DSDV using the ETX, minimum hop count, and our interference-aware metric between all 380 node pairs, for $\text{Bit\_rate}=1\text{Mb/s}$, $P_w=18\text{dBm}$ and $\text{Pkt\_size}=128$. In the figure, there are essentially two main areas. On the right side lie node pairs that communicate directly, whose achieved packet delivery ratio exceeds 200 packets per second, on the left half are the node pairs for which the found routes exceed one hop. In addition to the CDF figure, the throughput histogram (in packets per second) of the paths found by each metric is presented in Fig. 5.1(b). While presenting the same data with the CDF figure, the histogram allows for a more direct comparison of the metrics’ performances.

All three metrics find the one-hop best route (right half side) as can be seen in both figures. In that area, neither ETX nor our interference-aware routing metrics can find higher throughput routes than those retrieved by minimum hop count. However, in the left half area, the sensitivity of our interference metric to interfering transmissions results in higher throughput paths than those of both the ETX and minimum hop count. This is clearly observed in Fig. 5.1(b), where our interference-aware routing metric finds up to 3 times more paths with high throughput (between 125 and 150 packets per second) when compared to ETX and minimum hop count. As soon as the path length is greater than a single hop, throughput degrades due to the 802.11 MAC mechanisms (exposed nodes) and intraflow interference (hidden, interfering nodes). Our interference-aware metric finds higher throughput paths because it takes explicitly into account the effect of interference. On the contrary, ETX and min-
5.4 Experimentation Results

(a) Throughput CDF (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

(b) Throughput histogram (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

**Figure 5.1:** One node-pair active: $\text{Bit Rate}=1\text{Mb/s}$, $P_w=18\text{dBm}$, $Pkt\_size=128$ bytes.
imum hop count metrics find more paths with lower throughput (between 100 and 125 packets per second) in comparison with our interference-aware metric. ETX accounts for lossy/asymmetric links using probe packets to estimate the delivery probability on a link. However, as admitted also in the ETX paper [CABM03], heavy load causes the MAC protocol to become extremely unfair, distorting the probe-based measurements. Thus, ETX might not accurately estimate the link delivery probabilities and accordingly result in suboptimal paths.

**Effect of packet size**

In another set of experiments we use 1024-byte data payload to study the effect of packet size on routing metric performance. Our interference model, does not take the packet size explicitly into account in the estimation of the probability $P(x_j)$ of successful reception. Moreover, in the experimental evaluation of our interference model (see section 4.4.4), we show that there is no significant change of the estimated probability $P(x_j)$ with the packet size. Nevertheless, in the actual implementation of the interference-aware metric design, the packet size and rate are implicitly included in the time the medium is sensed busy (transmission probability parameter), as a function of the busy time duration $b(t)_{total}$ (see Section 5.2.2).

Figure 5.2(a) plots the throughput for packets with $pkt\_size=1024$ bytes. In accordance with the aforementioned results, the advantage of our interference-aware routing metric is visible at paths of more than one-hops. Our interference-aware metric finds almost three times more paths with average throughput between 30 and 40 packets per second (see Fig. 5.2(b)). ETX find routes with average throughput between 10 and 20 packets per second (130 node pairs). In contrast with ETX and our interference-aware metric, minimum hop count finds more paths with low throughput; almost 30% more paths with throughput between 0
5.4 Experimentation Results

(a) Throughput CDF (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

(b) Throughput histogram (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

Figure 5.2: One node-pair active: Bit rate=1 Mb/s, $P_w=18$ dBm and Pkt size=1024 bytes.
and 10 packets per second. This is because minimum hop count does not have a mechanism to cope with asymmetric links or packet losses due to interference.

The specific set of experiments suggests that the change of the packet size does not have a significant impact neither on the absolute nor on the relative performance of the metrics. Our interference-aware metric performs at least as good as both ETX and minimum hop count.

Effect of transmit power

When nodes send at lower transmit power, the communication range is decreasing. Therefore, the network is less connected resulting in the increase of the average hop count required for nodes to communicate. Furthermore, routing metrics have fewer paths to select. In that specific set of experiments, we decrease the transmit power $P_w$ from 18dBm to 10dBm. We also did experiments for very low transmit power $P_w=0$dBm (1mW). The network in that specific set of experiments is very sparsely connected and the throughput of most of the node pairs is very close to zero; almost 60% of node pairs throughput for all three metrics is less than 10 packets (see Figure 5.3). Therefore, we evaluate the performance of the metrics for intermediate transmit power levels.

Figure 5.4(a) shows the throughput CDFs for $P_w=10$dBm and pkt_size=128 bytes. Comparing with the results for $P_w=18$dBm (see Fig. 5.1(a) all metrics find paths with relatively little throughput. More specifically, our interference-aware metric finds fewer more-than-one-hop paths with throughput between 125 and 150 packets per second; for $P_w=18$dBm, there are almost 100 node pairs, whereas for $P_w=10$dBm only 65 node pairs. However, it still finds more paths with high throughput than both ETX and minimum hop count (about 2 times more paths with high throughput values).
5.4 Experimentation Results

(a) Throughput CDF (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

(b) Throughput histogram (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

Figure 5.3: One node-pair active: Bit_rate=1 Mb/s, P_w=0dBm and Pkt_size=1024 bytes.
Interference-aware Routing

(a) Throughput CDF (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

(b) Throughput histogram (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

Figure 5.4: One node-pair active: $\text{Bit}_{\text{rate}}=1 \text{ Mb/s}$, $P_w=10\text{dBm}$ and $Pkt_{\text{size}}=128$ bytes.
The transmit power affects the performance of the metrics, since it directly determines the connectivity of the network. The advantage of our interference-aware metric over ETX and minimum hop count is more profound in densely connected networks (higher transmit power). The gain is smaller in sparsely connected networks, because available paths that can be found from a routing protocol are fewer and there is little margin for differentiation in the decisions made by the three metrics.

**Effect of transmission rate**

Another parameter that affects the performance of the routing metrics is the transmission rate. There is an inherent trade-off between high transmission rate and effective transmission/communication range. Higher transmission rate results in higher throughput but lower effective transmission range, hence looser connectivity (sparser network).

We evaluate the performance of routing metrics for transmission rates of 1 and 11 Bits per second. The sensitivity thresholds for the cards used in our experimental evaluation, as reported from the manufacturer, are -89dBm for 1 Mb/s and -82dBm for 11 Mb/s (for 8% packet error rate). Figure 5.5(a) shows the throughput CDFs for $\text{Bit_rate}=11$ Mb/s, $P_w=18$dBm and data packets of $\text{Pkt_size}=128$ bytes. In comparison with the $\text{Bit_rate}=1$ Mb/s experiments (Fig. 5.1), the overall throughput increases; 30% of pairs achieve throughput over 200 data packets per second for $\text{Bit_rate}=1$ Mb/s, while for 11 Mb/s the respective value is 60-70% for all metrics.

Looking into the performance of each metric, similar to the aforementioned results, the three metrics find approximately the same number of one-hop routes. The gain of the interference-aware routing metric is on the left half of the figure where it finds higher throughput routes of more than one-hop. This can be clearly seen in figure 5.5(b) where our interference-aware met-
Interference-aware Routing

(a) Throughput CDF (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

(b) Throughput histogram (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

Figure 5.5: One node-pair active: Bit rate=11 Mb/s, $P_w=18dBm$ and $Pkt\_size=128$ bytes.
ric outperforms ETX and hop count and finds almost 3 times more high throughput paths (between 500 and 600 packets per second) than ETX and minimum hop count. ETX finds more paths between 200 and 300 packets per second while minimum hop count find more paths with lower throughput (between 0 and 100 packets per second).

Similar behavior of the routing metrics is observed for different packet size and transmit power settings (Fig. 5.6, 5.7 and 5.8). Our interference-aware metric performs at least as good as ETX and minimum hop count in most scenarios independent of packet size, transmit power, and transmission rate. The advantage of our metric is for paths higher than a single hop. The presence of intraflow interference degrades the end-to-end throughput. Minimum hop count does not account for interference, while ETX estimates link losses based on probe measurements. However, under heavy load ETX probe packets are distorted, resulting in biased measurements. The essential advantage of our metric is the direct estimation of the effect of interference, the primary cause of packet loss in wireless networks.

5.4.2 Multiple Pairs Active.

The second set of experiments, we evaluate the performance of the three routing metrics under many simultaneous data flows. Figure 5.9(b) compares the throughput (in packet per second) of each sender-receiver pair (1-10 as illustrated in Table 5.3) for Bit\_rate=1 Mb/s, Pkt\_size=128 bytes, and $P_w=18$dBm. Generally, our interference-aware metric and ETX achieve higher throughput when compared with the minimum hop count. More specifically, for the node pairs 1, 2, 7, 8 and 9, the throughput of our interference-aware metric is higher than ETX (10% on average) and minimum hop count (30% on average). ETX achieves higher throughput for the node pair 10, while for node pairs 3, 4, 5, 6 the throughput is similar to our interference aware metric.
(a) Throughput CDF (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

(b) Throughput histogram (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

**Figure 5.6:** One node-pair active: \( Bit\_rate=11 \ M b/s,\)
\( P_w=10 dBm \) and \( Pkt\_size=128 \ bytes.\)
5.4 Experimentation Results

(a) Throughput CDF (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

(b) Throughput histogram (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.

Figure 5.7: One node pair-active: Bit_rate=11 Mb/s, P_w=10dBm and Pkt_size=1024 bytes.
Figure 5.8: One node-pair active: Bit-rate=11 Mb/s, $P_w=18$ dBm and $Pkt\_size=1024$ bytes.
Table 5.5: Average path length for all rounds. (Bit_rate=1 Mb/s, Pkt_size=128 bytes)

<table>
<thead>
<tr>
<th>Metric</th>
<th>$P_w=18$dBm</th>
<th>$P_w=10$dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference-aware</td>
<td>3.26</td>
<td>3.36</td>
</tr>
<tr>
<td>ETX</td>
<td>3.4</td>
<td>3.56</td>
</tr>
<tr>
<td>Minimum hop count</td>
<td>3.2</td>
<td>3.29</td>
</tr>
</tbody>
</table>

While ETX finds lower but comparable throughput paths to the interference aware-metric, minimum hop count achieves concisely the lower throughput for all node pairs.

Figure 5.9(a) presents the throughput (in packet per second) for lower transmit power, namely $P_w=10$dBm. Lower transmit power, as we have seen in section 5.4.1, may eventually result in lower throughput because fewer paths are available towards a destination. Among the three metrics, the transmit power impacts more significantly the performance of minimum hop count. For node pairs 1, 2, 4 and 10 the throughput drops up to 50% below that obtained with transmit power of 18dBm.

**Impact of path length**

Now, the question that arises is why our interference-aware routing metric finds higher throughput paths than both ETX and minimum hop count? Table 5.5 presents the average path length of all experiment rounds for transmit power $P_w$ equal to 10dBm and 18dBm. To calculate the average path length (for each experiment repetition), we keep track of the paths taken by data packets. The minimum hop count has the shortest average path length (3.2 and 3.29) followed by the interference-aware metric (3.26 and 3.36) and ETX (3.4 and 3.56).

Looking in more detail, Fig. 5.10(a) illustrates the bar chart of the average paths length for each node pair (for $P_w=18$dBm). The error bars represent the 95% confidence intervals. The bar chart
Figure 5.9: Multiple node-pairs active: Throughput (in packets per second) of paths found by DSDV using ETX, minimum hop count and our interference-aware metric.
5.4 Experimentation Results

![Graph showing average path length for different node pairs.](image)

(a) Bit\_rate=1 Mb/s, $P_w=18$dBm and Pkt\_size=128 bytes.

(b) Bit\_rate=1 Mb/s, $P_w=10$dBm and Pkt\_size=128 bytes.

**Figure 5.10:** Multiple node-pairs active: Average path length used by ETX, minimum hop count and our interference-aware metric.
exhibits that the minimum hop count has the shortest average path length in most pairs, followed by the interference-aware metric and ETX. Similar results are obtained for $P_w=10$dBm (see Fig. 5.10(b)). Nevertheless, the small diversity in path length among the ETX, minimum hop count, and interference-aware metrics does not justify the difference in throughput for both experimental settings. Therefore, as routing metrics select paths with approximately equal average length, there should be another reason differentiating the performance of the three metrics.

**Load distribution**

In this subsection we zoom our analysis in on the distribution of data traffic across network nodes. In Fig. 5.11 the traffic load distribution with the 95% confidence intervals of the average values is shown. More specifically, the bar chart shows the average number of packets sent and/or received per second at each node, i.e., nodes selected from the routing metrics to forward data traffic. In Fig. 5.11(b) we observe that routing metrics favor different nodes for forwarding data traffic. Nodes 11 and 12 are selected from ETX, while our interference-aware metric pushes the traffic to nodes 2, 4, 15, 17 and 18. Minimum hop count favors nodes 11 and 12 similar to ETX, but with lower data volume.

Similar load distribution patterns are observed at the second experiment with lower power $P_w=10$dBm (see Fig. 5.11(b)). ETX routes traffic towards nodes 11 and 12, as much it does for $P_w=18$dBm. Our interference-aware metric also favors the same nodes as for $P_w=18$dBm, but with different volume, adapting to the new topology; 88 and 75 packets on average per second at nodes 4 and 17, respectively, versus 92 and 72 packets per second on average at nodes 17 and 4.

Figure 5.12 presents the same data complementing Fig. 5.11, only values are sorted according to the data volumes. The red horizontal line corresponds to the minimum expected number
5.4 Experimentation Results

![Graph showing load balancing metrics](image)

(a) Bit\_rate=1 Mb/s, $P_w=18\,\text{dBm}$ and $Pkt\_size=128\,\text{bytes}$.

(b) Bit\_rate=1 Mb/s, $P_w=10\,\text{dBm}$ and $Pkt\_size=128\,\text{bytes}$.

**Figure 5.11:** Multiple node-pairs active: Histogram of traffic load (average number of packets sent/received per second) at all nodes.
of packets sent/received from each node, as nodes 1-10 send 10 UDP packets per second, while nodes 11-20 are correspondingly the destination nodes. This figure shows that ETX and our interference-aware routing metric generate equivalent values of data traffic volumes in the network. On the contrary, minimum hop count does not achieve to support high data traffic volume, in accordance with the low achieved throughput as presented in Fig. 5.9(a) and 5.9(b).

Therefore, our interference-aware routing metric performs better than both ETX and minimum hop count because it finds higher throughput paths. Taking into account Fig. 5.11 and 5.12 the only qualitative difference between our interference-aware routing metric and ETX, while the total volume of data is approximately equivalent, is that our metric distributes the traffic over higher throughput paths.

Summarizing this section, we list the main findings of the performance evaluation of the three metrics:

- The essential advantage of our interference-aware routing metric is the direct estimation of the effect of interference, the primary cause of packet loss in wireless networks.

- The packet size, transmit power and transmission rate do not have a significant impact on the relative performance of the metrics.

- Our interference-aware routing metric performs at least as good as the ETX and minimum hop count in most experimental scenarios.

5.5 Conclusion and Discussion

In this section we presented the design and the performance evaluation of our interference-aware routing metric. First, we demon-
5.5 Conclusion and Discussion

![Graph with three lines representing different load balancing methods: ETX, Interference-aware, and Hop Count.](image)

(a) Bit_rate=1 Mb/s, $P_w=18$ dBm and Pkt_size=128 bytes.

(b) Bit_rate=1 Mb/s, $P_w=10$ dBm and Pkt_size=128 bytes.

**Figure 5.12:** Multiple node-pairs active: Traffic load (average per second number of packets sent/received per second) sorted for all nodes.
strated the usability of our interference model as a metric for interference-aware routing. Adopting the essential properties of the state-of-the-art routing metric, we developed an interference-aware routing metric based on our model.

We compared its performance at the TIK-Net testbed with the ETX and minimum hop count metrics in a large set of experiments; in the presence only of intraflow interference (one node pair active) and both intraflow and interflow interference (many simultaneous data flows). The results showed that our interference-aware routing metric performs at least as good as ETX and better than the minimum hop count.
Chapter 6

Conclusions and Future Work

We conclude our work with a summary of our main results and contributions. We also identify assumptions and possible weaknesses of our work and discuss still open research issues that deserve further attention.

6.1 Summary of Main Results

Multipath Routing

In this thesis, multipath routing is investigated in the context of our pursuit towards more efficient routing in wireless multi-hop networks. We carry out an extensive performance evaluation study to thoroughly understand the advantages and limitations of single-path and multipath routing protocols. Our study demonstrates that multipath routing performs better than single-path in networks with high density and network load. Furthermore, we find that the use of two, maximum three, paths represents the best tradeoff between routing overhead and performance.
Interference Model

We propose an analytical model for the probability of successful reception at a node in the presence of interference from simultaneous transmissions of other network nodes. We first derive a MAC-agnostic model, which does not take into account the engineering details of the IEEE 802.11x suite of protocols. We then extend our analytical derivation to capture the carrier sense function of real-world MAC protocols. The essential advantage of our interference model is that the probability of successful reception in the presence of interference is derived exploiting five parameters known locally at each node: node degree, node transmission probability, radio propagation environment, network card reception sensitivity and sender-receiver distance.

To assess the prediction capacity of our analysis under realistic conditions, we evaluate our model against experiments in a real testbed. The results obtained from the testbed show close match with the analytical predictions. Furthermore, we compare our model with another, state-of-the-art model for interference (GMI) [QZW+07], which attempts to capture the details of 802.11x protocols. Notably, both models yield comparable accuracy in predicting the probability of successful delivery. However, our model has distinct advantages over GMI; it is simple, it does not require seed measurements, it can be directly used from network layer protocols and it can accommodate mobility. The steady-state spatial node distribution resulting from a range of mobility models widely used in literature such as the random waypoint [BRS03], random walk, and random direction [NTLZ04] can have a direct use in our model.

Interference-aware Routing

We design and implement an interference-aware routing metric based on our interference model. The goal of our interference-
6.2 Assumptions and Weaknesses

Modeling interference in wireless networks is a difficult problem. The main objective of our interference model is its direct use in routing. Therefore, instead of capturing all the engineering details of MAC protocols and wireless physical layer complex models, our work focuses on their basic properties. For example, our model does not account for the IEEE 802.11 ACKs. Nevertheless, evaluation results in real-world testbed experiments exhibit the accuracy of our model in predicting the probability of successful reception in the presence of interference, in realistic radio propagation conditions and real-world MAC protocols.

First, our model considers the interference at the receiver, but not at the sender node. According to the 802.11 MAC distribution coordination function (DCF), a successful transmission requires the successful ACK reception at the sender. For this, we assume that the probability of unsuccessful ACK reception is very small, since ACK packet size is very small compared with a
data packet. Furthermore, in the QoS-aware enhancement of the 802.11 standard (802.11e), MAC-level ACKs are optional \(^1\) [IEE].

Second, our analytical derivation for the successful packet reception does not explicitly account for the packet size and the transmission rate. Nevertheless, our results suggest that there is no significant change of the probability of successful reception in the presence of interference with packet size. Note that both parameters are implicitly accounted for in the metric computation, where the transmission probability \(\gamma\) is approximated by measuring the time that the medium is busy with transmissions (see Section 5.2.2).

Third, we assume that all nodes are similar and experience the same conditions (uniform node assumption). Allowing for node heterogeneity questions the model tractability. Note that this assumption is common to all analytical interference studies we are aware of. Regarding the metric, we assume node positioning information. Nowadays, as more and more devices are equipped with positioning systems [ZBR02], we expect that this is easy to obtain.

Finally, to derive a close form for the probability of successful reception in the presence of interference, we assume the uniform node distribution. This derivation is also used in our interference-aware metric. The uniform node distribution represents the general case for spatial node distribution including two mobility models (random walk and direction). Furthermore, the propagation model used in the model does not account for fading. In further work, we will relax this assumption.

\(^{1}\)The MAC would not send an ACK when it has correctly received a frame, when the "no ACK" policy is used. This option is proposed to improve the overall MAC efficiency for time-sensitive traffic, such as VoIP, where data has very strict lifetime.
6.3 Future Work

In this section we discuss open research issues. First, the design and development of our interference-aware routing metric for on-demand/reactive routing protocols such as DSR [JM96] and AODV [PBRD03] is a challenging issue. Reactive mechanism to accommodate frequent link metric changes impose additional routing overhead. A prominent solution in this problem is to use a proactive background mechanism for link metrics maintenance as proposed in [DPZ04a].

Second, the experimental evaluation of our model in a larger testbed, including indoor, outdoor and mobile nodes would give more insights on the prediction capacity of our model in a larger set of experiments. Furthermore, a comparison with proposed extensions of ETX in order to obtain a better understanding of our interference-aware routing metric with respect to active probe-based approaches.

Third, in our interference model nodes transmit with the same power. The enhancement of our model with adaptive transmit power control represents an interesting issue that would enable our model to be used also for topology control and efficient power consumption.

Finally, in order to model the effect of a propagation environment on a radio signal, a more realistic radio propagation model such as the Rayleigh fading can be used in our interference model. This would obviously increase the complexity of our model; the tradeoff between complexity and predictability represents an interesting issue.
Appendix A

A.1 Wireless Testbed

In this section, we present the 20-node TIK-Net testbed; the topology, the hardware and the software used.

A.1.1 Hardware, Software, Topology

Topology

TIK-Net consists of 20 personal computers distributed at random spots throughout the G-floor of the ETZ building (Department of Information Technology and Electrical Engineering at ETH Zurich) covering a physical area of roughly 2250 m^2. Figure 4.9 is a snapshot of the exact position of the 20 nodes. Each numbered circle serves also as a corresponding IP alias of the node, which makes it remotely accessible through the ETH wired network (e.g. node 3 can be reached by the alias “tik-wifi3”). The final position of the 20 nodes assures no partitioning in the wireless network and provides full functionality to the user of the TIK-Net testbed.
Hardware

The 20 PCs used can be roughly separated into two categories: i) Dell PCs with 2GHz processor and 512MB RAM memory, and ii) PCs with 866MHz processor and 512MB RAM memory. All of them are currently equipped with the 802.11b/g D-Link G-520 wireless NIC based on the Atheros AR5212 chipset and an external omni-directional antenna.

Software

The operating system selected is GNU/Debian Linux with a Linux kernel version of 2.6.18-4. As already mentioned each node can be accessed remotely through the ETH wired network (e.g. using ssh) using its alias (e.g. ssh tik-wifi5.ethz.ch for accessing node 5). In the current implementation, node 4 (tik-wifi4.ethz.ch) plays the role of a management “server”.

Because the wireless NIC installed in every node of the wireless testbed uses Atheros chipset, the decision of using MADWiFi [ww] (Multiband Atheros Driver for WiFi) was pretty straightforward. In particular, we used the Madwifi-ng (next generation) driver, which is a Linux driver for 802.11a/b/g universal NIC cards - Cardbus, PCI, or miniPCI - using Atheros chip sets. Madwifi drivers are commonly used by the research community because they are open-source and allow for versatile and flexible configuration of the wireless card. It is also widely documented (at least in the context of initial experimentation).

As routing substrate, we installed in each node the Click Modular Router software toolkit [MKJK99]. The Click toolkit is a general purpose software tool for implementing modular router configurations. In the Click toolkit, the “Grid” router element includes the implementation of the DSDV and DSR routing protocols for wireless multihop networks. The routing protocol state information (e.g. routing tables, link tables, ARP caches, etc.)
can be accessed through Click. More details in setting up and configuring of the Click toolkit are provided in [MKJK99].

A.1.2 Link-level Measurements

Performance evaluation using a wireless testbed has some clear advantages against simulation-based experimentations. Simulations often rely on simplified wireless signal propagation models, which have not been validated using today’s wireless radios. Real hardware-based experimentation fills in the gap between conventional assumptions (depending strongly on the accuracy of the models used and the protocol’s code implementation) and real world behavior. However, this does not come without a cost. Setting up a testbed experiment involves a lot of parameters that need to be taken into consideration.

It is exactly in this general context that understanding the wireless behavior of the TIK-Net testbed (link asymmetries) is very important before moving on to analyzing results of higher layers mechanisms (routing and transport protocols). Therefore, we have conducted a set of experiments and processed the collected data to accurately understand the link-level behavior of the TIK-Net testbed.

In order to measure the loss ratio for all possible direct links (19x20 = 380 in total), each node took a turn transmitting 3000 broadcast packets uniformly spread in an interval of 30 seconds. Within these 30 seconds every other node recorded the number of packets received. Each experiment lasted 600 seconds and provided us with the pair-wise link delivery ratios in the following simple way; the delivery ratio from node A to node B is calculated by dividing the packets B received from A to the total number of packets that A sent. Experiments were conducted for different wireless configurations (transmit power: 0, 15dBm, packet size: 180, 1080bytes and transmission rate: 1, 11Mbps). We used 802.11 broadcast packets because they involve no link-level ac-
Figure A.1: Pair-wise delivery ratios at 30mW, 1Mbit/s, small packets

Figure A.2: Pair-wise delivery ratios at 30mW, 11Mbit/s, small packets

knowledgements or retransmissions and effectively capture the actual packet loss rate of a link between two nodes.

Link Asymmetries

In Fig. A.1 and A.2 (where small packets with 100-bytes payload were used) each vertical bar corresponds to both ways of a direct radio link between a pair of nodes; the two ends of each vertical line represent the two delivery ratios of each direct link (one in each direction). The above figures reveal a fundamental charac-
Figure A.3: Pair-wise delivery ratios at 30mW, 1Mbit/s, large packets

Figure A.4: Pair-wise delivery ratios at 30mW, 11Mbit/s, large packets

teristic of real-world wireless networks; the asymmetry between the two directions of a single direct link.

Among the 190 node pairs in Fig. A.1 (1Mbit/s), there are 121 pairs out of 380 that delivered packets in at least one direction. Among those links, 37 are asymmetric with forward and reverse delivery ratios that differ by at least 25%. That is around 30% of the active links that have quite emphasized delivery ratio asymmetry. The respective results for Fig. A.2 (11Mbit/s) are 111 out of 380 active links and 35 (around 31%) asymmetric links.
We can see that the asymmetry remains around the same percentage as for 1Mbit/s. This is something that we expected since only the payload is transmitted at 11Mbit/s (the MAC header is transmitted at 1Mbit/s).

We repeated the experiments using large packet size (1000-bytes payload) and lower transmit power (1mW). The results are presented in Fig. A.3, A.4. For large packet size we observed that the asymmetric links are fewer (percentage-wise) compared to the previous results with small packet size (around 26% for Fig. A.3 and 17% for Fig. A.4). It seems that for large packet size the
asymmetry of the links is less pronounced. Also the transition from low values of delivery ratios to high values of delivery ratios is sharper.

In Fig. A.5, A.6 we present the results for low transmit power (i.e., 1mW). We can see clearly that the number of node pairs with packets delivered in at least one direction is dropped compared to the previous set of experiments with higher transmit power. Low transmit power results in a sparsely connected network and an increased network diameter. Finally, it is also interesting to note that the highest percentage value of asymmetric links (around 33%) occurs for low transmit power (1mW) and small packet size.

Link asymmetry in wireless networks has been also reported from several independent research groups ([ABB+04], [PYC06]). Since 802.11 uses link-level ACKs to confirm delivery, both directions of a link must work well in order to avoid retransmissions. Therefore, link asymmetry becomes an essential design factor for routing protocols of 802.11 wireless networks. Focusing on the results presented in Fig. A.1-A.6, we can easily distinguish links with extreme asymmetry, even zero delivery ratios in one direction and near 80% in the other direction. In such an extreme case and keeping in mind that 802.11 uses MAC-level ACKs, direct communication between two nodes becomes nearly impossible.

Although asymmetric signal propagation is impossible due to the fundamental reciprocity theorem (i.e. if the role of the transmitter and the receiver changes, the instantaneous signal transfer function between the two remains the same), there are a variety of factors that can contribute to link asymmetry. These factors are listed in a comprehensive way in [Jud06]. For example, transmit power differences exist not only between different models of wireless cards, but also among wireless cards of the same model. Likewise, the receiver sensitivity (i.e. the capability of the receiver to decode incoming packets as a function of the received signal strength) can differ significantly between different wireless NICs.
Receiver noise variation in the means of interference variations at the receiver or even the performance of the LNA (Low Noise Amplifier) amplifier can also contribute to link asymmetry. Finally, when there is wireless traffic in the network the spatial distribution of the MAC collisions (due to ineffectiveness of the carrier sense mechanism) can contribute as well to link asymmetry.
Bibliography


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evaluation/ Networks Lab, Communication Systems Group.


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Curriculum Vitae

Georgios Parissidis was born in Kavala, Greece on January 13, 1977. He obtained his high school degree in natural sciences in 1994. His interest in technical sciences motivated him to study Computer Engineering where he received in 2000 his Diploma from the Electronic and Electrical Engineering at the Technical University of Crete Hania (Greece). In 2001 he received a Master’s degree in Communication Networks from the university “Paris 6” in France.

Since 2002, he is with the Communication Systems Group at the Swiss Federal Institute of Technology (ETH Zurich), pursuing doctoral studies. His research interests are in the area of wireless, ad hoc networking.

He worked on various research projects including the design, implementation and evaluation of a synchronous cross-platform e-learning system (ET&L project) and the “Interference-aware routing for wireless multihop networks” project. He was also active in various teaching activities and he setup the first large-scale wireless network testbed at ETH (TIK-Net, http://tiknet.ee.ethz.ch).