DEPARTMENT OF COMPUTER SCIENCE

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

QoS Routing – Discovery and Assessment of Routes with Statistical Minimum Reliability

Author:	Christopher Kohlstruck
1. Advisor:	Prof. Dr. Reinhard Gotzhein
2. Advisor:	M. Sc. Kiran Mathews

Issue Date:	January 2nd, 2018
Submission Date:	August 23rd, 2018

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

Ich versichere hiermit, dass ich die vorliegende Masterarbeit mit dem Thema *QoS Routing – Discovery and Assessment of Routes with Statistical Minimum Reliability* selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe.
Die Stellen, die anderen Werken dem Wortlaut oder dem Sinn nach entnommen wurden, habe ich durch die Angabe der Quelle, auch der benutzten Sekundärliteratur, als Entlehnung kenntlich gemacht.

Kaiserslautern, den August 9, 2018 Christopher Kohlstruck

Abstract

In this thesis a network model based on link reliabilities is defined. In the context of this model, a set of routing metrics is formally expressed. To evaluate the performance of these metrics with respect to route selection bquality, a flexible and modular routing protocol is devised that has support for different routing metrics for route selection. Basic support for QoS requirements is also part of the protocol's specification. Protocol and routing metrics are then implemented in ns-3, and conseqeuently assessed and evaluated in simulated experiments. Performance data is recorded and prepared for different traffic patterns and network topologies.

Contents

1. Introduction

1.1. Task and Motivation

With the rise of the IoT paradigm along with its applications such as monitoring and controlling in industry, home automation or emergency systems and the thereby implied heterogeneity of quality of service (QoS) requirements, research on QoS routing protocols for wireless sensor networks (WSNs) gained new momentum. However, guaranteeing hard real-time constraints for systems that run on top wireless communication topologies poses a great and difficult challenge. Instead, stochastic real-time constraints can be supported.

In this thesis a stochastic network model based on link reliabilities for wireless networked control systems will be developed. In context of this model, several routing metrics to quantify the quality of possible routes will be formally defined, analyzed and implemented. To allow for a detailed evaluation and comparison of network performance under different routing metrics, a simple, modular and extensible routing protocol is developed that in addition supports stochastic guarantees on the minimum reliability of routes. To enable network wide bandwidth management, the routing protocol is compatible with an optional bandwidth management layer. In a last step, the routing metrics are evaluated along with the routing protocol in context of exhaustive simulation experiments of different scenarios on randomly generated topologies. The effects on the network's performance with enabled bandwidth management are also examined.

1.2. Objective and Structure of the Thesis

Subsequent to this introduction, Chapter 2 of the thesis will provide an overview of the current state of research and related works. In Chapter 3 the network model as well as the routing metrics to be assessed will be formally defined. This theoretical chapter is followed by the specification of the stochastic QoS routing protocol along with descriptions of its core mechanisms in Chapter 4. Chapter 5 will provide details on the setup and execution of the simulation experiments, along with an introduction to the framework used to carry out the simulations as well as its configuration. A thorough evaluation and analysis of the experiment's results regarding the performance of the different routing metrics and the whole protocol is given in Chapter 6, followed by thoughts on future work and the conclusion in Chapter 7.

2. Related Work

In this chapter an introduction into related research is given. First an overview on routing in wireless sensor networks is provided. Different classes of routing protocols are introduced, along with examples. Section 2.2 covers the important subject of routing metrics, a concept tightly coupled with routing functionality. Advances regarding quality of service (QoS) in IEEE 802.11 networks are covered in Section 2.3.

2.1. Routing in Wireless Sensor Networks

To direct communication over large networks, routing is the key functionality [5]. Due to the high number of different applications for wireless sensor networks, finding a single routing protocol well suited for every application is very difficult. Hence, over several years of intensive research, many different routing protocols designed for the specific requirements of wireless communication emerged [12], each tailored to a specific domain of applications. In [3, 4, 2, 16] extensive surveys on architecture, applications and communication protocols for wireless sensor networks (WSNs) are provided. The demands and challenges posed on routing protocols are vast and diverse. On the one hand, many applications require a minimum quality of service with respect to latency, reliability, jitter or bandwidth [11]. A network might also consist of several different types of nodes, varying in power, battery size or other capabilities (a so-called heterogeneous network). An especially hard challenge to the routing protocol poses node mobility. In addition and most importantly from an economical point of view, energy efficiency is a key requirement as the batteries of already deployed devices are usually not replaced.

The routing protocols in literature can be classified according to how the task of satisfaction of these diverse requirements is tackled. One can differ between *Data-centric Protocols* such as SPIN [14] or Shah and Rabaey's energy aware routing protocol introduced in [22]. In these protocols routing is data-centric, meaning queries are made for specific data instead of sensor nodes. Another important class are *Hierarchical Routing Protocols*. Here, clusters are formed to aggregate data and minimize energy consumption. Well-known members of this class are LEACH [13] and its derivatives such as PEGASIS [18] or TEEN [20]. *Location-based Routing Protocols* leverage location information to efficiently route packets, this makes protocols such as GEAR [26] and GAF [24] especially well-suited in combination with mobile nodes.

Routing protocols that are specifically designed to handle more constrained traffic e.g. in wireless multimedia sensor networks (WMSN) typical to the internet of things (IoT), can be categorized similarly [11]. However, a classification according to the type and number of QoS constraints each protocol considers is also viable [11].

2.2. Routing Metrics

In routing protocols, the optimal path is determined based on routing metrics [5]. For Ad Hoc networks, the hop count metric usually is chosen, as new paths need to be found rapidly [7]. High-quality routes, as they result from more complex metrics, might not be found in due time. Whenever node mobility is excluded however, the static topology benefits these more complex, quality-aware routing metrics [15]. With a bigger complexity budget, the requirements of QoS routing can be granted more attention.

The set of routing metrics available in literature is large and diverse. Each metric constitutes a more or less unique combination of design goals, factors of influence, mathematical properties and implementation characteristics [5]. For example, the well-known hop count metric aims to minimise the number of hops (design goal), is determined mainly by influences external to the network such as node placement and overall interference (factors of influence), uses addition as concatenation operator (mathematical properties) and can be implemented on either data link or network layer using active probing or passive deduction to acquire information (implementation characteristics) [5]. This approach to characterizing routing metrics is only one among many, which emphasizes the diversity and vastness of routing metrics as a field of research.

Apart from characterizing each routing metric to facilitate comparison, a consistent categorization of routing metrics is important to be able to choose the possibly best of many options. In [5], the categories suggested are:

- *Traffic-based metrics*: such as delay or queue length and packet loss ratio. Also ETX and ETT, of which derivatives are used in this thesis, are considered traffic-based.
- *Radio information*: for example signal-to-noise ratio or medium time.
- *Topology*: Metrics such as hop count or the number of paths to a node belong to this category.
- *Geography*: Examples for this category are geographic distance and movement speed of a node.

- *Energy-based*: The current battery level is the obvious example here, energy consumption per packet is another one.

Of course not every routing metric is equally well suited to satisfy a set of QoS requirements. The most obvious example probably being hop count, as its value is fixed in any immobile network and cannot reflect any dynamic of runtime characteristics such as delay or delivery rate. The question of which combination of metrics in a routing protocol is benificial to supporting QoS requirements is one aspect this thesis aims to shed some light on.

2.3. Best-effort and QoS Routing in IEEE 802.11

As this thesis uses the IEEE 802.11 Wireless Communication Standard [1], only research applicable to this technology will be covered in this section. IEEE 802.11 itself was developed as a simple and cost-effective wireless technology for best effort services [27]. Hence, any assertions regarding reliability – much less hard QoS guarantees – cannot be expected. There exist various proposed solutions to provide QoS mechanisms for 802.11. The main concepts used by these solutions can be summarized as follows:

- *Service differentiation*: Using priorities and fair scheduling, one can achieve a better than best effort service [27]. Hard QoS guarantees however, can not be achieved by these enhancements. Using prioritization, channel access is bound to different traffic classes. Fair scheduling is achieved by regulating wait times based on traffic classes. In scenarios with high traffic load, performance of service differentiation is lacking due to the inefficiency of IEEE 802.11 MAC [17].

- *Admission control and bandwidth reservation*: Under increased load, where service differentiation does not perform well, better results can be achieved by adding reservations. However, in wireless networks, as the exact network condition at a given time is unknown and the medium is accessed using contention-based CSMA/CA mechanism, precise provisioning of bandwidth is not possible. Consequently, this leads to only soft QoS guarantees.

- *Link adaptation*: By adapting transmission rates and signaling mechanisms to the channel quality, thoughput can be maximized under dynamic channel conditions. IEEE 802.11 does not specify mechanisms for rate adaptation [1, 27], which provides potential for optimiziation through solutions external through the standard. Most works use either SNR, RSS, average payload length, acknowledgements or combinations of those as metrics to control transmission rates.

But for all that, QoS with respect to 802.11 still has potential for improvement for many applications and scenarios.

2.4. Stochastic Routing

The term *Stochastic Routing* is very different from the topic of this thesis, which covers routes with a statistical minimum reliability. In the literature, stochastic routing is the concept of routing a packet stochastically over different paths. One of the first works on this topic is [19], where probabilistic local broadcasts are used to transfer a packet. The next hop depends on the stochastic result of a node's local broadcast transmission. The actual route taken by a packet is fully determined only via actual transmission and depends on random system events. This mitigates congestion and balances power consumption among the nodes of the network.

In [23], the movement of each packet is modelled as a random walk. Transition probabilities are assignmed based on a set of requirements: Load distribution, convergence, meaning moving the packet closer to the destination and guaranteed delivery. The core concept of their modeling framework are Markov chains [6].

3. Concepts

In this chapter, the formal concepts that form the base for this thesis are introduced. A network model is developed to capture the concept of link reliabilities as weighted edges in a graph. This network model is detailed in Section 3.1. Subsequently, in Section 3.2, each routing metric is formally defined, based on the terms established in the network model. Definitions of the global network performance metrics in Section 3.3 used to evaluate the performance conclude this chapter.

3.1. Network Model

First, a network model is required that captures the notion of link reliabilities. Then, the notation required in the rest of this work is introduced. At the end of this section some terminology is established to disambiguate concepts such as packet, frame and transmission.

3.1.1. Definition

As usual, the network is modelled as a graph. Instead of the traditional definition of a graph, as a set of nodes and a set of edges, a set of nodes and a function will be used. The purpose of this function is to map pairs of nodes to reliabilites. An edge between two nodes is defined as the special case where the function returns a value greater than zero for these two nodes.

Let $G := (V, r)$ be a structure with

- V: the set of nodes
- r: a function defined as $r\colon (V \times V) \to \mathbb{R}_{[0,1]}$ where $r(v,u) \in \mathbb{R}_{[0,1]}$ denotes the probability for successful single-hop delivery of packets between nodes $v, u \in (V \times V)$ (reliability).
  - *Alternative notation:* $r\colon E \to \mathbb{R}_{(0,1]}$, where $r(e) \in \mathbb{R}_{(0,1]}$ denotes the probability for successful single-hop delivery of packets over link $e \in E$, in short r_e. Note: r_e can never be 0.
- E: $\{(u,v) \in (V \times V) \mid r(u,v) > 0\}$, the set of edges.

Based on this graph definition, the concept of paths is defined as follows, along with syntax to directly refer to length, individual edges and an individual edge's reliability of a path.

- $< v_0, v_1, \ldots, v_n >$ with $v_0, v_1, \ldots, v_n \in V$ and $\forall i \in [1, n]\colon (v_{i-1}, v_i) \in E$, is a cycle-free path from node v_0 (source) to node v_n (destination).
- l_p: the length $\mid p \mid = n$ of path $p = < v_0, v_1, \ldots, v_n >$, i.e. the number of links.
- $e_{p,i}$: i-th edge in path p. $e_{p,i} := (v_{i-1}, v_i)$, with $p = < v_0, v_1, \ldots, v_n >$
- $r_{p,i}$: reliability of link e_i, with $e_i = (v_{i-1}, v_i) \in E$ of a given path $p = < v_0, v_1, \ldots, v_n >$.

The notation provided in the table below is used to facilitate the definitions of the routing metrics in the next section.

Notation	Meaning
$r_{p_{min}}$	A configurable requirement. The minimum reliability of a path to be considered for a route.
$r_{e_{min}}$	A requirement, derived from $r_{p_{min}}$. The minimum reliability of each link in a path p such that p can be considered for a route.
$r_p = \prod_{i=1}^{l_p} r_{p,i}$	Aggregated reliability of a path p.
$ETX_e = 1/r_e$	Expected number of transmissions over link e
$ETX_p = \sum_{i=1}^{l_p} ETX_{e_i}$	Average number of transmissions for success over path p
$MTX_e = \underset{n \in \mathbb{N}}{\arg\min}\ 1 - (1 - r_e)^n \geq r_{e_{min}}$	Minimum number of transmissions to achieve $r_{e_{min}}$ over link e
$\mu_{r_p} = \frac{1}{l_p} \sum_{i=1}^{l_p} r_{p,i}$	The mean reliability of path p
$\sigma_{r_p}^2 = \frac{1}{l_p} \sum_{i=1}^{l_p} (r_{p,i} - \mu_{r_p})^2$	The empirical variance of the reliability of path p

3.1.2. Terminology

The following terminology is used throughout the thesis. Note that some terms overlap with the ones established in the network model (see Section 3.1.1). A path in the network model may serve as a route during simulation. In the same way, an edge in the network model is considered a link in the simulation.

Packet A packet is a piece of data, wrapped by layers of processing information. It is created on the application layer and then processed and subsequently passed down by all layers of the network stack. A packet can be transmitted in one or more *frames*,

Frame A frame is a data *transmission* unit on the physical layer. It is the smallest communication unit of relevance for this thesis.

Transmission A transmission is the process of sending a *frame* over a *link* between two nodes for the first time.

Retransmission A frame that contains the same information as the previous frame is sent over the same link between two nodes.

Flow A flow is a sequence of *journeys* of *packets* that travel along a *route* between two nodes of the network.

Journey A sequence of *transfers* of a single *packet* along a *route*.

Transfer A sequence of one or more *transmissions* (and *retransmissions*) of *frames* over a *link* in order to deliver a *packet*.

Route A sequence of *links* connecting two nodes in the network.

Link Two nodes have a link between them if and only if they are in transmission range of each other's transceivers.

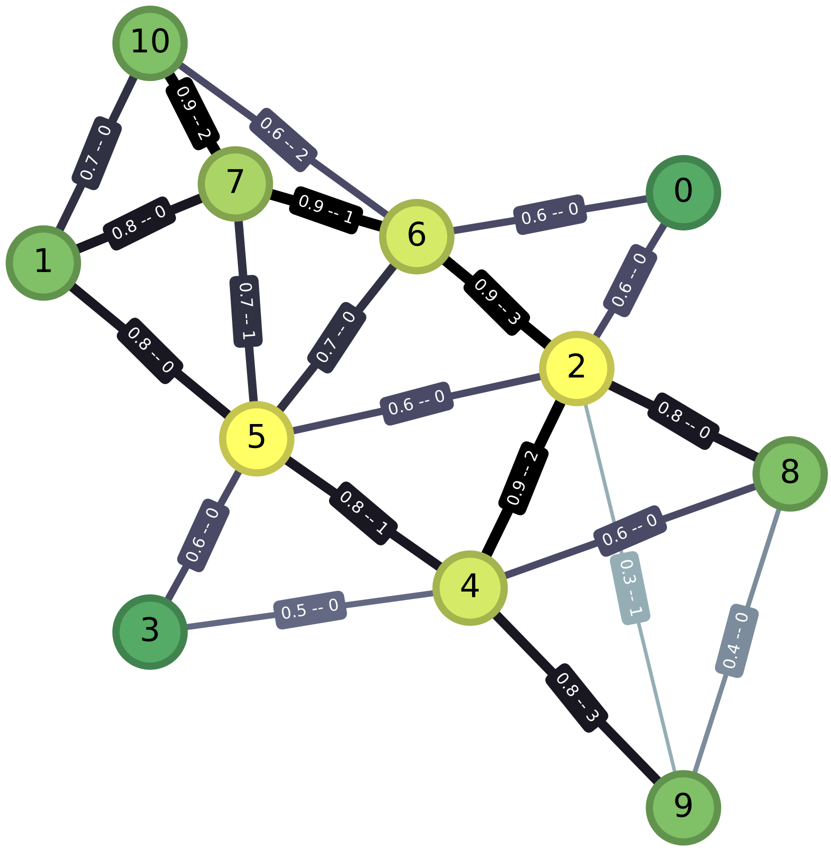

Figure 3.1.: Example graph to demonstrate route selection. The edge annotations are the respective link reliabilities and the usage statistic. The label [0.8 - 4] means that the link has a reliability of 0.8 and that four transmissions were made using this link.

3.2. Routing Metrics

In the context of routing in network systems, a routing metric defines a measure for the quality of a connection when using a specific route. With respect to the quality this may include any factors of interest that influence the preference for a route such as latency, bandwidth or hop count. Whether a high numeric value corresponds to high or low quality routes is defined by the metric. The selection process for a route generally reduces to a minimization or maximization over the used routing metric's quality value. In this section, the routing metrics examined in this thesis are introduced and formally defined. The corresponding selection process for each metric is also defined. In this model a route is selected from a list of candidate paths P, the path selected in the end is called p^+.

To give an example of how each metric works and to support the development

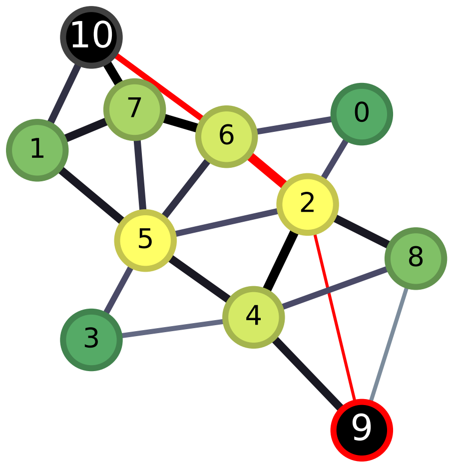

Figure 3.2.: The route as chosen by *HC*

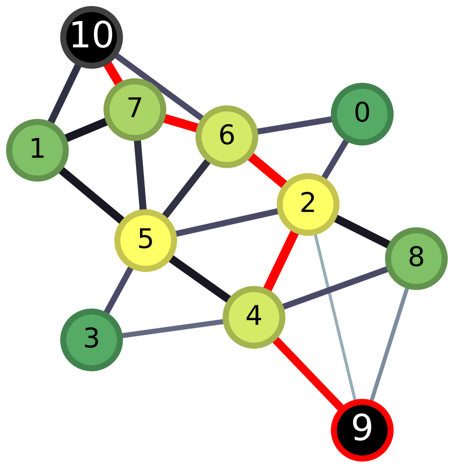

Figure 3.3.: The route as chosen by *PR*

of an intuition, Figure 3.1 depicts a simple exemplary network which will be used to visualize the route resulting in the best quality value for each metric. The line weight and darkness of a link in the plot increases, the higher a link's reliability. The first value in each link's label shows the exact reliability. The second value in the label shows the number of usages of this link, this value is also used by some of the metrics. The color of the node turns from dark green to yellow, the higher the degree of a node. Along with the definition of most of the metrics, an exemplary figure is given that shows the route that would result from this metric in the example graph in Figure 3.1, based on a route request for a packet from node 9 to node 10. The chosen route is marked with red, the source node is black with a red circle, the destination node is just black.

3.2.1. Hop Count

The hop count metric *HC* measures the number of hops required to send a packet from one node to another. This makes *HC* a purely topology based routing metric. When selecting routes based on this metric, the route with the lowest hop count will be picked, see Figure 3.2. This leads to a minimal number of nodes involved in the journey of a packet through the network which may reduce latencies and used bandwidth. On the other hand, link reliabilities do not influence the selection at all. As a consequence, application of *HC* usually results in routes with weak, long-distance links (see link `[9,2]` in Figure 3.2) and a poor path reliability value.

$$HC(p) = l_p$$
$$p^+ = \arg\min_{p \in P} HC(p)$$

3.2.2. Path Reliability

The path reliability metric PR uses the product of the reliabilities of all links of a route as the quality value. The route with the highest product is selected. Similar to ETX, reliable links are preferred and the actual length of a route is ignored. The product of the reliabilities corresponds to the probability that the packet will travel the complete journey along the route without retransmissions, so PR is a traffic based metric [5]. Links of very high reliability are practically free to use in the context of this metric. As 1.0 is the multiplicative neutral element when calculating the metric's value for a route, adding links with reliability of 1.0 does not affect the result, although the route's length increases. As a consequence, this characteristic may lead to detours over highly reliable links.

$$PR(p) = r_p$$
$$p^+ = \arg\max_{p \in P} PR(p)$$

3.2.3. ETX

ETX is a common choice for quality-based routing in WSNs [5, 7]. In fact, ETX probably was the first metric specifically designed for mobile ad hoc networks (MANETS) [5, 8].The definition given in the literature needs to be adapted to the network model used in this study, but is semantically analagous.

The expected transmission count metric ETX uses the (stochastic) expected value for the number of transmissions to transfer a packet from one node to another. This is a traffic based metric value [5]. The route with the minimum ETX is selected, see Figure 3.4. Similar to HC, this leads to a preference of short routes, while incorporating the quality of links. A bad link that leads to many retransmissions is likely to be avoided when using ETX. On the other hand, highly reliable links are preferred, which may lead to congestion especially in the center of the network [5].

$$ETX(p) = ETX_p, \text{ (see Section 3.1.1)}$$
$$p^+ = \arg\min_{p \in P} ETX(p)$$

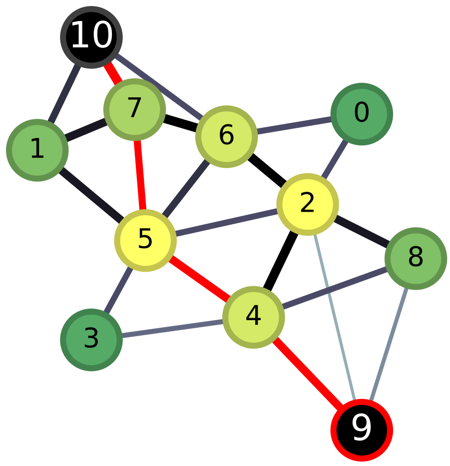

Figure 3.4.: The route as chosen by *ETX*

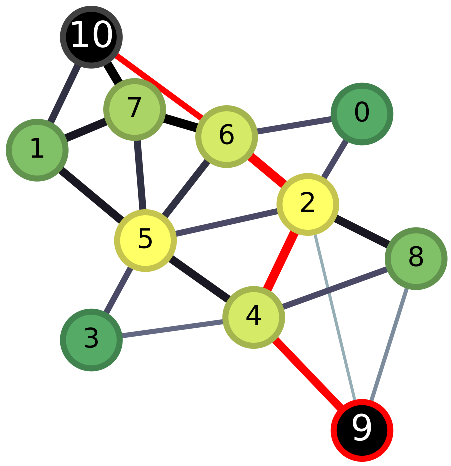

Figure 3.5.: The route as chosen by *MTX*

3.2.4. MTX

The minimum transmission count metric MTX counts the minimum number of transmissions needed to achieve a certain reliability $r_{p_{min}}$ over a route. We call the attribution of extra transmissions to a link *boosting*. For example, a route over a single link of reliability $r = 0.7$ between two neighboring nodes and a value for $r_{p_{min}}$ of 0.9 requires one extra transmission on average. In other words, we sacrifice latency for reliability and pretend the route has two hops and an r_p of 0.9.

To find the minimum number of transmissions needed to match a given reliability target for a single link is straight forward, see the formula for MTX_e given in Section 3.1.1. However, MTX is defined for routes. For the resulting value to be the minimum, we need to maximize the effect of each extra transmission, hence the weakest links are boosted first. The algorithm to calculate MTX works then by boosting the weakest link in the route until the specified $r_{p_{min}}$ is satisfied. An example implementation in pseudocode can be found in Listing A.1. The route with the least number for transmissions plus boosts is selected, see Figure 3.5.

$$p^+ = \arg\min_{p \in P} \; MTX(p)$$

3.2.5. ETT

The expected transmission time metric ETT combines the already introduced ETX metric (Section 3.2.3) with the notion of available bandwidth [10]. The resulting quality value is the ratio of the expected number of transmissions to the available bandwidth. This is expected to lead to an increased usage of less overloaded links compared to plain ETX [10]. As available bandwidth is a runtime characteristic, an example is not provided here. If the available bandwidth is constant for all links in the network, ETT is equivalent to ETX (see Section 3.2.3).

$$
\begin{aligned}
b_e &:= \text{TX time currently available over link (or edge) } e \\
b_p &:= \frac{1}{l_p - 1} \cdot \sum_{i=0}^{l_p - 1} b_{e_{p,i}} \\
ETX(p) &= \sum_{i=1}^{l_p} ETX_{e_i} \\
p^+ &= \operatorname*{arg\,min}_{p \in P} \ \frac{ETX_p}{b_p}
\end{aligned}
$$

3.2.6. MTT

The minimum transmission time metric MTT combines the already introduced MTX metric (Section 3.2.4) – by the same mechanism as ETT – with the notion of available bandwidth. The ratio of minimum number of transmissions to match a required reliability to the available bandwidth on that link is the resulting quality value of a route when MTT is applied. The expected effect is the same as in using ETT over ETX: the links selected should be less overloaded compared to using plain MTX. With available bandwidth being a runtime characteristic, an example is not provided at this point. For constant available bandwidth on each of the network's links, MTT is equivalent to MTX.

$$
\begin{aligned}
b_e &:= \text{TX time currently available over link (or edge) } e \\
b_p &:= \frac{1}{l_p - 1} \cdot \sum_{i=0}^{l_p - 1} b_{e_{p,i}} \\
MTT(p) &= \frac{MTX_p}{b_p} \\
p^+ &= \operatorname*{arg\,min}_{p \in P} \ MTT(p)
\end{aligned}
$$

3.2.7. Link Usage

The link usage metric LU sums the number of usages of each link of a route, The route with the least sum of usages is selected, see Figure 3.6. As the sum is

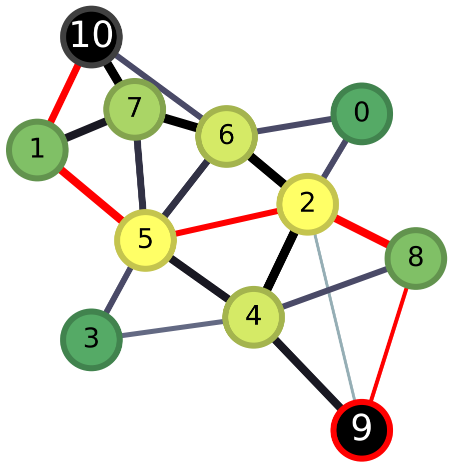

Figure 3.6.: The route as chosen by *LU*

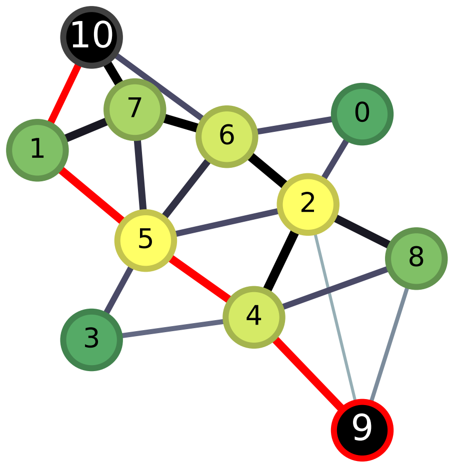

Figure 3.7.: The route as chosen by *NU*

used to aggregate link usage values (not the average), *LU* is also likely to select shorter routes. The usage counter of each link is incremented whenever a transmission takes place. Hence, failed (not received) transmissions also increment the counter. The intention behind this metric is that links not used much might be less congested, have small queues and might connect nodes with still good battery. Application of this metric should result in a balanced usage of links in the network.

$$
\begin{aligned}
u_{p,i} &:= \text{usage of link } i \text{ of path } p \\
LU(p) &= \sum_{i=1}^{l_p} u_{p,i} \\
p^+ &= \operatorname*{arg\,min}_{p \in P} \; LU(p)
\end{aligned}
$$

3.2.8. Node Usage

The node usage metric *NU* sums the number of usages of each node of a route. This is in analogy to the *LU* metric. Failed transmissions increment the usage counter for both, the sending and receiving node. Intention and expected effects of *NU* are as described for *LU* (see Section 3.2.7). In the case of constant packet size, the *NU* metric values allow for inference on the remaining battery capacity. Among the metrics analyzed in this thesis, *NU* comes closest to what can be described as an energy-based routing metric.

$$
\begin{aligned}
u_{v_i} &:= \text{usage of a node } v_i \\
NU(p) &= \sum_{v_i \in p} u_{v_i} \\
p^+ &= \underset{p \in P}{\arg\min}\ NU(p)
\end{aligned}
$$

3.3. Global Metrics

Whereas routing metrics are applied to a path and provide the user with a notion of its quality, they cannot be used to evaluate global network performance. A set of well-defined global network performance criteria (or global network performance metrics) is required to compare network performance under application of different routing metrics.

During execution of the experiments, various statistics on network performance and behaviour are recorded such as the point in time for each transmission, source and intended destination or whether the transmission was successful or not. Retransmissions and the selected route are also recorded. From these statistical records, values for global performance metrics can be calculated. The latency of a journey for example can be calculated by extracting the timestamps for start and end of the journey.

Network performance criteria In the following paragraphs a list of definitions of network performance criteria, which will be used for network performance evaluation, is given. Let $j_{s,d}$ with $s, d \in V$ be a journey from node s to d and let J be the set containing all the started journeys in the network. Also, let $J_{succ} \subseteq J$ be the set containing all successfully finished journeys. To define the performance criteria, the following functions are used:

$\tau_t : J \to \mathbb{N}$	timestamp of the start of a journey
$\tau_r : J \to \mathbb{N} \cup \infty$	timestamp of the reception of the last packet of a journey at the final destination node, or ∞ if the packet was not successfully delivered
$n : V \to \mathbb{N}$	number of transmissions performed by a node
$n_{bytes} : V \to \mathbb{N}$	bandwidth used by a node
$n_{bytes,\ avail} : V \to \mathbb{N}$	total bandwidth available at this node during the experiment
$n_{failed} : V \to \mathbb{N}$	number of failed transmissions performed by a node

Based on these functions, we can define the following network performance metrics:

Average latency The average latency of successful journeys. With increasing network load and potential for congestion, smart route selection is required to keep latencies low. A short delay between the start of a packet's journey and its end is a common requirement of applications and therefore an established route performance and quality criterion. The average delay of all packet journeys in a network with routes selected using a specific metric is used as one of the global network performance metrics in this thesis. As the latency of failed journeys is undefined, they do not influence this statistic.

$$D_{e2e,avg} = \frac{1}{\mid J_{succ} \mid} \sum_{f \in J_{succ}} (\tau_r(f) - \tau_t(f))$$

Average number of retransmissions A high number of retransmissions indicates waste of bandwidth, long latencies, and increased energy consumption. As a consequence, a good routing metric should result in a low number of retransmissions. However, a high number of failed journeys shadows this metric for long routes.

This effect might become clearer with help of an example: Metric m_1 results in a successful journey over a route r_1 of 12 hops, with a total of 7 retransmissions. Another routing metric m_2 results in a route r_2 that fails on the first hop, after only 3 retransmissions. With respect to the number of retransmissions r_2 is preferrable over r_1. However, m_1 results in a clearly better route. As a consequence, the number of failed journeys should be considered first, before consulting the number of retransmissions.

$$N_{reTX,avg} = \frac{1}{\mid J \mid} \cdot \sum_{v \in V} n_{failed}(v)$$

Standard deviation of transmissions on nodes To increase the lifetime of the network and to minimize congestion, a balanced distribution of transmissions among the nodes in the network is desirable. One possibility to capture the quality of this distribution is to calculate the standard deviation of the transmission counters of the nodes in the network. A high standard deviation indicates an unbalanced distribution of transmissions among the network's nodes. For this metric to be conclusive, a sufficient number of transmissions among a sufficient number of nodes is required. A low rate of successful journeys may lead to a lower (and better) standard deviation for a metric, which is why the number of successful journeys should be consulted first.

$$\mu = \frac{1}{\mid V \mid} \sum_{v \in V} n(v)$$
$$\sigma_{Tx}^2 = \frac{1}{\mid V \mid} \sum_{v \in V} (n(v) - \mu)^2$$
$$\sigma_{Tx} = \sqrt{\sigma^2}$$

Rate of successful journeys A failed journey indicates the failure of a route which is an obvious consequence of a bad route selection. A routing metric that gives no route for a pair of nodes is considered favorable to a metric which results in a route that results in a failed journey.

$$P_{succ} = \frac{\mid J_{succ} \mid}{\mid J \mid}$$

4. Stochastic QoS Routing Protocol

The final goal for this protocol is to provide stochastic real-time constraints regarding latencies, delivery rates and bandwidth usage. In this first specification, a modular and extensible protocol architecture is introduced with the purpose to assess the applicability of a network model based on stochastic link reliabilites for route selection. In addition, first promising concepts towards the provision of stochastic real-time constraints are incorporated.

In this chapter, the specification of the devised stochastic QoS routing protocol is given in Section 4.1. As the protocol does not cover the distribution of network status information for decentral routing deicisions, the concept of a central coordinator is introduced in Section 4.2. The mechanisms actual route selection comprises of are covered separately in Section 4.3.

4.1. Protocol Specification

As of the OSI model, the *network layer* is where routing and forwarding of packets take place. Routing is done whenever a packet with some payload is passed from the transport layer down to the network layer: A route through the network to the packet's destination is determined, the next hop (or the full route) is embedded in the packet, and the packet is passed on down to the data link layer.

Forwarding is done when a packet is passed from a lower layer up to the network layer. If the current node is not the final recipient of the packet, the packet is sent further (handed over to the next lower layer in the network stack) along the route embedded in the packet.

This is the general approach to routing and forwarding and its implementation into this protocol is very similar.

4.1.1. Routing

This is the case where a packet `pkt` is created at the top of the network stack (see Figure 5.1), passes the stack from top to bottom and consequently reaches the network layer (and this routing protocol) from the top. A new packet `out_pkt` is created and the whole packet `pkt` is copied to the `out_pkt.payload` field (see Table 4.1). The `out_pkt.destination` and `out_pkt.source` fields are set

Table 4.1.: Packet Format

Field	Size	Content
`payload`	variable	Payload data, passed from upper layers
`destination`	fixed	Address of the destination note
`source`	fixed	Address of the source node
`id`	fixed	Unique ID of this packet
`next_hop_list`	variable	List of addresses of next hops (the route)
`mtx_list`	variable	List of MTX values for each link along the route

to `pkt.destination` and `pkt.source`, respectively. Also, a new unique ID is generated and stored in `out_pkt.id`. As the current node is the originator of the packet, no route to the destination node is established, yet. So a route to the identifier in `pkt.destination` is requested, obtained (described in detail in Sections 4.2 and 4.3) and stored in the `out_pkt.next_hop_list` field. This field is a list of node identifiers of variable length, where each element has a fixed size, equal to the length of a node identifier. The `out_pkt.mtx_list` field is filled with the MTX_e value of each link of the obtained route.

Now, all fields specified in Table 4.1 are populated and the packet is passed onto the next layer. The packet will then be processed by a MAC layer implementation and transmitted to the node specified in `out_pkt.next_hop_list[0]`, with a maximum number of tries as stated in `out_pkt.mtx_list[0]`.

Intention of the `mtx_list` Field The `mtx_list` is a key component to the QoS aspect of the protocol. The field in the Stoachstic QoS Routing Protocol header is used to control on which links how many retransmissions may be used to deliver a packet. For example, if some links on the route are significantly less reliable than previously determined (e.g. through collisions), more retransmissions are required to deliver the packet. However, these retransmissions increase latency and bandwidth usage. By restricting the total number of retransmissions for a route, an upper limit for runtime latency (soft, as e.g. backoff due to congestion is not incorporated) and bandwidth usage (hard) is created. In this context, the number of potential retries can be pictured as a resource that is bought with latency. The more retries are granted to the links of the route, the higher the upper limit for the latency will be (excluding waiting time due to congestion). The resource is invested into links to maximize the route's reliability. An equal distribution among all links would be a bad investment, as reliable links would seldomly deplete their retry budget whereas less reliable links would benefit from additional retries. Hence, the retry budget is invested with respect to each link's reliability. To satisfy the QoS requirement of a statistical minimum route reliability, the protocol invests just enough retries to satisfy this requirement. If a route's reliability during operation deviates too far from what was anticipitated during the selection process, the route will fail, as the retry budget is depleted. This is intended, as the assumptions during the selection process are now likely to be inaccurate, which also invalidates the guaranteed path reliability. As a consequence, a new route has to be selected.

4.1.2. Forwarding

This is the case where a packet `pkt` is received at the bottom of the stack and traverses the stack from bottom to top. So the network layer, where routing and forwarding is handled, is invoked from a lower layer. At this point, the `pkt.destination` field is checked; if the current node is the final recipient, the packet is simply passed on up to the next layer. If the destination is different, the packet is forwarded along the route specified in the packet's fields. All the information required to process the packet is available. The payload field `pkt.payload` is extracted and read into a structure `s`, which matches the expected packet format (see Table 4.1). The first entriy of each of the two list fields, namely `next_hop_list` and `mtx_list` is removed. These values correspond to the last link the packet was transferred on and are no longer valid. Then, a new packet `out_pkt` is created with all fields set as specified in the structure `s`, that was used to parse the wrapped packet.

All fields are now set correctly and the packet is passed down to the next layer. Just as described previously in Section 4.1.1, the packet will be transmitted to `out_pkt.next_hop_list[0]`, with a maximum number of tries as set in `out_pkt.mtx_list[0]`.

4.2. Central Coordinator

The protocol specification does not cover the distribution of routing information, as this is out of the scope of this thesis. For the implementation and the experiments an all-knowing central coordinator is assumed. This central coordinator has full knowledge of every aspect of the network such as topology and link reealiabilities. It can also access runtime information, for example usage counts of links and nodes or the amount of available bandwidth at each node. The central coordinator implements all the routing metrics defined in Section 3.2. Currently, all route requests are handled by this central coordinator. It also provides the nodes with the MTX_e values for the `mtx_list` field in the packet header, as the complete information needed to calculate the MTX_e values exists only at the coordinator. In our framework, access to the central coordinator to request routes etc. is instant and without cost for a node.

Table 4.2.: Protocol Configuration Parameters

Parameter	Value	Description
`minimumLinkReliability`	0.1	Minimum link reliability required for a link to be considered for routing.
`numCandidatePaths`	128	Size of the initial path candidate set where routes are selected from.
`candidatePathLengthFactor`	2.0	Factor that results in the maximum length of a route when multiplied by the length of the shortest path between two nodes.
`targetPathReliability`	0.9	Target reliability each route should match. Also a parameter for MTX

The protocol is designed and implemented in a way, that allows for the central coordinator to be replaced by decentral routing mechanisms at a later stage.

4.3. Route Selection

The route selection algorithm basically consists of three steps (see also Figure 4.1): First, a set of candidate paths is generated. Second, this set is filtered. Third, from the filtered set of candidate paths, the optimal path with respect to the routing metric is selected.

The algorithm is executed by the central coordinator upon request of a route by one of the nodes. Selection takes place among a set of candidate paths, as selection among *all* paths between two nodes is not feasible. In fact, the number of possible paths between two nodes in a network grows so fast with the network's size, that even listing all paths is an NP-complete problem. Hence

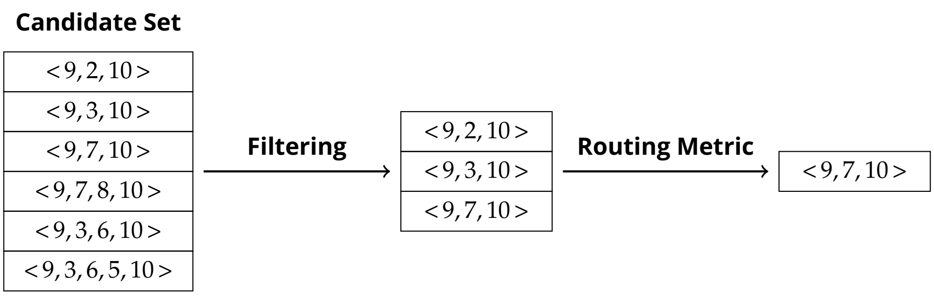

Figure 4.1.: The route selection process.

it is necessary to limit the number of paths in the candidate set. The way the candidate path set is created is important, as paths which are not part of the set cannot be selected, even if they were optimal with respect to the current routing metric.

As hop count is a metric that has very low computational overhead and usually fits well with path finding algorithms such as Dijkstra's algorithm [9], hop count was chosen as the criterion by which candidate paths are selected. Using Yen's algorithm [25], the k-shortest paths between source and destination node are calculated, with k being configurable. In the simulations, k was set to `numCandidatePaths` (see Table 4.2). If the number of paths between source and destination in the network is lower than `numCandidatePaths`, the k-shortest paths algorithm stops and the route selection process continues with the filtering step (see Figure 4.1). Links that do not exhibit a reliability of at least `minimumLinkReliability` (see Table 4.2) are not considered for routing.

After the candidate set is generated, it is filtered. Filtering is useful to enforce specific route characteristics. For example, a path might be preferred due to its superb reliability by some metric, although its length exceeds that of the shortest path fourfold. Depending on the application it may be desirable to trade a shorter route length for more retransmissions. Another important aspect is that candidate path filtering can be used to satisfy further QoS requirements. All candidates that do not match the requirements are identified and removed from the candidate set. Among the remaining paths in the set, the final route can then be selected based on any metric, as the QoS requirements are satisfied by all of them.

Before filtering, the set of candidate paths contains (at most) `numCandidatePaths` many shortest paths between the source and destination of the route request. Each link that is part of a path in this set satisfies the `minimumLinkReliability` requirement. Among these k-shortest paths, first the ones which length exceeds the length of the shortest path multiplied by the factor `candidatePathLengthFactor` (see Table 4.2) are filtered. This way, paths that take long detours to achieve e.g. high reliability are discarded. When configuring this `candidatePathLengthFactor`, one has to consider the possibility that source and destination might have a direct link between them. This results in a shortest path length of 1. The direct link however might be highly unreliable, which is why the set of possible alternative paths should not be constrained too much by `candidatePathLengthFactor`. A value of 2.0 is the smallest value that lead to viable results in the simulations. When source and destination are connected directly as described above, a factor of 2.0 allows all candidate paths with a length up to 2.

For the simulations in this thesis, candidate paths are only filtered by length. Additional filters can be added, and are likely to improve network performance further. The final selection of a route is done using one of the routing metrics introduced in Section 3.2. Which metric is used can be freely configured. As this aspect of the protocol is a self-contained module, any routing metric is supported. With the configured routing metric, each candidate path's metric value is calculated. Afterwards, the path which is optimal with respect to the metric is chosen. The requesting node then embeds this route in the packet as specified in Section 4.1.1 and begins the transfer of the packet.

5. Experiments: Setup and Execution

To evaluate and analyze the stochastic QoS routing protocol introduced in Chapter 4, the protocol was implemented as a protocol layer in the network simulator ns-3. Experiments were carried out on several randomly generated networks of sizes from 20 to 40 nodes. In this chapter, the simulation framework implemented in ns-3 is introduced in Section 5.1. Then, in Section 5.2, the process to determine the network's link reliabilities is explained, along with a description of the propagation loss model used in the simulator. In Section 5.3, the concept of transmission schedules is introduced, followed by Section 5.4 covering the actual experiment execution.

5.1. Simulation Framework in ns-3

ns-3 is an open-source, discrete-event network simulator for internet systems targeted primarily at research and educational use. Most areas of computer networking are covered such as IPv6, WiFi or 6LoWPAN. Various simulation models e.g. for mobility and energy consumption are also available. The architecture of ns-3 suggests the following simulation workflow:

- **Topology definition:** Define position of nodes.
- **Model development:** Define and configure models for propagation loss, delay, etc.
- **Configuration of nodes and links:** Configure transmission parameters, and the role of each node.
- **Execution of simulation:** Execute the defined schedule (see Section 5.3) of events.
- **Performance analysis:** Analysis of output generated by the implemented protocols.
- **Visualization:** Visualize the results.

ns-3 was chosen as the framework for the simulations in this thesis as it is free, opens-ource, expandable, versatile and commonly used in other projects of the networked systems group.

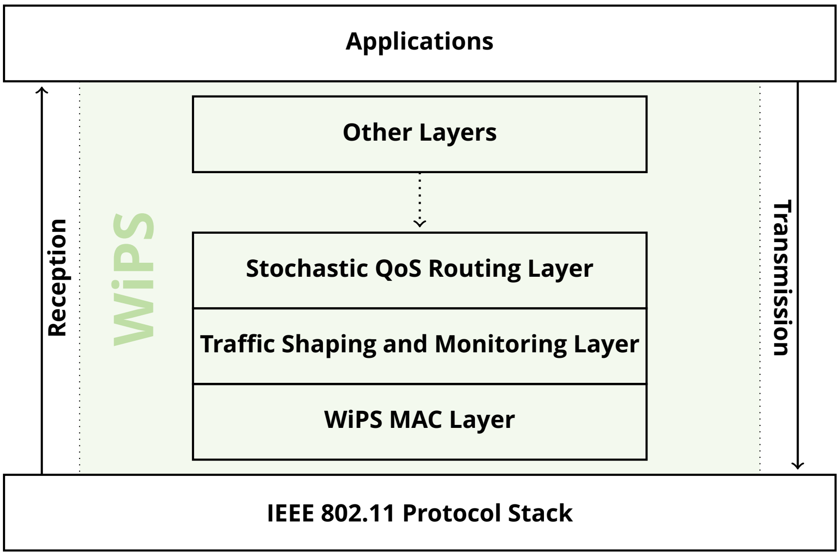

Figure 5.1.: Architecture of the WiPS framework.

WiFi Protocol Stack The simulation framework used in ns-3 incorporates the WiFi Protocol Stack (WiPS), a framework designed and implemented by this group and intended to simplify the development of WLAN based protocols. WiPS is splitted into extensible layers (see Figure 5.1) and encapsulates the complexity introduced by different platforms and transceivers using libpcap. In the following Sections 5.1.1 and 5.1.3 to 5.1.5, a short description of each layer depicted in Figure 5.1 is provided.

5.1.1. Application Layer

In the application layer, events that trigger packet creation are processed. The created packets travel the stack from top to bottom until they are finally transmitted. Upon reception of a packet at its final destination, the application layer is the final layer that handles a received packet. At application layer level, routing, forwarding, bandwidth management etc. are abstracted away. For the user, there is no visible difference between sending a packet diagonally through the whole network using routing and forwarding via several nodes and to a node in direct proximity.

5.1.2. Other Layers

As there are no hard dependencies between layers (at least in an ideal scenario), any number of layers may be added below application and above the Stochastic QoS Routing layer.

5.1.3. Stochastic QoS Routing Layer

In this layer, the protocol as specified in Section 4.1 is implemented. Here, routing and forwarding are handled as well as the generation of most of the diagnostic and tracing information for evaluation and analysis. Some of the metrics (e.g. MTT and ETT) access information provided by lower layers such as the bandwidth management layer. Inclusion of this layer is not a hard requirement. If it is omitted, metrics will use constant values instead of the missing runtime information. However, the significance of the resulting quality values will be lower.

5.1.4. Bandwidth Management layer

This optional layer handles traffic shaping, monitoring and bandwidth management. The goal is to distribute transmissions more evenly over time by restricting each node to a transmission time budget. This is achieved using token bucket based traffic shaping, as described in [21]. If too many transmission requests occur in a time frame, the transmissions are delayed until the transmission time budget of the node is refilled. Its exact implementation is not a subject of this thesis. The runtime information regarding available bandwidth is obtained from here.

5.1.5. WiPS MAC Layer

By using its own MAC layer implementation for acknowledgements, addressing, sequence numbers and retransmissions instead of the IEEE 802.11 MAC layer, WiPS enables users to configure transmission rates per frame or to precisely control the mechanisms that handle retransmissions. The IEEE 802.11 MAC layer is still part of the stack, however all frames are sent as broadcasts. The WiPS MAC layer is added on top of IEEE 802.11. As the WLAN adapters are operated in monitor mode, the WiPS MAC layer processes every frame received by the (simulated) transceiver.

The sochastic QoS routing protocol makes use of several of these features. For example, the maximum number of retransmissions is set dynamically for each link. Also, during reliability determination, retransmissions are disabled completely (see Section 5.2).

5.2. Determination of Link Reliabilities

The core network property the stochastic QoS routing protocol operates on is the reliability value of a link. As defined in Section 3.1, the link reliability is the probability that a packet is transferred successfully over a link using a single transmission. In real world scenarios, this probability is influenced by many factors such as the range between two nodes, the transmission power, the noise level or the presence of obstacles. As this list is already long and by no means complete, the link realiabilities are not calculated but determined through simulation. Each possible link (any unique pair of nodes in the network) is operated in isolation using so called *reliability probes*. These reliability probes are small enough to fit in a single IEEE 802.11 frame and are not forwarded by other nodes. Apart from that, the reliability probes traverse the network stack (Figure 5.1) just like a normal packet. After each transmission of a reliability probe, the sending node expects an ACK frame. The numbers of sent and successfully ACKed probes is recorded. Their ratio is then used as the initial link reliability during the experiments. To assess link quality, 32 reliability probes are transmitted on each possible link.

5.2.1. Propagation Loss Model

In ns-3, the loss inflicted on a signal on propagation can be configured flexibly. As it is close to real world loss characteristics and commonly used [28], the so-called log-distance propagation model is used. It is described by the following formula:

$$L = L_0 + 10 \cdot n \cdot \log_{10}(\frac{d}{d_0})$$

Where n is the path loss distance exponent, d_0 the reference distance, L_0 the path loss at reference distance, d the distance and L the resulting path loss. All distances are in Metres, path loss is given in dB. To have more control over the resulting link reliabilities without sacrificing real world applicability of the propagation model, a random propagation loss model was added on top of the log-distance propagation model. The random propagation loss is configured as a normal distributed value around a mean of $\mu = 12$ with a variance of $\sigma^2 = 16$. The goal while choosing the parameters μ and σ was to obtain a heterogeneous set of reliabilities, while retaining the strong dependency on the distance between nodes. μ and σ were obtained through experimentation. The complete formula for the propagation loss model is as follows:

$$L = L_0 + 10 \cdot n \cdot \log_{10}(\frac{d}{d_0}) + X, \text{with } X \sim N(\mu, \sigma^2)$$

To summarize, every transmission receives a loss based on the distance between the sender and any receivers (log-distance loss in dB) and a randomly distributed loss around a mean of 12 dB with a variance of 16. An exemplary random graph with annotated reliabilities as determined through the described simulation process can be found in Figure B.1.

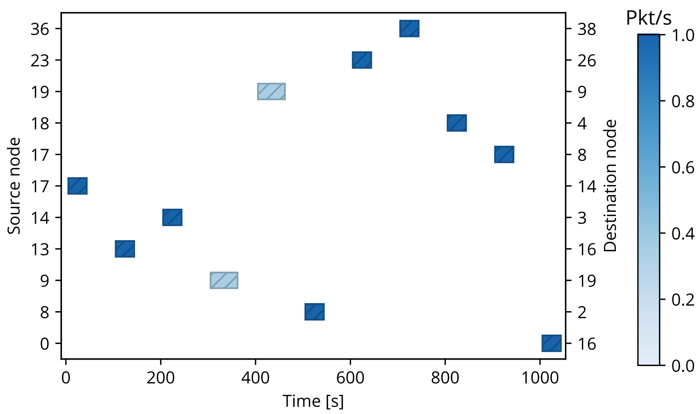

Figure 5.2.: A simple transmission schedule.

5.3. Transmission Schedules

As the defined network is to be operated, we need to generate events that trigger transmissions on nodes. As the point in time of transmission, the position of the sending node and the destination of the packet strongly influence network performance, these parameters have to be chosen wisely. To simplify configuration, the concept of *transmission schedules* is introduced. A transmission schedule provides each node with a list of tuples that each contain three elements: a timestamp, the address of the destination node and the size of the payload. On each node, this list is translated into a series of sequential events which are then processed during simulation. The required notion of time at each node is provided by ns-3. A simple schedule with events for just a few nodes is visualized in Figure 5.2. The left y-axis shows the source node of the packet, the x-axis gives the time in seconds and the right y-axis shows the destination node. Each flow (see Section 3.1.2 for a definition of the term) of packets is visualized using a bar that covers the time between the first and the last packet of the flow. The darker the bar, the higher the number of packets in that period.

Transmission schedules are also used to evaluate the network's performance under different traffic patterns. For example, schedules to simulate random, sensor-to-sink or bursty traffic patterns were designed and their impact on the network analyzed. The schedules used in the experiments are detailed Figures C.1 to C.5.

5.4. Experiment Execution

The network simulator ns-3 was programmed to execute a single schedule on a single graph. All randomly generated graphs can be found in Figures B.2 to B.4, the transmission schedules in Figures C.1 to C.5. The routing metric (see Section 3.2) applied by the routing protocol as well as the inclusion of the bandwidth management layer (Section 5.1.4) can also be configured per simulator run. This results in a number of experiments equal to the product of number of graphs, number of schedules and number of routing metrics. The experiments were run twice, once with and once without the bandwidth management layer. All in all, the number of individual simulator runs to acquire the data analyzed in this thesis is 720.

During the experiments, nearly all events in the routing protocol and the MAC layer are logged to files. These files are then used to analyze network and metric performance, reconstruct selected routes, identify failed journeys (see Section 3.1.2 for a definition) and transmissions as well as latencies of successful ones. An exhaustive analysis and evaluation of these results can be found in Chapter 6.

6. Evaluation

Using the data obtained through the experiments described in Chapter 5, the stochastic QoS routing protocol as specified in Section 4.1 is analyzed and evaluated under application of eight different routing metrics. As we aim to find the best metric for a reliable stochastic QoS routing protocol, the eight metrics are tested individually.

As one is likely to expect, the results show that each metric has its unique advantages and applications. None of them results in consistently very good routes in every scenario – with as well as without bandwidth management. However, some metrics outperform others consistently in every domain.

Several testing scenarios were identified that pose specific challenges to route selection. The variables are: sequential versus parallel operation of routes, amount of traffic, and the communication pattern.

- *Low Traffic Scenario:* Routes are operated sequentially, each flow is finished before the next one is about to start (see schedule in Figure C.1). The amount of traffic sent along the routes is low. In this scenario, a route with minimal impact on the network should be selected, as the demands on the route are low. This scenario serves as a baseline to identify the influence of different topologies.

- *Low Saturation Scenario:* Routes are operated in parallel, which means that routes may overlap and influence each other (see schedule in Figure C.2). The amount of traffic is low. Route selection should focus on minimization of influence on other flows.

- *High Traffic Scenario:* Routes are operated sequentially, however, the amount of traffic is high (see schedule Figure C.3). A route that can sustain the high demand should be selected.

- *High Saturation Scenario:* Routes are operated in parallel with a high amount of traffic (see schedule Figure C.4). The route selection should lead to successful journeys. Overlapping routes operated with many packets make a balanced distribution of transmissions in the network necessary.

- *Node-to-Sink Scenario:* The network is used to transport regular messages from every node to a single sink (see schedule Figure C.5). Many routes are operated in parallel, the amount of traffic in each flow is moderate.

As there are as many flows as there are nodes, the overall network load is high. Route selection should avoid congestion.

To compare the performance of the routing protocol under application of the different routing metrics, the following global performance metrics are used. Motivation and a formal definition of these global metrics in the context of the network model is provided in Section 3.3.

- Average Latency
- Average number of Retransmissions
- Standard Deviation of Transmissions on Nodes
- Rate of successful Journeys

6.1. Metric Evaluation

Each routing metric is tested individually in several experiments. Its performance is analyzed with a focus on the scenarios depicted above. The configuration parameters and the simulator are covered in Chapter 5.

Note: As mentioned in Sections 3.2.5 and 3.2.6, the routing metrics ETT and MTT rely on the availability of bandwidth usage information. This requires the inclusion of the bandwidth management layer, which adds an additional set of advantages and drawbacks. If the layer is not included, ETT / MTT is equivalent to ETX / MTX, respectively.

6.1.1. Low Traffic Scenario

Hop Count The performance of the protocol using this metric in low traffic scenarios is below average. The route selection solely depends on the network topology: a link that minimizes the number of hops is always selected even if it only nearly satisfies the requirements. This leads to a strong preference of long links. However, long links also tend to be less reliable. The values for average latency (Figure 6.1) and number of necessary retransmissions (Figure D.2) are both the highest of all metrics. In addition, the rate of successful journeys (Figure D.3) is lowest and fails to meet the required minimum of 90 %.

Path Reliability As the routes selected with PR are per definition the most reliable, only congestion paired with collisions can lead to failing journeys. In a scenario with low traffic, this does not occur. Consequently, the PR metric excels under these circumstances with an average journey success rate of close

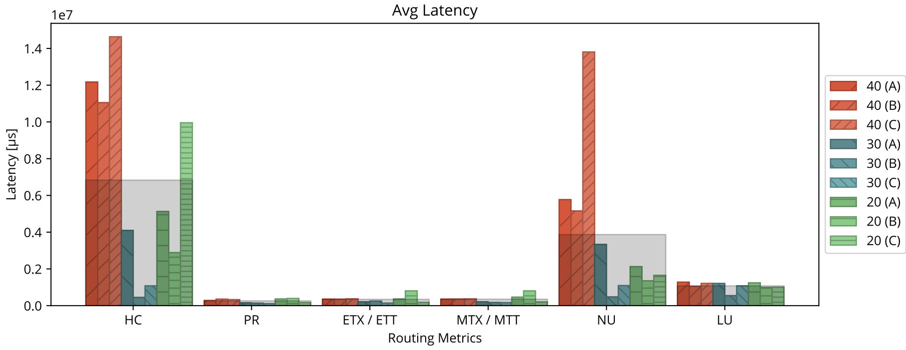

Figure 6.1.: Low traffic scenario, average latencies. No bandwidth management.

to 100 % (Figure D.3). Latencies are also low (Figure 6.1) as well as the average number of retransmissions necessary to finish a journey (Figure D.2).

Estimated Number of Transmissions In this simplest of assessed scenarios, network performance using the ETX metric is very good. Latencies are low (Figure 6.1), as is the average number of retransmissions (Figure D.2). Very good journey success rates (Figure D.3) and an averagely balanced distribution of transmissions between nodes (Figure D.4) can be added to the list.

Minimum Number of Transmission In the low traffic scenario, the network performance is on a similar, very high level as with the ETX and PR metrics: Low latencies and retransmissions (Figures D.2 and 6.1), high success rate (Figure D.3), and an averagely balanced transmission distribution among the networks' nodes (Figure D.4).

Link & Node Usage The similar behaviour to hop count of both NU and LU leads to suboptimal route selections in many cases. LU always results in better performance than NU and HC, however, the reliability-based metrics have better latencies (Figure 6.1) and a lower demand for retransmissions (Figure D.2). At least the distribution of transmissions is the best among the metrics with LU (Figure D.4), whereas NU is outperformed in this aspect by all metrics except hop count.

With Bandwidth Management

Estimated / Minimum Transmission Time In this scenario, the performance with ETT and MTT is largely identical. ETT and MTT perform well, but worse than the other reliability-based metrics (PR, ETX and MTX) with respect to all

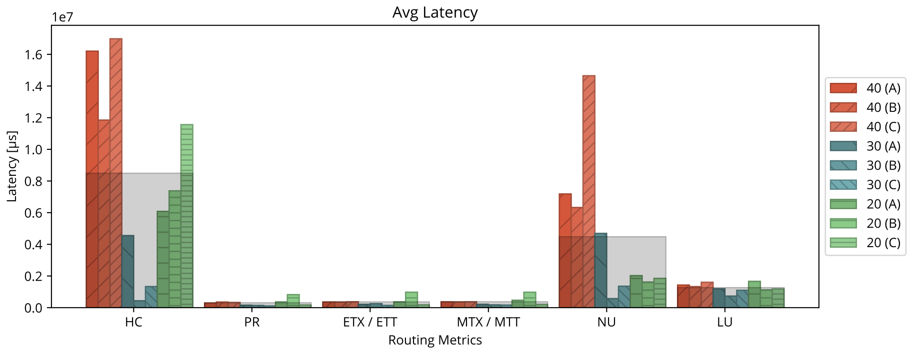

Figure 6.2.: Low traffic scenario, average latencies. With bandwidth management.

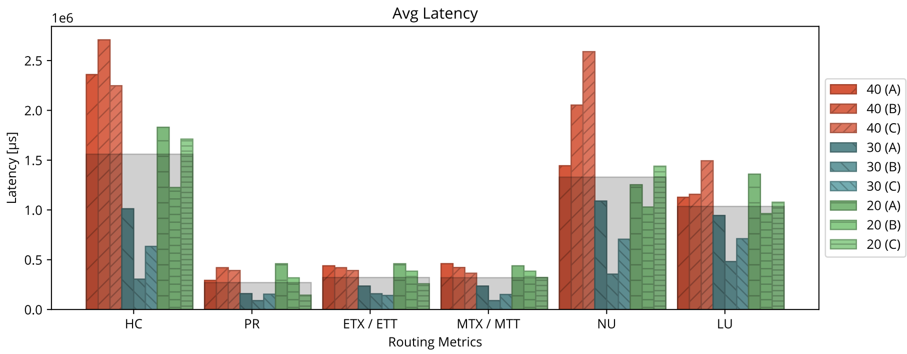

Figure 6.3.: Low saturation scenario, average latencies. No bandwidth management.

global performance criteria. Especially regarding latencies, the values are more than twice as high with *ETT* and *MTT* (Figure 6.2). *HC*, *LU* and *NU* cannot keep up in any domain, the only exception being the very good transmission distribution with *LU* (Figure D.8).

Other Metrics As expected, latencies increase slightly with the bandwidth management layer. On the other hand the numbers for necessary retransmissions and success rate improve. None of the metrics overproportionally benefits from bandwidth management in this scenario, the relative performance differences remain unaffected.

6.1.2. Low Saturation Scenario

Hop Count The statements made regarding the performance in the *low traffic scenario* also apply here. The distribution of transmissions in the network, which becomes more important when routes are operated in parallel, also is the worst with HC among all metrics assessed (Figure D.4). As only the shortest paths are selected as routes, the links crossing the center of the network are more likely to be used than the links on the edges of the network, which leads to a high standard deviation for the transmission counts.

Path Reliability In this scenario, with several parallel flows, an even distribution of transmissions becomes more important. In case of the PR metric, sequences of links with a high aggegated reliability are preferred. This sometimes leads to a highway-effect: sequences of links with a high reliability in the center of the network are part of many routes selected. The higher the number of operated routes, the stronger this effect. The number of routes in this scenario, however, is not high enough to make this effect visible. All global performance metrics suggest that PR is a very good choice in this scenario as well (Figures D.10 to D.12 and 6.3).

Estimated Number of Transmissions As in the low traffic scenario, using ETX to select routes gives very good results (Figures D.10, D.11 and 6.3). Together with the other reliability-based metrics, values for all relevant performance metrics are very good. The distribution of transmissions is only significantly better with the LU metric (Figure D.12).

Minimum Number of Transmission Performance of MTX is practically identical to that of ETX in this scenario.

Link & Node Usage Operating routes in parallel compared to sequentially does not change much for LU and NU (Figures D.10, D.11 and 6.3), performance is still closer to that of HC than to the reliability-based metrics, except for the distribution of transmissions, which is better than that of hop count (Figure D.12). In the case of LU, transmission distribution is the best of the tested metrics.

With Bandwidth Management

Estimated / Minimum Transmission Time With parallel operation of routes, the deficits of ETT and MTT regarding latencies become less striking (Figure 6.4). However, the results still provide no reasons to prefer ETT or MTT

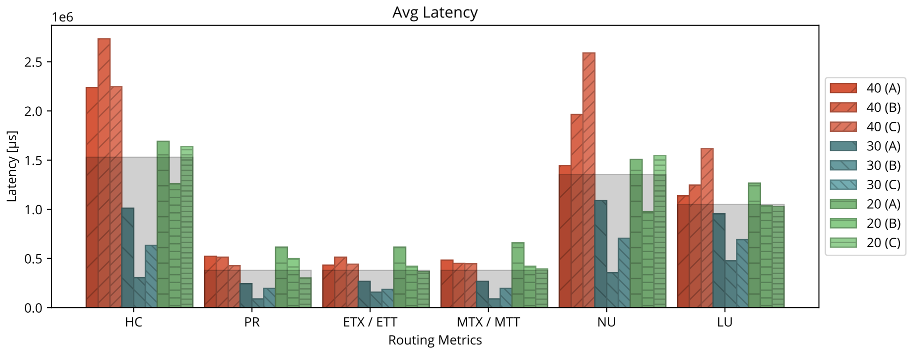

Figure 6.4.: Low saturation scenario, average latencies. With bandwidth management.

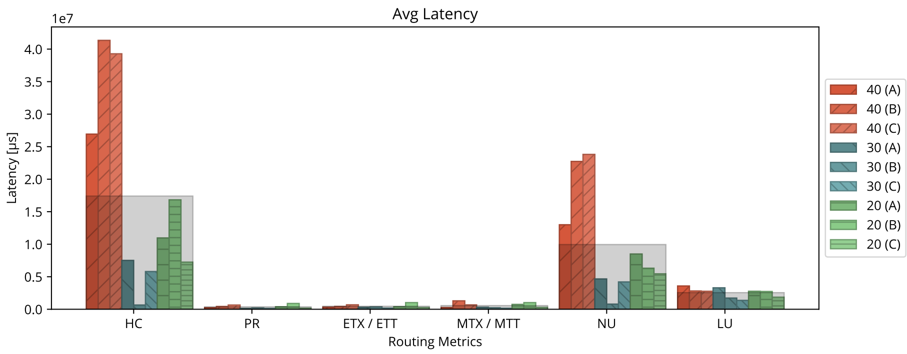

Figure 6.5.: High traffic scenario, average latencies. No bandwidth management.

over any of PR, ETX or MTX in scenarios with parallel route operation under low network load.

Other Metrics In this scenario, the effect of enabling bandwidth management is very low. As the network traffic is less bursty than in the low traffic scenario (Figures C.1 and C.2), latencies do not increase significantly either (Figure 6.3 compared to Figure 6.4). The relative differences in network performance resulting from each metric remain.

6.1.3. High Traffic Scenario

Hop Count As the route selected using hop count might only nearly fulfill the route requirements regarding reliability, high load on the route may lead to a high number of retransmissions and failing journeys. In comparison with the other routing metrics, the success rate of journeys (below 80 %, Figure D.19) in this scenario is again the lowest, regardless of the network size. The number of retransmissions required to complete the journeys is again high (Figure D.18), although not as far behind as in the previous scenarios.

Path Reliability As the routes selected by PR are of high reliability, high traffic between a pair of nodes is handled well. The average latency is the best among all metrics in this scenario (Figure 6.5), as is the number of retransmissions (Figure D.18). The highway-effect is still not visible and the rate of successful journeys is well above the target of 90 % (Figure D.11).

Estimated Number of Transmissions With the increase in network traffic, established performance advantages with ETX become more obvious. The average latencies are lower by several magnitudes (Figure 6.5) than the non-reliability-based metrics (HC, NU and LU). Very good journey success rates (Figure D.19) and low numbers of retransmissions (Figure D.18) can still be observed.

Minimum Number of Transmissions In this scenario, too, performance of MTX is practically identical to that of the other reliability-based metrics.

Link & Node Usage The increase in network traffic punishes selection of unreliable routes. Hence, the difference regarding latencies between LU / NU and the reliability-based metrics expands to several magnitudes (Figure 6.5). However, LU remains the better choice, as with LU the average latencies are only $\frac{1}{3}$ of that of NU. The advantage of LU in context of distribution of transmissions remains (Figure D.20).

With Bandwidth Management

Estimated / Minimum Transmission Time An increase in network load leads to the same conclusions regarding performance as in the related low traffic scenario: Considering a nodes' available bandwidth in route selection actually seems to be detrimental to network performance. PR, ETX and MTX give better results in every domain (Figures D.22 to D.24 and 6.6).

Other Metrics As in the low traffic scenario, latencies increase with bandwidth management. In this scenario, the overall network traffic is much higher, consequently the increase in latency is larger, too. By restricting each node to a transmission budget, bandwidth management decreases the overall network load, which results in fewer retransmissions (Figure D.22) and better success rates (Figure D.22) with all metrics in this scenario.

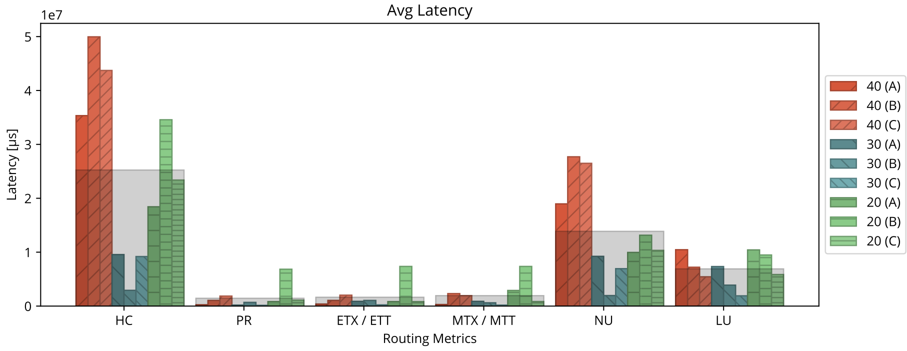

Figure 6.6.: High traffic scenario, average latencies. With bandwidth management.

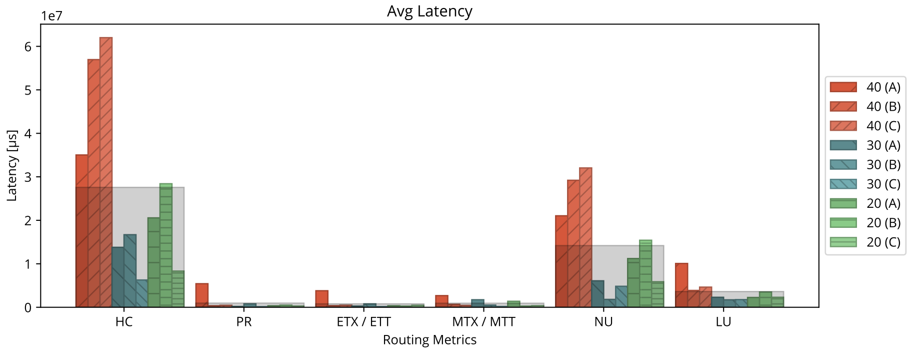

Figure 6.7.: High saturation scenario, average latencies. No bandwidth management.

6.1.4. High Saturation Scenario

Hop Count The problem described in Section 6.1.2 on low network saturation exists here, too: Paths crossing the center of the network are more likely to be part of a shortest path between two nodes, which leads to a bad distribution of transmissions. No other metric leads to a stronger concentration of transmissions on few nodes in this scenario as hop count (Figure D.28). As this leads to congestion and interference, hop count's success rate of journeys (Figure D.27) and latency values (Figure 6.7) are still the worst in the field, and the number of retransmissions required in the high saturation scenario is still very high (Figure D.26).

Path Reliability Similar to what applies to the high traffic scenario, *PR* performs well even in scenarios where the network is saturated (Figures D.26 to D.28 and 6.7).

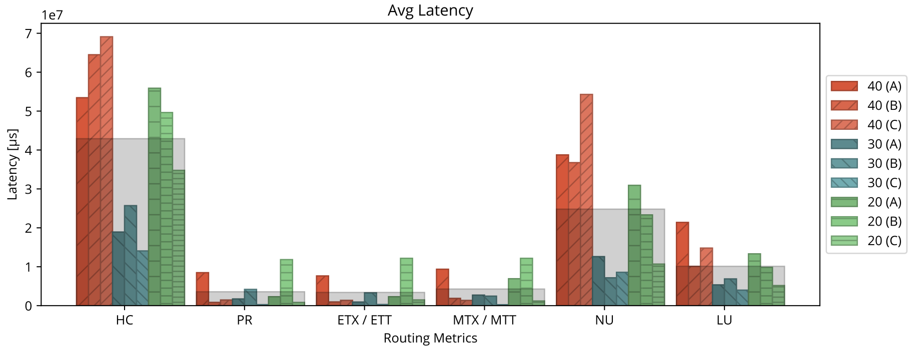

Figure 6.8.: High saturation scenario, average latencies. With bandwidth management.

Estimated Number of Transmissions Parallel operation of routes with ETX results in the same observations regarding network performance as in the high traffic scenario.

Minimum Number of Transmissions Parallel operation of routes with MTX from the high traffic scenario does not lead to shifts in relative metric performance. The observations made on the other scenarios tested, apply here, too.

Link & Node Usage As was the case for the low traffic scenarios, parallel operation of routes with LU or NU does not result in better performance relatively to that of the other metrics (Figures D.26 and D.27). The grave disadvantage regarding latencies persists (Figure 6.7), the slight advantage with the more balanced distribution of transmissions (Figure D.28), too.

With Bandwidth Management

Estimated / Minimum Transmission Time In this scenario, too, the performance data collected in the experiments gives no reason to prefer ETT and MTT whenever PR, ETX or MTX are an option (Figures D.30 to D.32 and 6.8).

Other Metrics The effect of an inclusion of bandwidth management in this scenario is equivalent to the high traffic scenario. On the one hand, latencies increase, on the other hand the performance metrics success rate and number of retransmissions slightly improve (Figures D.30, D.31 and 6.8).

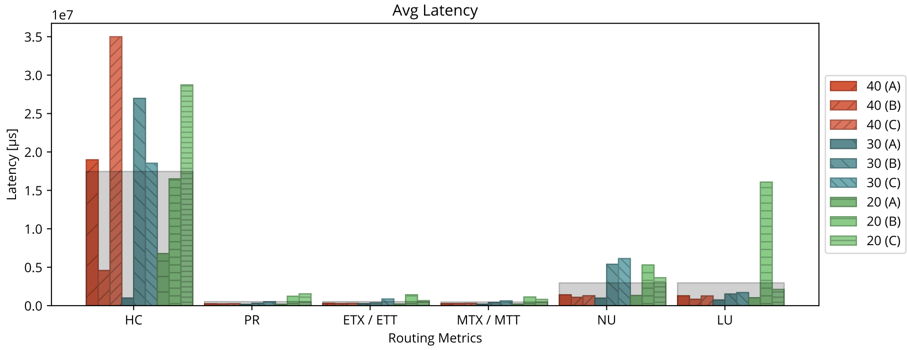

Figure 6.9.: Node-to-sink scenario, average latencies. No bandwidth management. Each bar represents one randomly generated graph, the number of nodes in each graph can be found in the legend on the right side. The bigger, transparent bars show the average latency over all graphs for each metric.

6.1.5. Node-to-Sink Scenario

Hop Count As in all previous scenarios, application of the hop count metric results in the worst performance. Especially the latencies measured are about ten times as long as with other metrics (Figure 6.9).

Path Reliability In this scenario, with its high number of parallel routes, the distribution of transmissions among the nodes in the network finally indicates what was described as the highway-effect earlier: reliable link sequences in the center of the network are much more frequently part of selected routes and experience higher load (Figure D.36). However, a significantly detrimental effect on overall network performance is not observed. The average latencies (Figure 6.9), retransmission numbers (Figure D.34) and success rates (Figure D.35) are still the best of all metrics.

Estimated Number of Transmissions Similar to the observations reported for PR in this scenario, the distribution of transmissions among the networks' nodes (Figure D.36) indicates a highway-effect. But this effect also seems not to negatively influence the other performance metrics to a significant degree (Figures D.34, D.35 and 6.9). The distribution of transmissions is clearly worse with ETX in this scenario, the advantage regarding performance – when compared to the non-reliability-based metrics – remains.

Minimum Number of Transmissions As reported in the sections on PR and ETX, a highway-effect is visible when MTX is used, but is seemingly no detri-

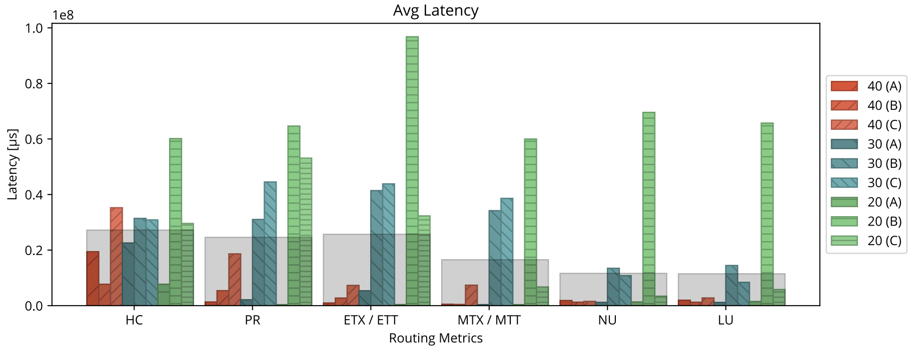

Figure 6.10.: Node-to-sink scenario, average latencies. With bandwidth management.

ment to network performance.

Link & Node Usage On a first glance at the results, the perception established by the previous scenarios seems to be confirmed. With the usage statistics based metrics, latencies suffer greatly (Figure 6.9). In this scenario the statement definitely remains true for *NU*. In the case of *LU*, however, there is a glaring outlier in the average latencies of one of the 20-node networks. Without this outlier, average latencies with *LU* might at least be considered of the same magnitude as the average latencies with reliability-based metrics. On closer inspection, this 20-node network (Figure B.2) is a special case, as the sink is located at the end of a subgraph very closely reassembling the structure of a line graph. With *LU*, this leads to routes with long detours, and surging latencies as a consequence.

With Bandwidth Management

Hop Count With bandwidth management in the node-to-sink scenario, *HC* is not the worst metric in all measured network performance aspects for the first time. Latencies for example are on the same level as with *PR* and *ETX* (Figure 6.10). The number of transmissions is also lower than with the *NU* metric, however the disappointing success rate of flows (below 80 %) does not permit a comparison of the retransmission numbers.

Path Reliability Many routes operated in parallel with moderate to high load in a network paired with bandwidth management, triggers a set of detrimental properties of the path reliability metric. The path sequences of high reliability in the center of the network are part of many routes, the inclusion of a bandwidth managing layer now distributes this high traffic over time. The *PR* metric's latency values increase overproportionally (Figure 6.10), when bandwidth management is added in the node-to-sink scenario. In all other scenarios, PR results in exceptionally low latencies. This suggests that the highway-effect is a likely cause for this overproportional increase, as this effect is emphasized by high network load. Interestingly, the success rates experience a slight decrease of about 3 % with bandwidth management (Figure D.39).

Estimated / Minimum Number of Transmissions With the ETX and MTX metrics similar effects through the inclusion of bandwidth management as with PR can be observed. There is a strong increase in latency (with an advantage for MTX) and a decrease of about 3 % in the success rate. As with PR, the latency surgy is likely caused by the highway-effect.

Estimated / Minimum Transmission Time Finally, with continuous load-to-sink communication across the whole network, the expected advantage of ETT and MTT over the remaining reliability-based routing metrics can be observed. The two metrics require more retransmissions on average to finish a journey (Figure D.38), which indicates the selection of less reliable routes (which was verified). However, these routes are also less congested and provide much lower average latencies (Figure 6.10) under an equal success rate (Figure D.39). In addition, the distribution of transmissions (Figure D.40) is on the same level as with NU and LU, which is a significant improvement to the transmission distribution with PR, ETX and MTX.

Link & Node Usage In the node-to-sink scenario, both NU and LU benefit from the inclusion of bandwidth management: No other metric results in shorter latencies as NU and LU (Figure 6.10). As already observed with the other routing metrics in this scenario, the global network performance metrics apart from average latency remain stable (Figures D.38 to D.40), which leads to the conclusion that with NU and LU, congestion is reduced. This does not surprise, as the very idea behind these two metrics is to avoid links which are commonly used by already established routes.

6.1.6. Performance Summary

Hop Count The hop count routing metric (HC) is by far the most common and most intuitive routing metric. However, for WSNs and the like, it is not always the best choice. It leads to very short (in terms of hops) routes between source and target, which minimizes impact on network resources to a degree. However, the cost of using these most direct options of links is ignored: The reliabilities of links as defined in the network model (see Section 3.1.1) have no influence on route selection when the hop count routing metric is used. This leads to unreliable routes with suboptimal performance. Hop count is not a good choice as a routing metric in the scenarios tested, as was expected. Regardless of whether routes are operated in parallel or not, and independent of the traffic load in the network, hop count has the worst performance among the analyzed metrics. However, as hop count works very well in wired applications and is easy to implement and analyze, it would have been careless not to rule out this option first.

Path Reliability The path reliability metric (PR) can be considered the translation of the hop count metric to the domain of a network model based on link reliabilities. The approach is simple: The reliability of a path is modeled as the product of the reliabilites of its links. Choosing the most reliable path between two nodes in the network should therefore lead to a reliable route.

However, the drawback of hop count, which is ignoring the reliabilities assigned to the links of a path is also translated: PR ignores the length of a path. Two links of reliability 0.9 are considered equivalent to one link of reliability 0.81 connecting the same nodes. This can lead to strange phenomena in case links with a reliability of 1.0 exist in the network. As 1.0 is the multiplicative neutral element, links with a reliability of 1.0 can be used without a negative impact on the PR metric. In theory, with PR, a detour on a chain of dozens of nodes with reliability 1.0 is still considered an improvement over a single link with a reliability of 0.99. With respect to packet delivery rates this is true, but latencies will increase.

Aside from these rather artificial scenarios, PR as a routing metric works very well in the scenarios analyzed, even with bandwidth management enabled. Only in the node-to-sink scenario paired with bandwidth manegement, the preference for highly reliable links seemingly leads to congestion, high latencies, and an increase in failed journeys. In all other scenarios PR is a very good choice.

ETX Using the estimated number of transmissions (ETX) required to deliver a packet as routing metric can be viewed as a hybrid between hop count and path reliability. As with hop count, each link added to a possible route increases its metric value, and as with path reliability, links that are more reliable are preferred. By comibining both these aspects, ETX works very well as routing metric in the analyzed scenarios and topologies. Except for the slightly higher latencies, network performance with ETX remains largely unaffected by the inclusion of a bandwidth management layer. In case of a very high number of parallel routes (as in the node-to-sink scenario), congestion becomes a problem and leads to a strong increase in latency. Bandwidth management multiplies this drawback and renders other routing metrics a better choice in a node-to-sink scenario.

MTX The MTX metric aims to estimate the minimum number of required transmissions in dependency of the link reliabilities of a path and a target path reliability. The value of the metric is the expected number of transmissions required for a packet to travel to the destination along this path, with the provided target path reliability as probability of success. This way, the length of a path and its link reliabilities are taken into account. MTX differs from ETX in the way the influence of link reliabilities on the metric value is weighted.

All analyzed reliability-based metrics give similar levels in network performance. The conclusions drawn for PR and ETX apply here, too. MTX has the advantage of being seemingly less affected by the combination of frequent node-to-sink communication and strict bandwidth management, but is still outperformed by the usage statistic based routing metrics NU and LU in this scenario. The differences between MTX and PR / ETX in the node-to-sink scenario with bandwidth management also indicate that the reliability-based metrics are not equivalent.

ETT & MTT As can be derived from the definitions of ETT and MTT (see Sections 3.2.5 and 3.2.6), these two metrics are mere augmented versions of ETX and MTX, respectively. The only modification is the inclusion of available bandwidth as a quotient. The information on how much bandwidth is available for a node is provided by the bandwidth management layer. Both metrics do work without this layer, however, with the available bandwidth set to a constant, the resulting routes are equivalent to those selected by ETX and MTX, respectively.

Both metrics, ETT and MTT, base their quality values on link reliabilities and bandwidth available on each node. However, this advantage in intelligence on the network's state does not manifest in most scenarios. In fact, not considering the available bandwidth (see ETX and MTX) results in better routes in all but the node-to-sink scenario. This is a somewhat surprising result. A possible explanation might be that the reduced congestion gained by using less used and therefore likely also less reliable routes, might just not outweigh the resulting disadvantage regarding reliability. Interesting results can be expected from an analysis of the performance of variants of ETT and MTT, where different weights on the contribution of available bandwidth to the metric's value are used.

Link & Node Usage The last two metrics are quite similar, as they both only use usage statistics to select routes. Similar to hop count, the actual link reliabilities are not used. A path is preferred over another when its links' (LU) or its nodes' (NU) aggregated usage statistics are lower. The quality of the routes selected by these two metrics heavily depends on the strictness of the filtering mechanism (see Section 4.3) applied on the set of candidate paths. When paths are equivalent regarding their usage statistics, which is the case right after network startup, the shorter path is selected. This way, *NU* and *LU* first result in similar routes as hop count, while resorting more and more to less used nodes and links as the network is operated. When there are many routes operated in parallel over long periods of time, both metrics seem to result in a significantly less congested network. Strict bandwidth management additionally rewards the selection of less congested routes and makes *NU* and *LU* the best choice for at least these scenarios.

6.2. Impact of Bandwidth Management Layer

The most striking impact of bandwidth management is the increase in latencies (e.g. Figure 6.9 compared to Figure 6.10). As the time budget for transmissions on each node is restricted, the total number of possible transmissions per period of time is reduced. Only in the case where no node ever depletes its budget, bandwidth management has no detrimental impact on latencies.

In almost all cases, bandwidth management results in a (marginally) higher success rate of journeys. This comes at no surprise, as bandwidth management reduces the load on the network and therefore reduces the probability of frame loss due to collisions. However, this slight improvement is just high enough to increase success rate to match the specified reliability requirement (see Table 4.2) of 90 % for all scenarios, except node-to-sink communication. With respect to the journey success ratio, the node-to-sink scenario is a special case, as this is the only scenario where bandwidth management decreases success rates. A satisfying explanation for this decrease of about 3 % could not be verified in time for this thesis, however, it is suspected to be caused by a programming mistake in a physical layer configuration function in the ns-3 framework.

In general, the influence of bandwidth management on the relative network performance with different routing metrics strongly depends on the traffic pattern. In the node-to-sink scenario for example, the *NU* and *LU* metrics both profit greatly from the inclusion of a bandwidth management layer with respect to relative network performance (e.g. Figure 6.9 compared to Figure 6.10). In other scenarios, the impact is much lower and does not change the ranking between the metrics.

Another general observation that was made is that bandwidth management punishes the route selections that lead to higher network congestion. The highwayeffect most of the reliability-based metrics exhibit, becomes much more detrimental to performance (especially latencies) whenever bandwidth management is added (Figure 6.7 and Figure 6.9 compared to Figure 6.8 and Figure 6.10).

6.3. General Performance of the Routing Protocol

When evaluating this protocol based on the results provided and discussed in Section 6.1, it is very important to keep in mind that the distribution of information necessary to build the routes is not part of the protocol. However, this is a very important aspect in general, as well as specific to the performance of the protocol. As the focus of this thesis is on the feasibility of using link reliabilities as the anchor of the network model and the QoS aspects of the protocol, a solution to the problem of link-state information distribution in the network is not part of the specification in Section 4.1, and therefore also not implemented. A fair comparison between existing routing protocols for WSNs with the protocol, as introduced here, is not possible and therefore omitted.

Before the evaluation of the protocol, a short recapitalization on the aspects relevant to QoS is given: The stochastic QoS routing protocol introduced in this thesis (Section 4.1) aims to find routes that satisfy a minimum statistical reliability. To accomplish that, the edges of the graph modelling the network are assigned reliabilities (Section 3.1), that model the probability that a small packet (reliability probe, see Section 5.2) is successfully transferred over that link. Using this information, the number of possible retries to transfer a packet over a link is configured such that the packet is successfully received and ACKed with the required probability. When all detrimental effects to link reliability external to the route, namely collisions, can be excluded and the packet size does not exceed that of the reliability probes, the expected rate of packets successully reaching their destination should always match the configured target path reliability (see Section 4.3 for details).

For this mechanism to work as intended, the network needs to be operated in a way that minimizes deviation of the actual link reliabilities at runtime from what was used to select the specific route. It is obvious, that in areas of the network that experience high load, the actual link reliabilities will drop whenever collisions occur, as the initial determination process for link reliabilities excludes collisions. Even if the information on failed and successful transmissions during route operation is used to continuously update link reliabilities, a reliability drop can only be detected when it occurs. It cannot be anticipated or precalculated, at least not for irregular traffic patterns. As of now, a coping mechanism for this potential of collisions during route operation is not an explicit part of the route selection process. In the current protocol, the routing metrics (defined in Section 3.2 and evaluated in Section 6.1) are responsible to balance network load spatially and thus minimize reliability drops caused by frame collisions during route operation.

To evaluate how well the expected reliability target is met, the global metric *rate of successful journeys* (see Section 3.3) will be used, as it represents the percentage of packets that successfully travel the whole route to the destination. The scenario where practically no collisions can occur is the low traffic scenario (Figure C.1), each flow ends before the next one starts and traffic load is low enough such that all packets are also delivered before the next flow's first packet is transferred. In the respective plot (Figure D.3), the configured path reliability target of 90 % is met by all metrics, except hop count, which is slightly lower at about 88 %. This indicates, that the stochastic QoS routing protocol is actually able to satisfy this statistical minimum reliability requirement, given that link reliabilities are determined correspondingly. The minimum reliability target is met in other scenarios, too, when the better performing metrics (see Section 6.1) are used. When paired with bandwidth management, the target is only nearly missed for the node-to-sink scenario and met otherwise.

7. Conclusion & Future Work

In this thesis, a network model based on the concept of link reliabilities was developed and formally defined. In the context of this network model, several routing metrics were formally expressed. To evaluate the performance of these routing metrics in the process of route selection, a routing protocol was specified that provides the flexibility to employ any routing metric as well as optional bandwidth management, while maintaining support for statistical minimum reliability guarantees. The protocol, as well as the implemented routing metrics, were tested in simulations of different communication scenarios on several randomly generated networks of different size. A detailed evaluation of the results guided by formally defined global network performance metrics was provided in a last step.

The definition of the network model proved to be robust and capable of expressing various routing metrics. With the reliability of links as the anchor, all required graph theoretical concepts such as connectedness and paths are supported.

The routing protocol specified in this thesis is to be considered a base for future extension. Many aspects a complete routing solution needs to cover are left unspecified. This concerns distribution of network state information as well as adequate handling of broken routes. The concept of a central coordinator, introduced to overcome these gaps in the specification, is a temporal solution and should be replaced by decentral mechanisms in the future. The devised routing protocol also features basic quality of service mechanisms: a statistical minimum reliability requirement for routes is supported. The conducted simulation experiments show that this requirement is met, when the link reliabilities are determined accordingly. Advanced concepts such as bandwidth reservations, prioritization and traffic classes can be added in future work on the subject.

In context of the evaluation of the routing protocol, several routing metrics were also assessed and their performance analyzed. The hop count metric, very common in wired networks, provides suboptimal performance in the tested scenarios. Three reliability-based metrics, namely PR, ETX and MTX, resulted in an excellent network performance in almost all scenarios tested. Their only drawback is the lacking performance in scenarios that exhibit high traffic load-to-sink communication. Enhancing ETX and MTX by incorporating a node's available bandwidth into the metric value improved network performance only in the high traffic node-to-sink scenario. The two metrics based on usage statistics provide only an advantage with respect to a more balanced distribution of transmissions among the network's nodes.

As the results in this thesis look promising, further work on the subject is surely justified. The routing protocol still requires substantial work to be considered a complete and competitive solution to routing in wireless networks. The filtering mechanism offers an interface through which more sophisticated QoS requirements can be satisfied. If supported by well-designed mechanisms for reservations and prioritization, the protocol has potential to ensure very solid network performance, while providing applications statistical quality of service guarantees. Also the set of analyzed routing metrics can be expanded. As this aspect of the protocol is completely modular, practically any routing metric imaginable can be implemented and tested under freely configurable traffic scenarios and network topologies.

A. Algorithms

```
linkMTX(node1, node2, target) {
    r = getReliability(node1, node2);
    mtx;

    if (r == 0) {
        return infinity;
    }

    for (n = 1; ; n++) {
        if (1 - pow(1 - r, n) >= target) {
            mtx = n;
            break;
        }
    }

    return mtx;
}

pathMTX(path, target) {
    mtx = 0;
    for (n in path) {
        mtx_n = linkMTX(path[n-1], path[n], target);
        if (mtx_n == infinity) {
            mtx = infinity;
            break;
        }

        mtx += mtx_n;
    }

    return mtx;
}
```

Listing A.1: MTX implementation in pseudocode.

B. Randomly Generated Graphs

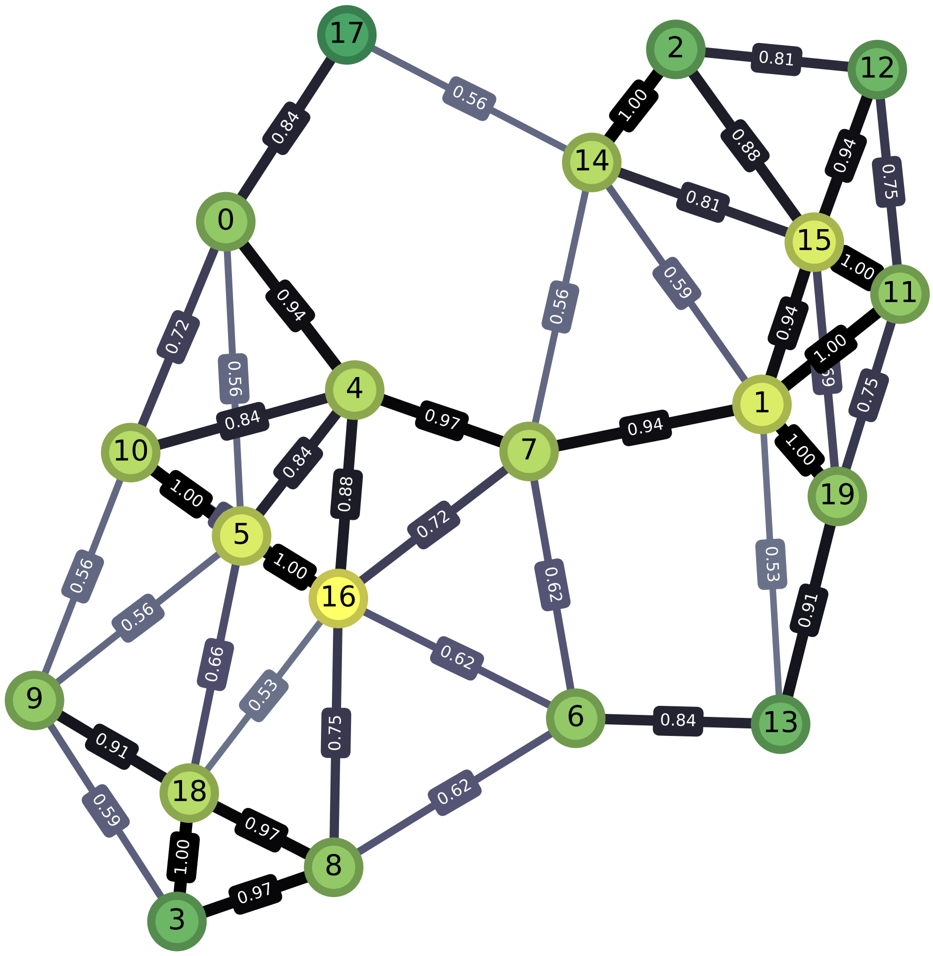

Figure B.1.: The 20 node graph, version A, annotated with link reliabilities as determined by simulation.

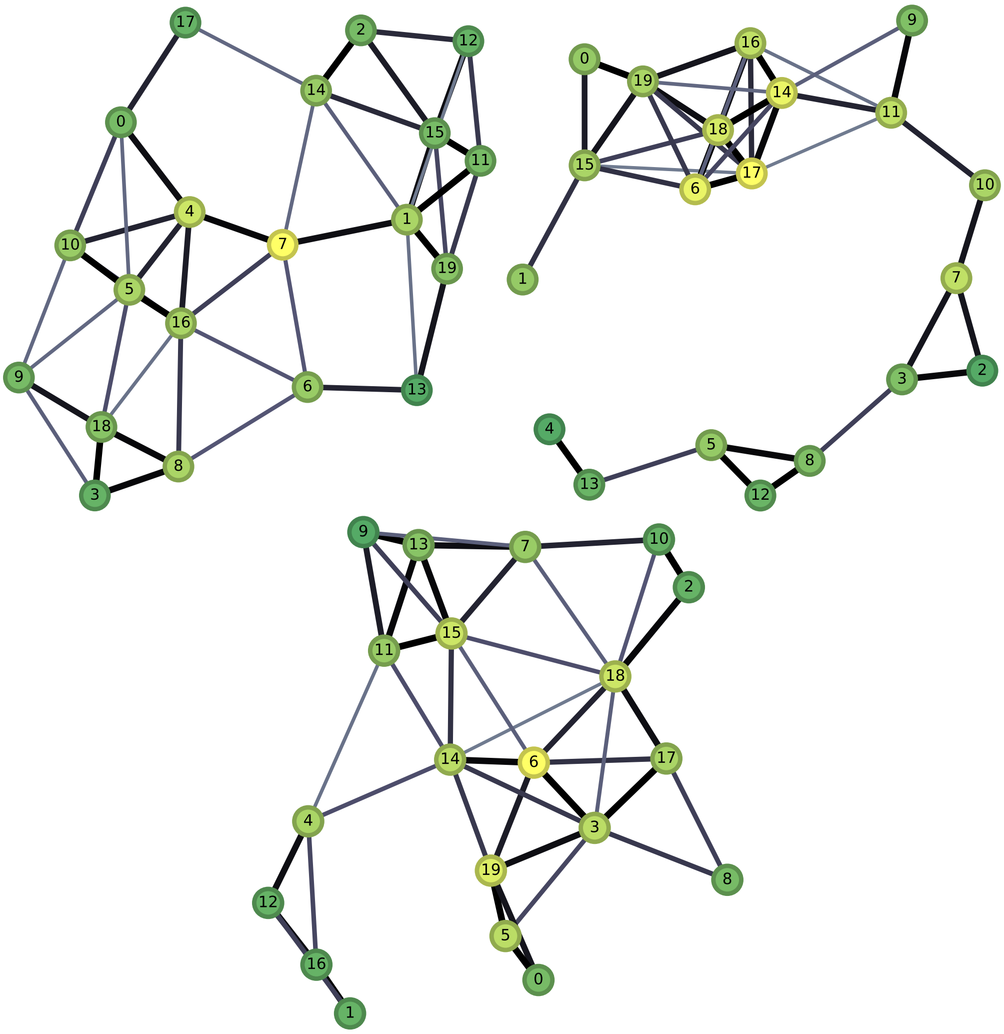

Figure B.2.: Three random graphs, each with 20 nodes. Left to right, from top to bottom: A, B and C.

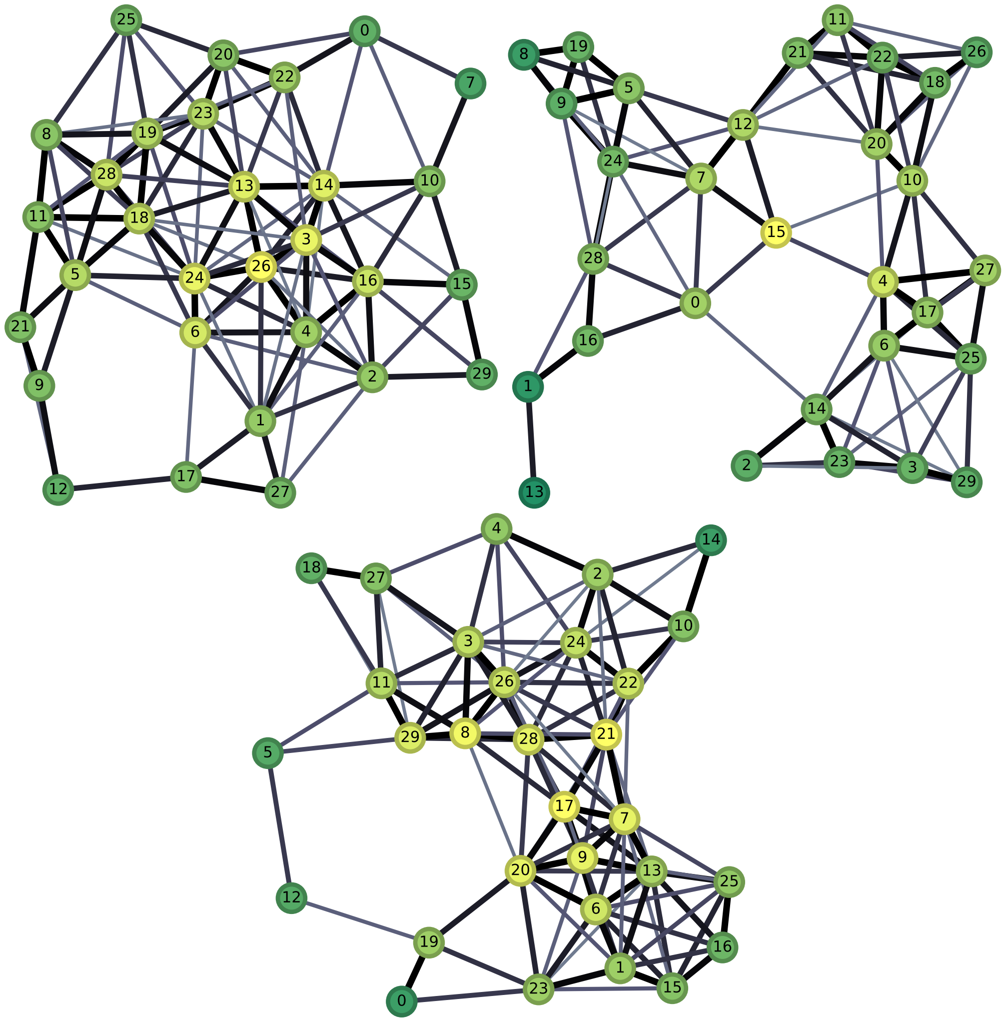

Figure B.3.: Three random graphs, each with 30 nodes. Left to right, from top to bottom: A, B and C.

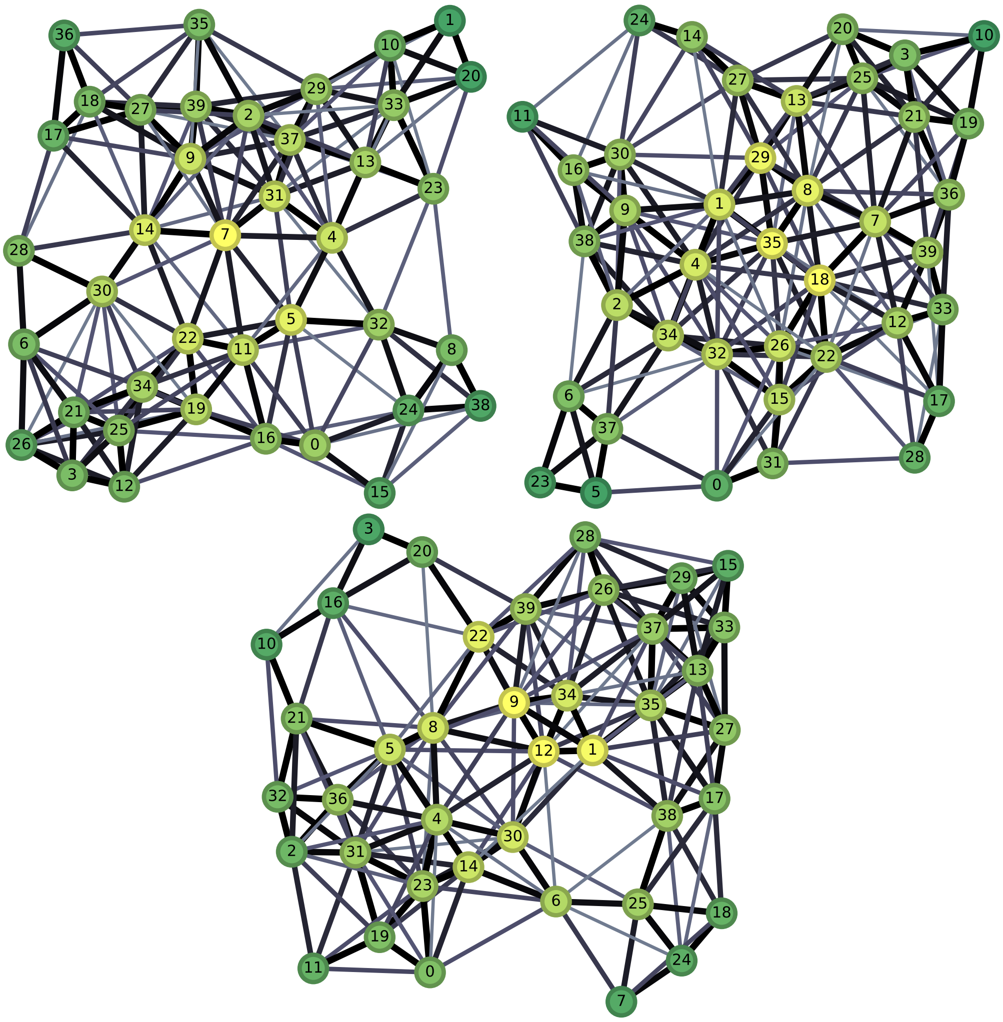

Figure B.4.: Three random graphs, each with 40 nodes. Left to right, from top to bottom: A, B and C.

C. Transmission Schedules

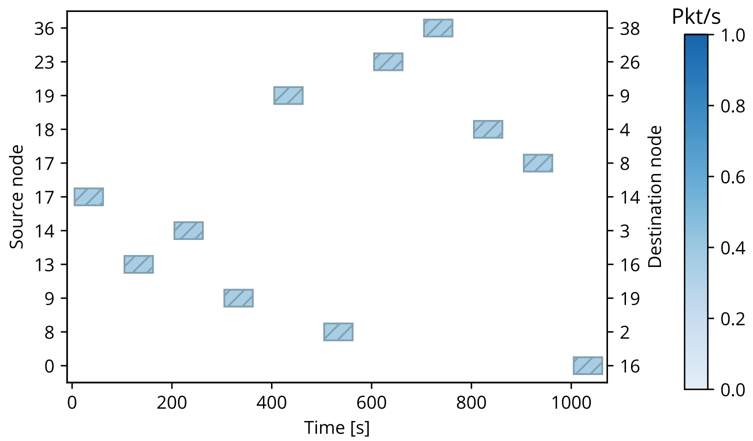

Figure C.1.: Schedule creating sequential packet flows. Overall network traffic is low.

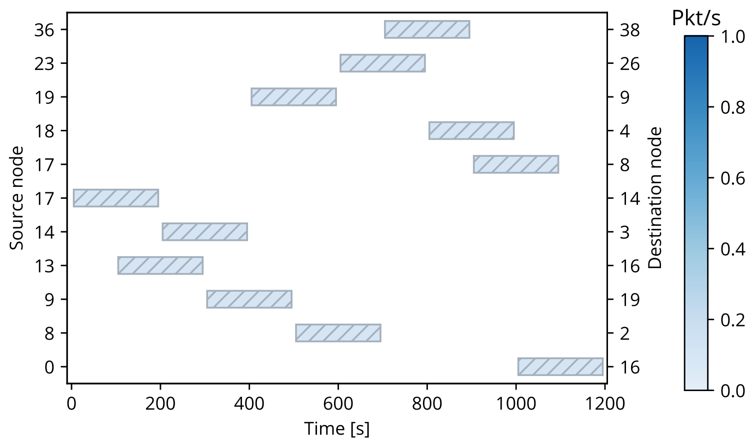

Figure C.2.: Schedule creating parallel packet flows. Overall network traffic is low.

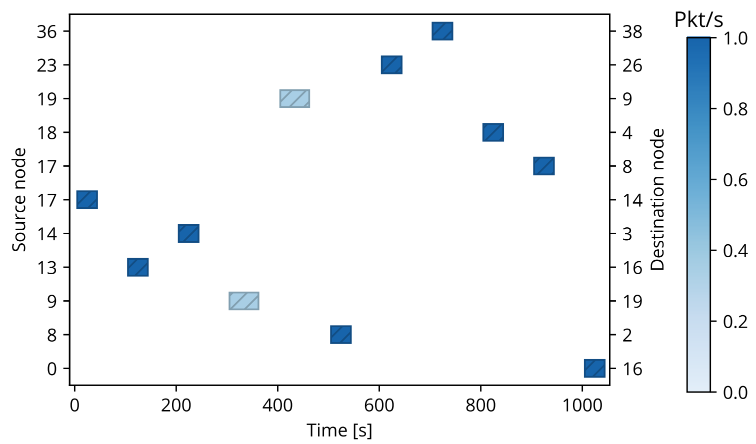

Figure C.3.: Schedule creating sequential packet flows. Overall network traffic is higher.

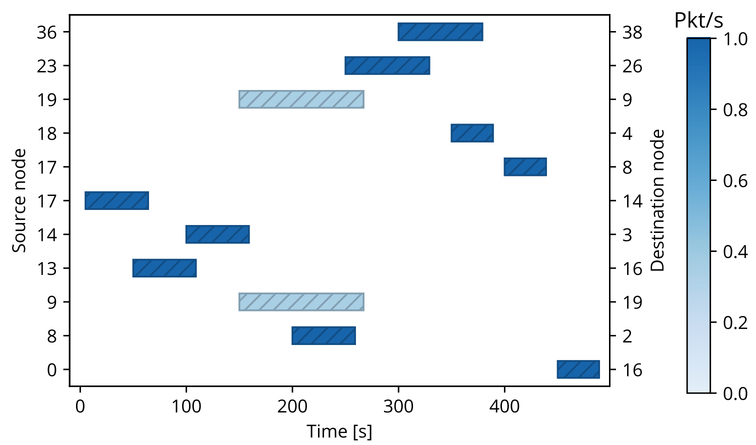

Figure C.4.: Schedule creating parallel packet flows. Overall network traffic is higher.

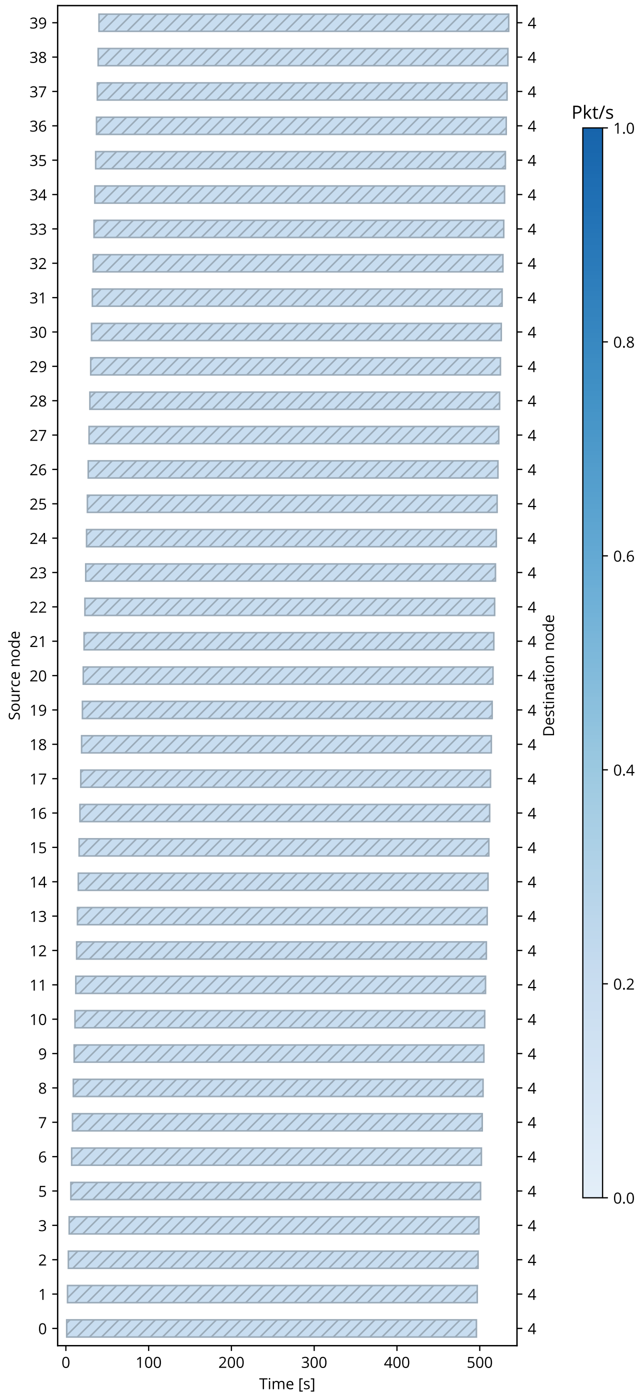

Figure C.5.: Schedule creating 100 packet flows on each node. Flows are created in a period of 500 seconds. The target of all packets is node 4, acting as a sink.

D. Experiment Results

To simplify the look up process of plot for the reader, there are no plots on this page.

Low Traffic Scenario

No Bandwidth Management

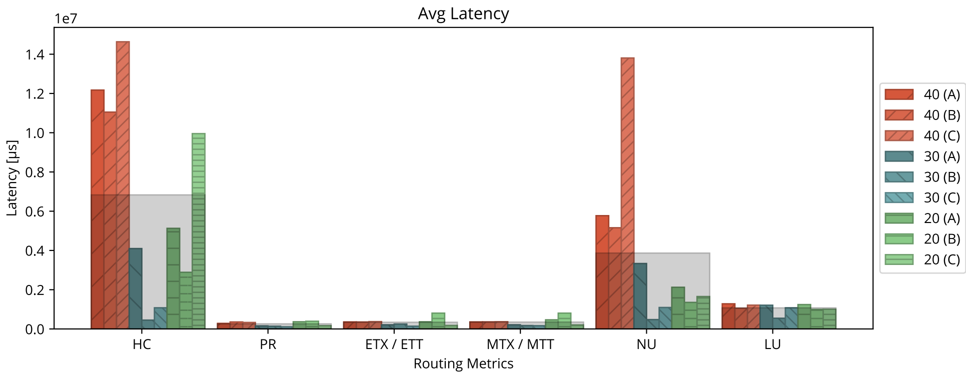

Figure D.1.: Low traffic scenario, average latencies. No bandwidth management.

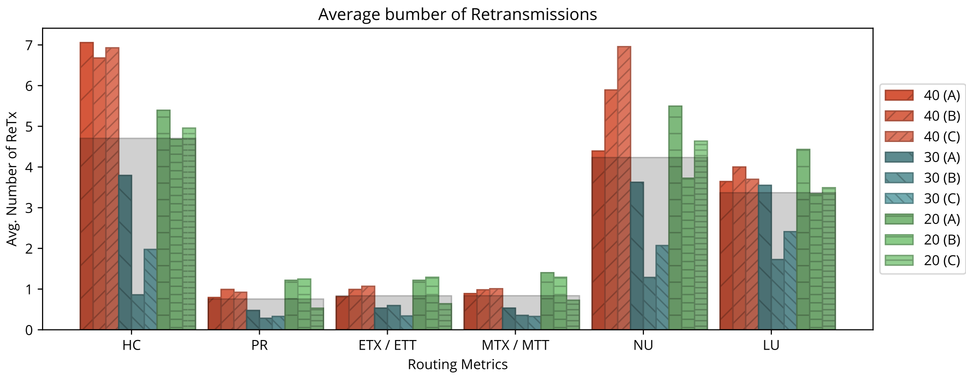

Figure D.2.: Low traffic scenario, average number of retransmissions. No bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

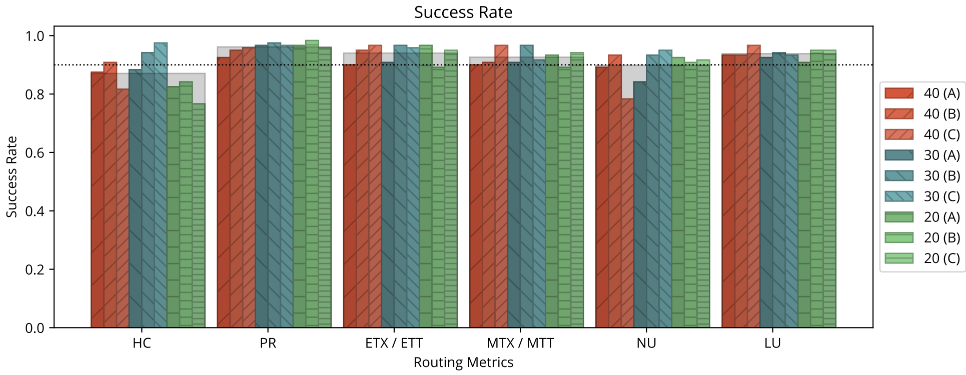

Figure D.3.: Low traffic scenario, success ratio of journeys. No bandwidth management.

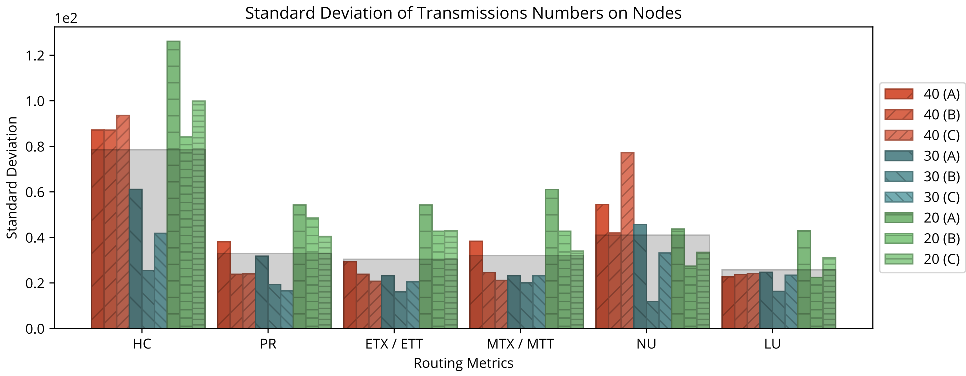

Figure D.4.: Low traffic scenario, standard deviation over the number of transmissions of each node in the network. No bandwidth management.

With Bandwidth Management

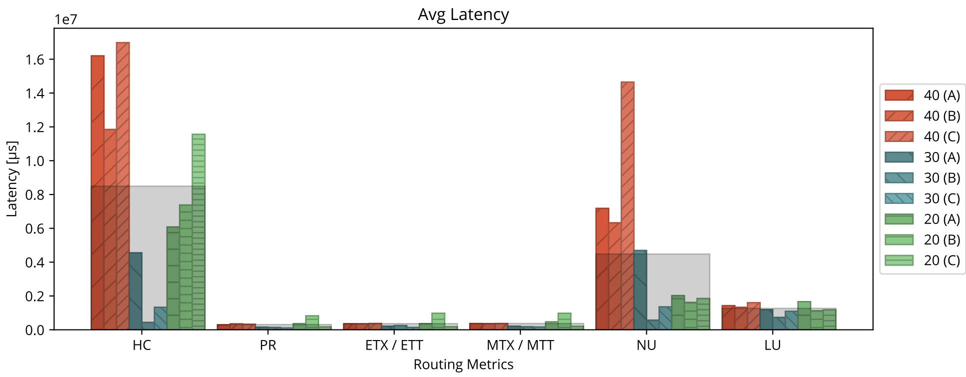

Figure D.5.: Low traffic scenario, average latencies. With bandwidth management.

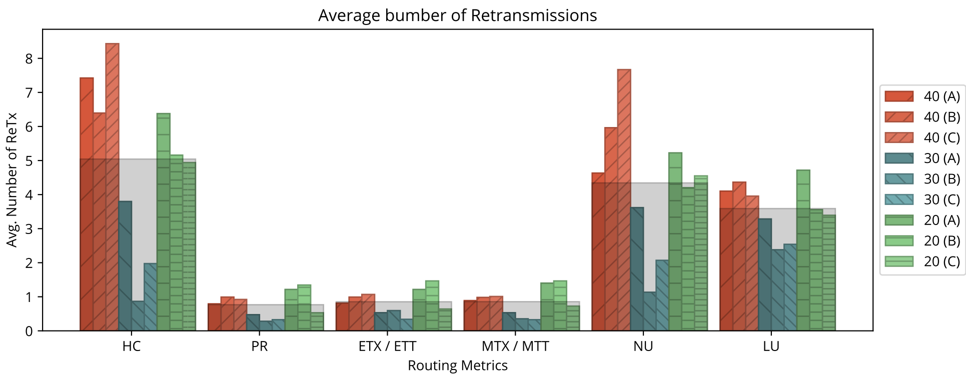

Figure D.6.: Low traffic scenario, average number of retransmissions. With bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

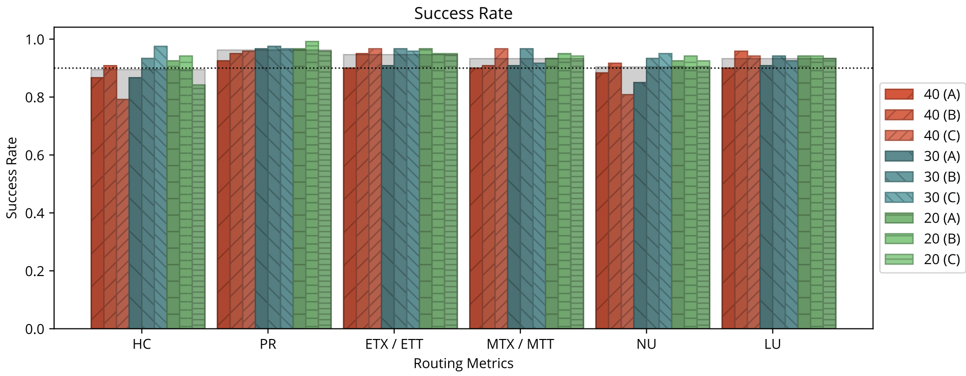

Figure D.7.: Low traffic scenario, success ratio of journeys. With bandwidth management.

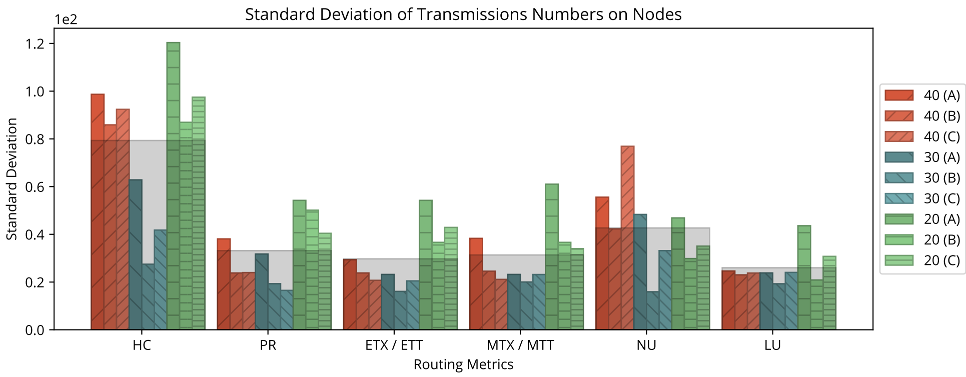

Figure D.8.: Low traffic scenario, standard deviation over the number of transmissions of each node in the network. With bandwidth management.

Low Saturation Scenario

No Bandwidth Management

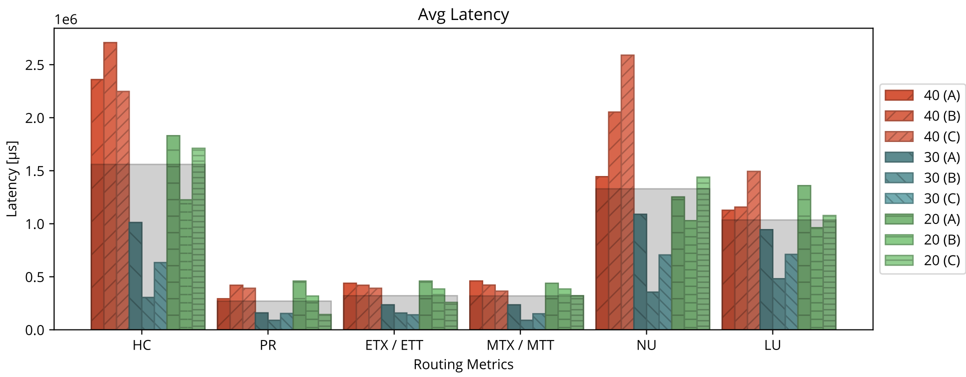

Figure D.9.: Low saturation scenario, average latencies. No bandwidth management.

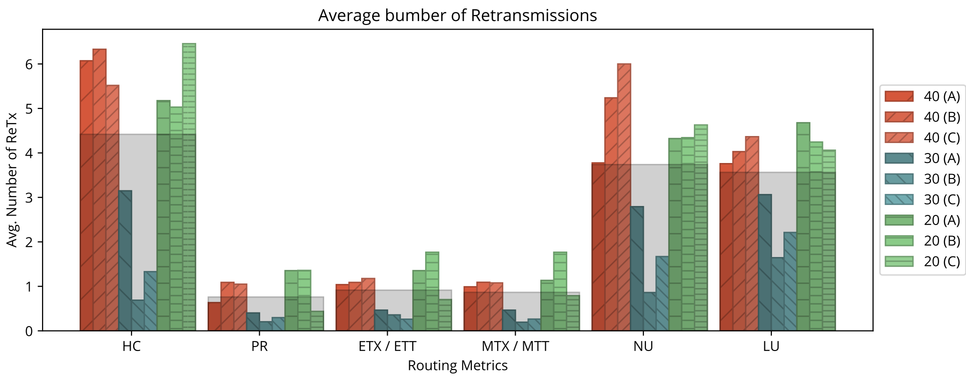

Figure D.10.: Low saturation scenario, average number of retransmissions. No bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

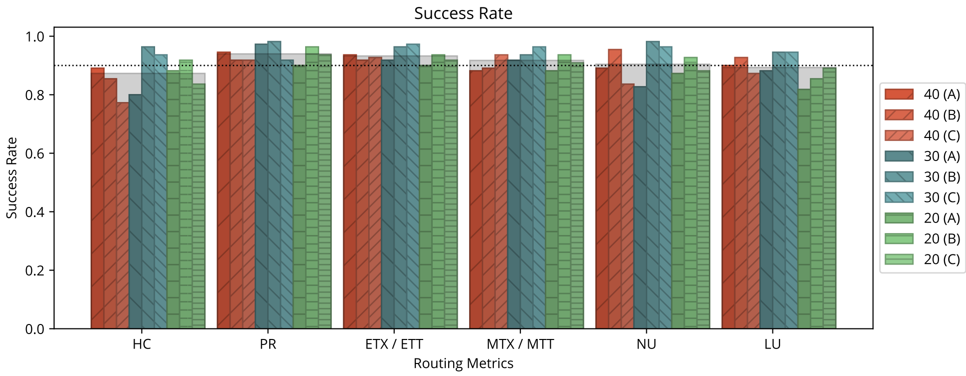

Figure D.11.: Low saturation scenario, success ratio of journeys. No bandwidth management.

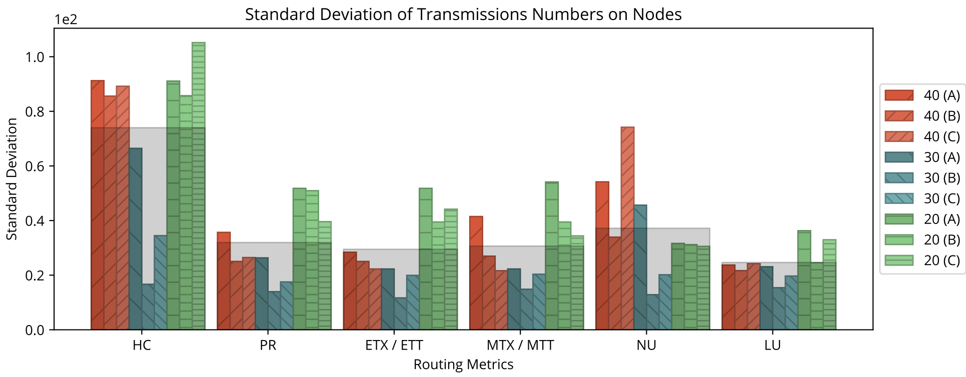

Figure D.12.: Low saturation scenario, standard deviation over the number of transmissions of each node in the network. No bandwidth management.

With Bandwidth Management

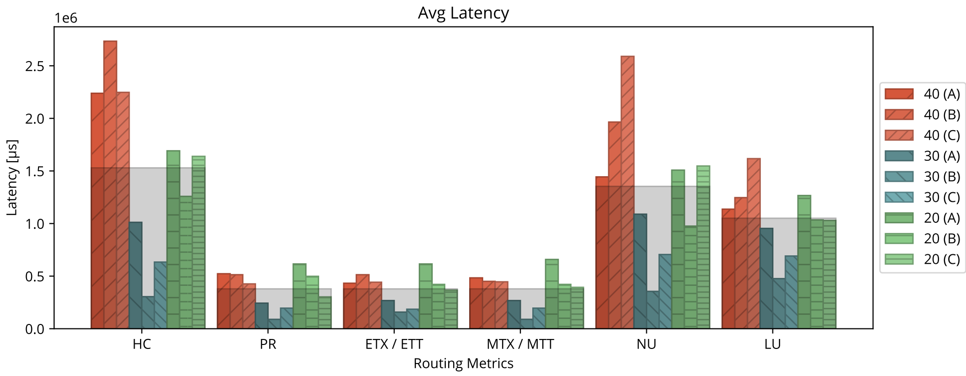

Figure D.13.: Low saturation scenario, average latencies. With bandwidth management.

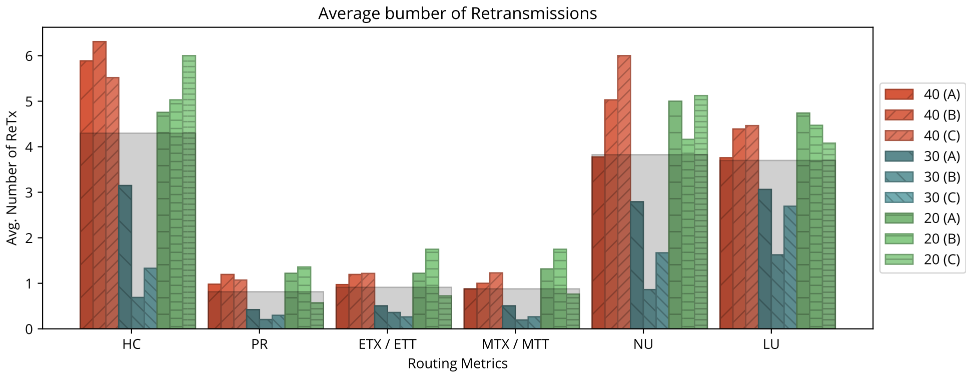

Figure D.14.: Low saturation scenario, average number of retransmissions. With bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

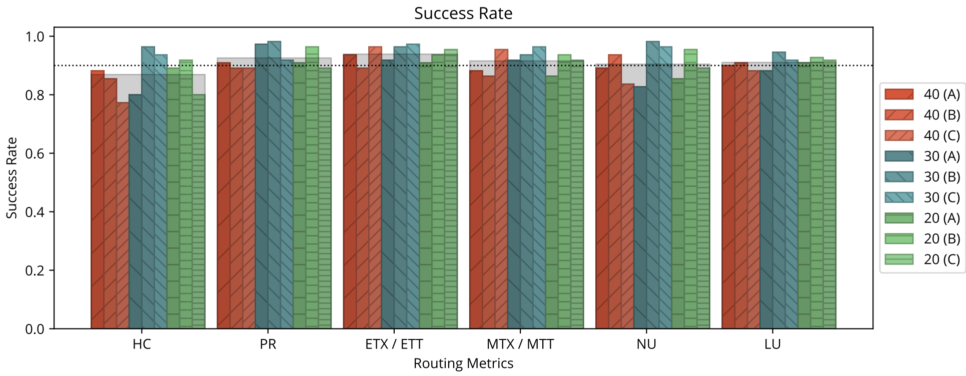

Figure D.15.: Low saturation scenario, success ratio of journeys. With bandwidth management.

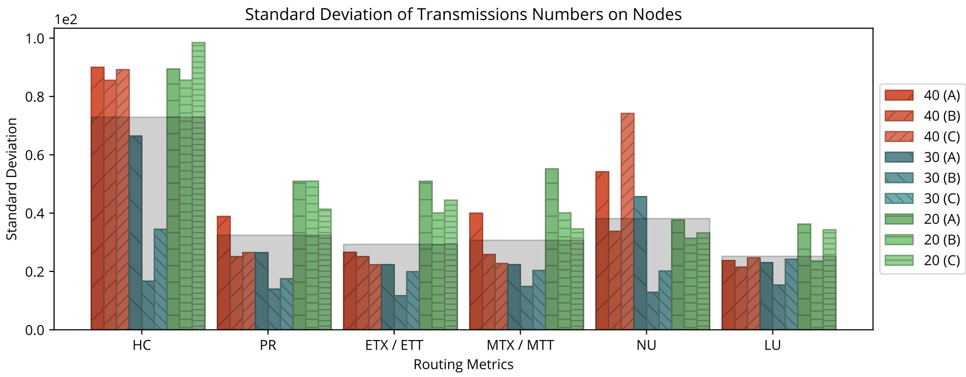

Figure D.16.: Low saturation scenario, standard deviation over the number of transmissions of each node in the network. With bandwidth management.

High Traffic Scenario

No Bandwidth Management

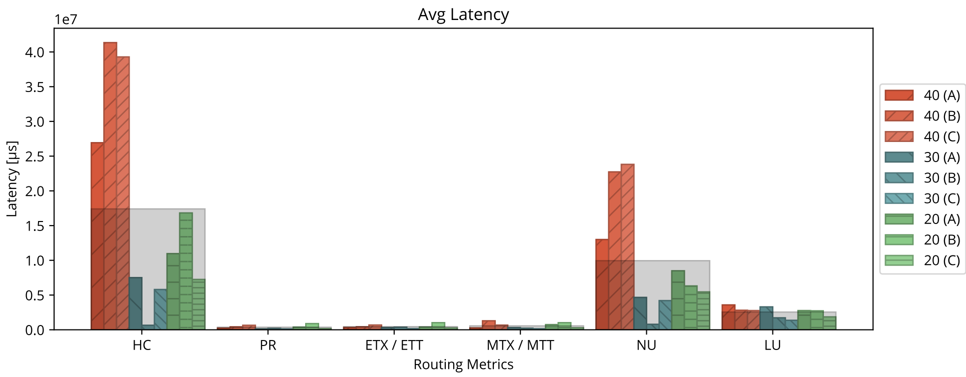

Figure D.17.: High traffic scenario, average latencies. No bandwidth management.

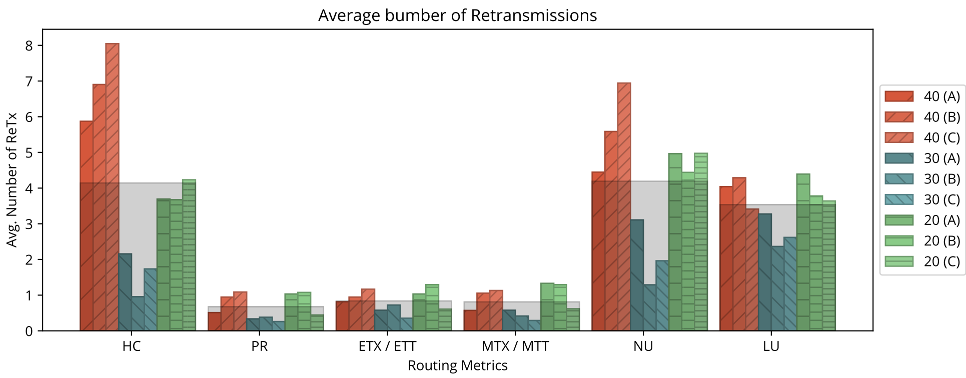

Figure D.18.: High traffic scenario, average number of retransmissions. No bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

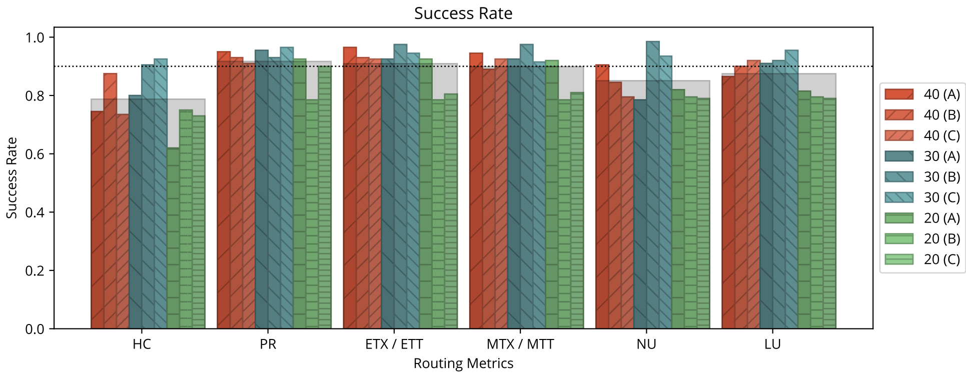

Figure D.19.: High traffic scenario, success ratio of journeys. No bandwidth management.

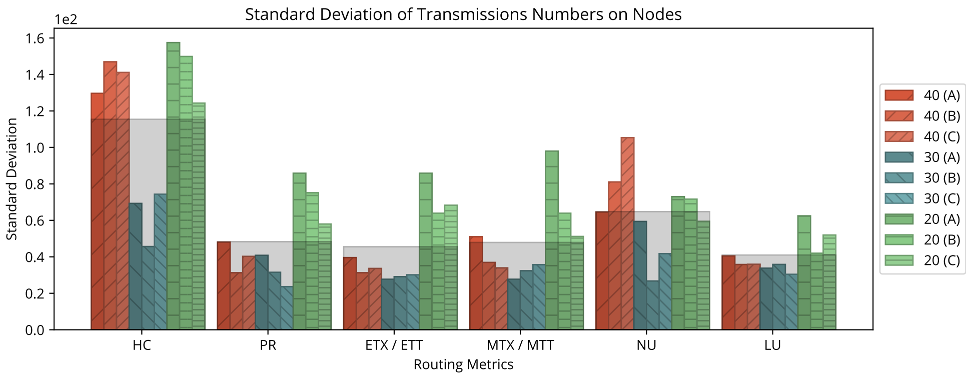

Figure D.20.: High traffic scenario, standard deviation over the number of transmissions of each node in the network. No bandwidth management.

With Bandwidth Management

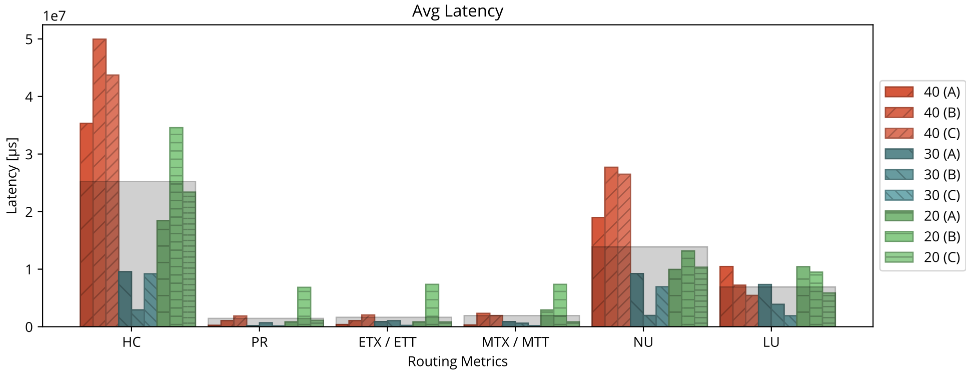

Figure D.21.: High traffic scenario, average latencies. With bandwidth management.

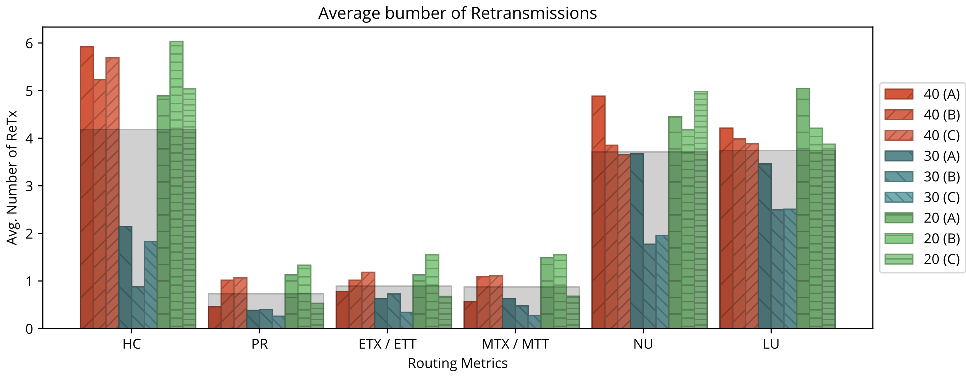

Figure D.22.: High traffic scenario, average number of retransmissions. With bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

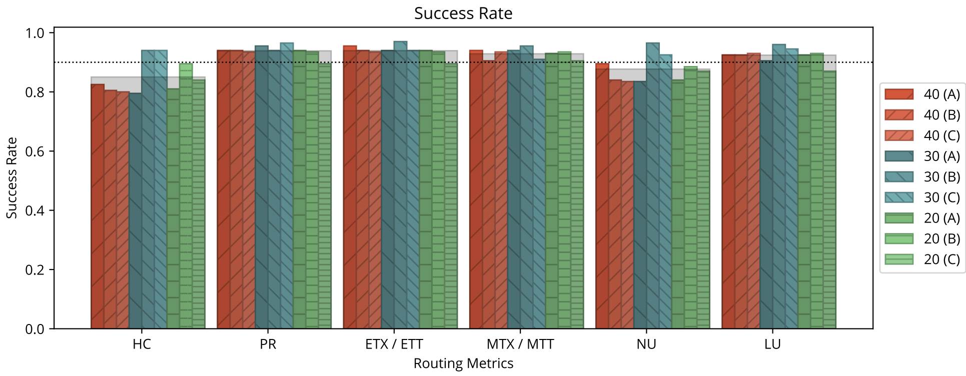

Figure D.23.: High traffic scenario, success ratio of journeys. With bandwidth management.

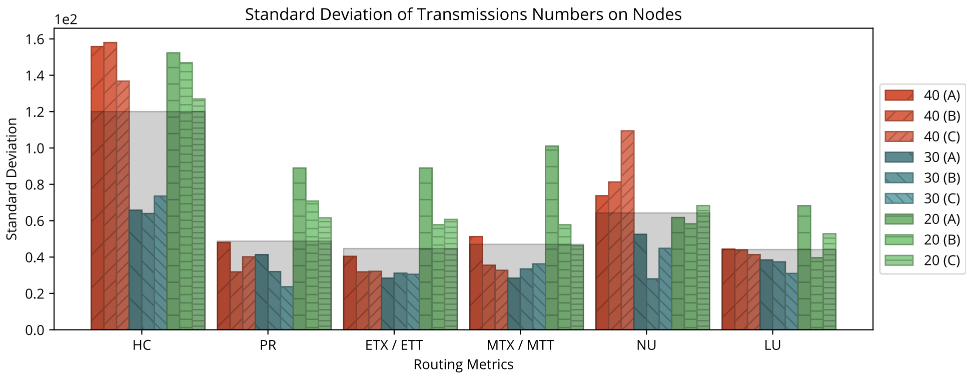

Figure D.24.: High traffic scenario, standard deviation over the number of transmissions of each node in the network. With bandwidth management.

High Saturation Scenario

No Bandwidth Management

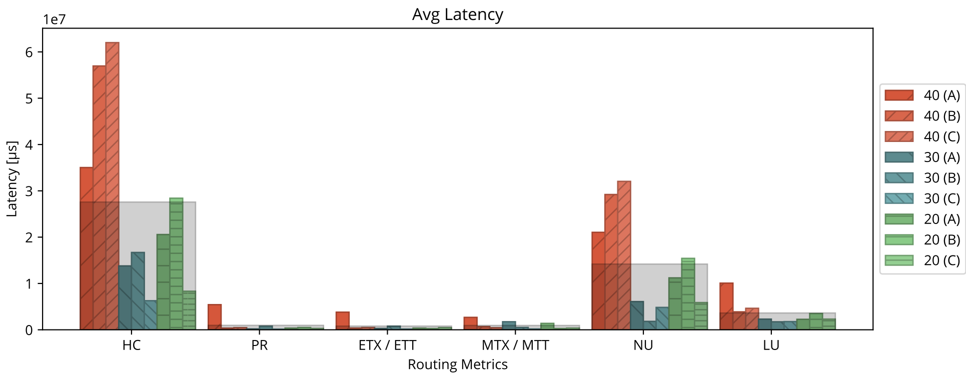

Figure D.25.: High saturation scenario, average latencies. No bandwidth management.

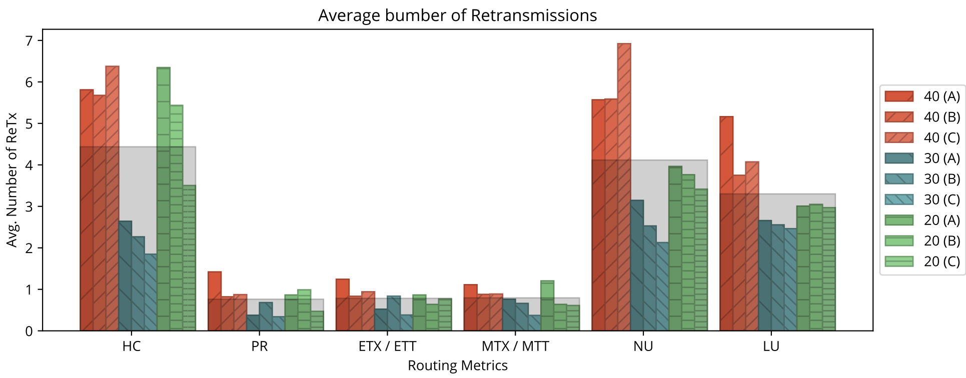

Figure D.26.: High saturation scenario, average number of retransmissions. No bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

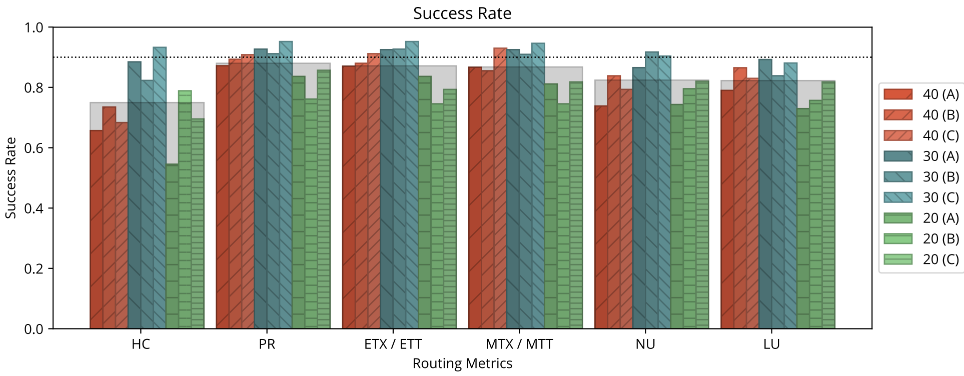

Figure D.27.: High saturation scenario, success ratio of journeys. No bandwidth management.

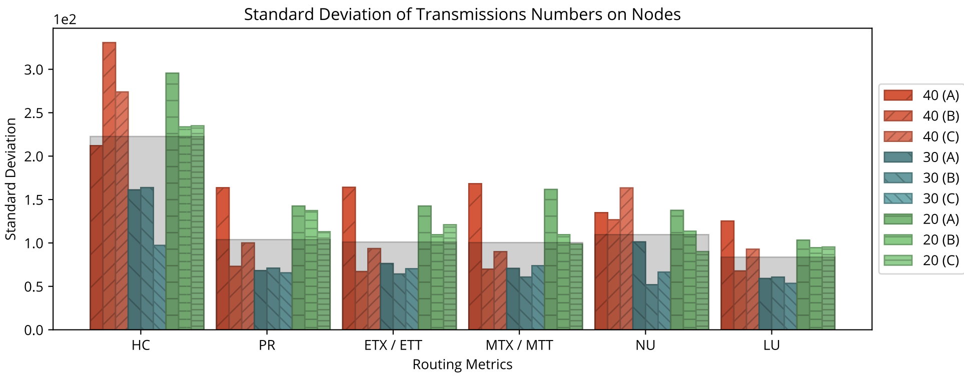

Figure D.28.: High saturation scenario, standard deviation over the number of transmissions of each node in the network. No bandwidth management.

With Bandwidth Management

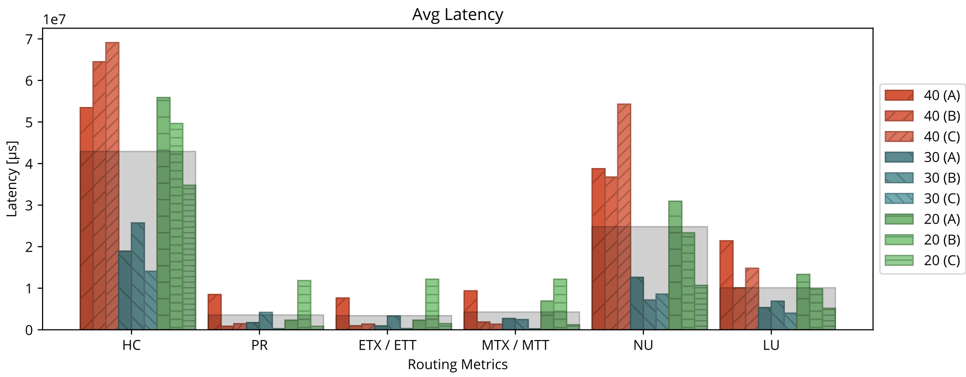

Figure D.29.: High saturation scenario, average latencies. With bandwidth management.

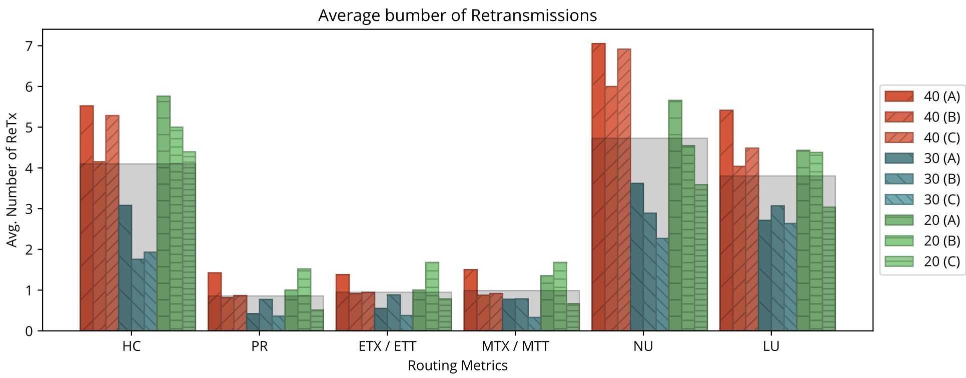

Figure D.30.: High saturation scenario, average number of retransmissions. With bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

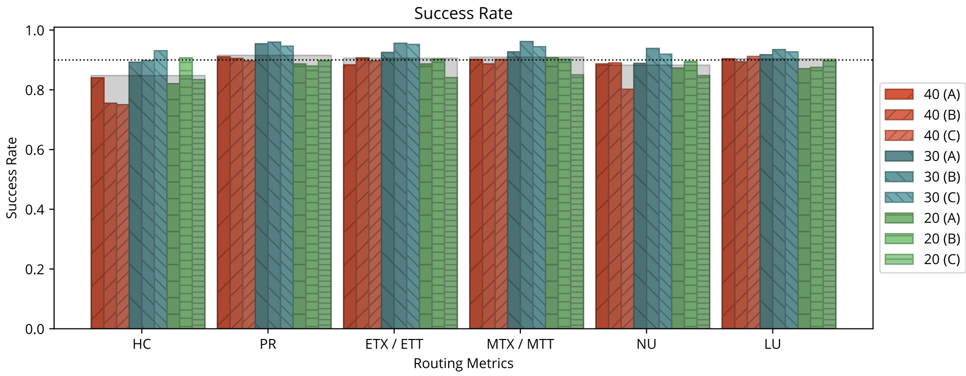

Figure D.31.: High saturation scenario, success ratio of journeys. With bandwidth management.

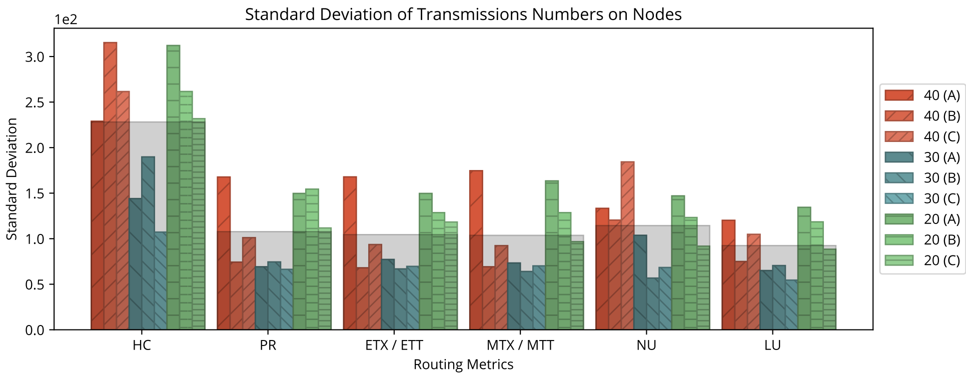

Figure D.32.: High saturation scenario, standard deviation over the number of transmissions of each node in the network. With bandwidth management.

Node-to-Sink Scenario

No Bandwidth Management

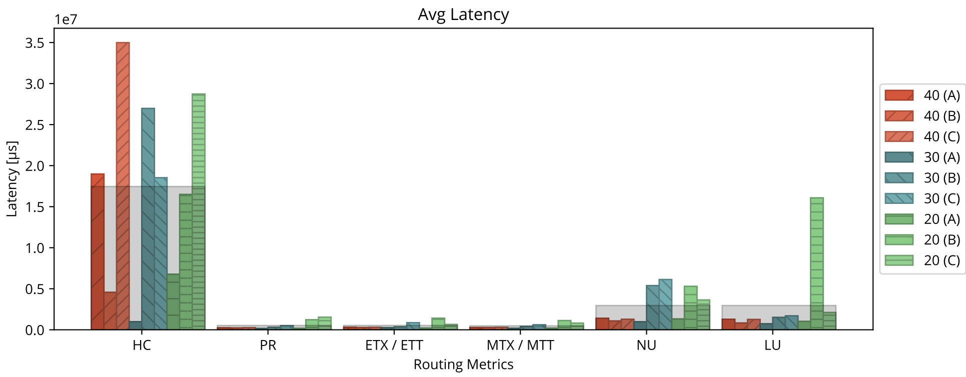

Figure D.33.: Node-to-sink scenario, average latencies. No bandwidth management.

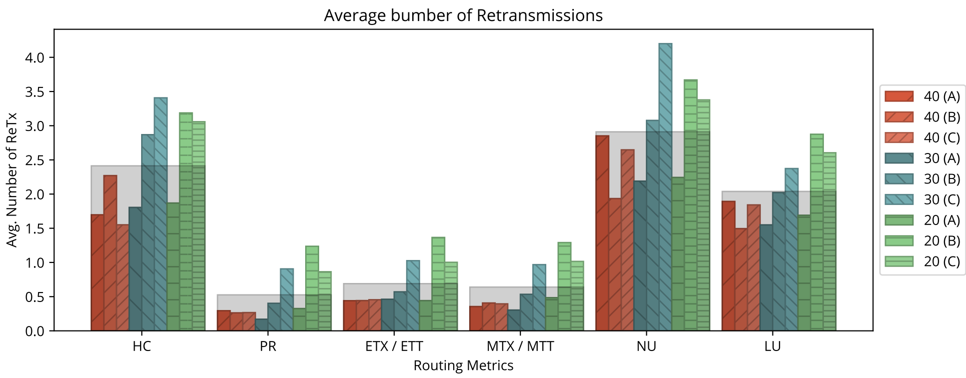

Figure D.34.: Node-to-sink scenario, average number of retransmissions. No bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

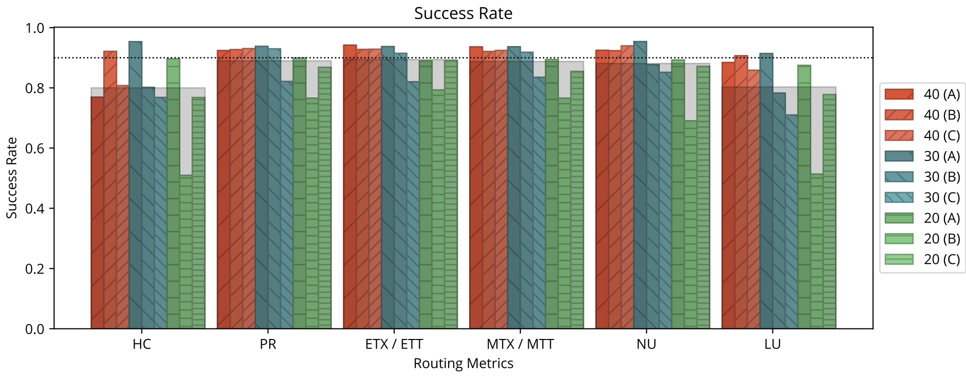

Figure D.35.: Node-to-sink scenario, success ratio of journeys. No bandwidth management.

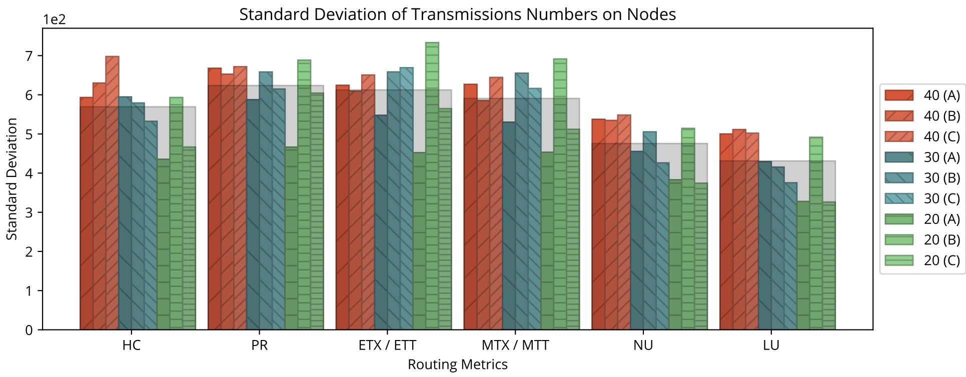

Figure D.36.: Node-to-sink scenario, standard deviation over the number of transmissions of each node in the network. No bandwidth management.

With Bandwidth Management

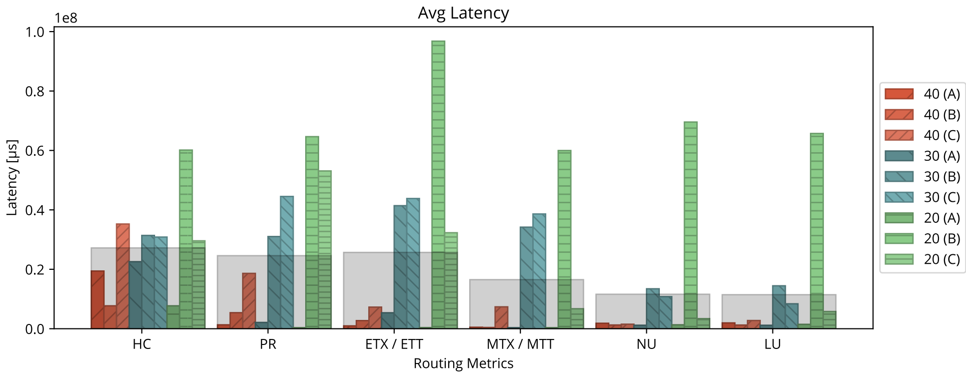

Figure D.37.: Node-to-sink scenario, average latencies. With bandwidth management.

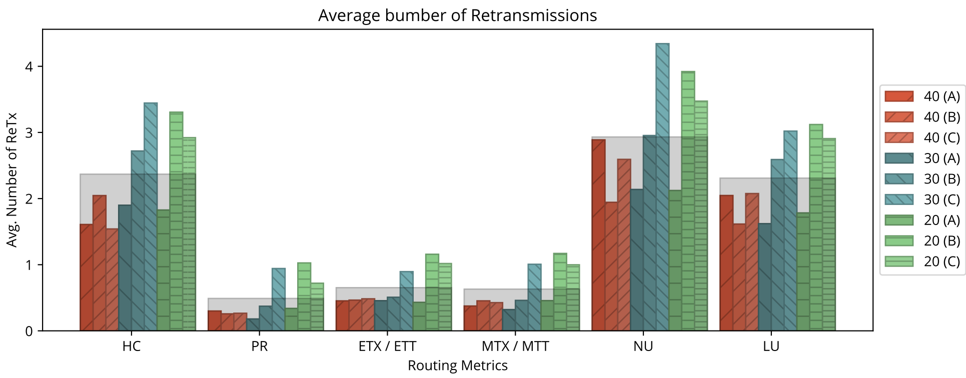

Figure D.38.: Node-to-sink scenario, average number of retransmissions. With bandwidth management. When comparing the total number of retransmissions, it is important to also refer to the success rate of journeys.

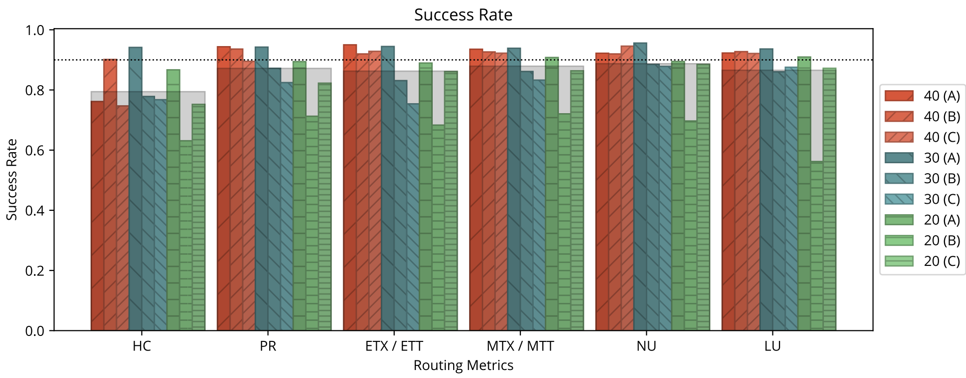

Figure D.39.: Node-to-sink scenario, success ratio of journeys. With bandwidth management.

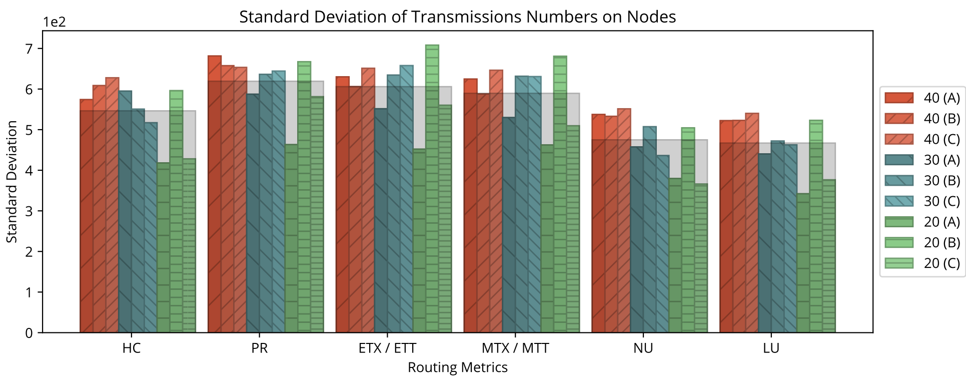

Figure D.40.: Node-to-sink scenario, standard deviation over the number of transmissions of each node in the network. With bandwidth management.

Bibliography

[1] IEEE Standard for Information technology– Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput. *IEEE Std 802.11n-2009 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, and IEEE Std 802.11w-2009)*, pages 1–565, Oct 2009.

[2] Kemal Akkaya and Mohamed Younis. A Survey on Routing Protocols for Wireless Sensor Networks. *Ad Hoc Networks*, 3(3):325 – 349, 2005.

[3] Ian F. Akyildiz, Tommaso Melodia, and Kaushik R. Chowdhury. A Survey on Wireless Multimedia Sensor Networks. *Computer Networks*, 51:921–960, 2007.

[4] Ian F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless Sensor Networks: a Survey. *Computer Networks*, 38(4):393 – 422, 2002.

[5] Rainer Baumann, Simon Heimlicher, Mario Strasser, and Andreas Weibel. A Survey on Routing Metrics. TIK Report 262, Computer Engineering and Networks Laboratory ETH-Zentrum, Switzerland, 2007.

[6] P. Bremaud. *Markov Chains: Gibbs Fields, Monte Carlo Simulation, and Queues*. Texts in Applied Mathematics. Springer New York, 2013.

[7] M. E. M. Campista, P. M. Esposito, I. M. Moraes, L. H. M. k. Costa, O. C. M. b. Duarte, D. G. Passos, C. V. N. De Albuquerque, D. C. M. Saade, and M. G. Rubinstein. Routing Metrics and Protocols for Wireless Mesh Networks. *IEEE Network*, 22(1):6–12, Jan 2008.

[8] Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris. A High-throughput Path Metric for Multi-hop Wireless Routing. In *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking*, MobiCom '03, pages 134–146, New York, NY, USA, 2003. ACM.

[9] E. W. Dijkstra. A Note on Two Problems in Connexion With Graphs. *Numerische Mathematik*, 1(1):269–271, Dec 1959.

[10] Richard Draves, Jitendra Padhye, and Brian Zill. Routing in multi-radio, multi-hop wireless mesh networks. In *Proceedings of the 10th Annual International Conference on Mobile Computing and Networking*, MobiCom '04, pages 114–128, New York, NY, USA, 2004. ACM.

[11] S. Ehsan and B. Hamdaoui. A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks. *IEEE Communications Surveys Tutorials*, 14(2):265–278, Second 2012.

[12] Luis Javier García Villalba, Ana Lucila Sandoval Orozco, Alicia Triviño Cabrera, and Cláudia Jacy Barenco Abbas. Routing Protocols in Wireless Sensor Networks. *Sensors*, 9(11):8399–8421, 2009.

[13] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient Communication Protocol for Wireless Microsensor Networks. In *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, pages 10 pp. vol.2–, Jan 2000.

[14] Wendi Heinzelman, Joanna Kulik, and Hari Balakrishnan. Adaptive Protocols for Information Dissemination in Wireless Sensor Networks. Aug 1999.

[15] C. E. Koksal and H. Balakrishnan. Quality-Aware Routing Metrics for Time-Varying Wireless Mesh Networks. *IEEE Journal on Selected Areas in Communications*, 24(11):1984–1994, Nov 2006.

[16] Yanjun Li, Chung Shue Chen, Ye-Qiong Song, and Zhi Wang. Real-time qos support in wireless sensor networks: A survey. *IFAC Proceedings Volumes*, 40(22):373 – 380, 2007. 7th IFAC Conference on Fieldbuses and Networks in Industrial and Embedded Systems.

[17] A. Lindgren, A. Almquist, and O. Schelen. Evaluation of Quality of Service Schemes for IEEE 802.11 Wireless LANs. In *Proceedings LCN 2001. 26th Annual IEEE Conference on Local Computer Networks*, pages 348–351, 2001.

[18] S. Lindsey and C. S. Raghavendra. PEGASIS: Power-efficient Gathering in Sensor Information Systems. In *Proceedings, IEEE Aerospace Conference*, volume 3, pages 3–1125–3–1130 vol.3, 2002.

[19] C. Lott and D. Teneketzis. Stochastic Routing in Ad-hoc Networks. *IEEE Transactions on Automatic Control*, 51(1):52–70, Jan 2006.

[20] A. Manjeshwar and D. P. Agrawal. TEEN: A Routing Protocol for Enhanced Efficiency in Wireless Sensor Networks. In *Proceedings 15th International Parallel and Distributed Processing Symposium. IPDPS 2001*, pages 2009–2015, April 2001.

[21] K. Mathews, C. Kramer, and R. Gotzhein. Token Bucket Based Traffic Shaping and Monitoring for WLAN-based Control Systems. In *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pages 1–7, Oct 2017.

[22] R. C. Shah and J. M. Rabaey. Energy Aware Routing for Low Energy Ad-hoc Sensor Networks. In *2002 IEEE Wireless Communications and Networking Conference Record. WCNC 2002 (Cat. No.02TH8609)*, volume 1, pages 350–355 vol.1, Mar 2002.

[23] F. Sivrikaya, T. Geithner, C. Truong, M. A. Khan, and S. Albayrak. Stochastic Routing in Wireless Sensor Networks. In *2009 IEEE International Conference on Communications Workshops*, pages 1–5, June 2009.

[24] Ya Xu, John Heidemann, and Deborah Estrin. Geography-informed Energy Conservation for Ad Hoc Routing. In *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking*, MobiCom '01, pages 70–84, New York, NY, USA, 2001. ACM.

[25] Jin Y. Yen. Finding the K Shortest Loopless Paths in a Network. *Management Science*, 17(11):712–716, 1971.

[26] Yan Yu, Ramesh Govindan, and Deborah Estrin. Geographical and Energy Aware Routing : a Recursive Data Dissemination Protocol for Wireless Sensor Networks. 2001.

[27] Hua Zhu, Ming Li, I. Chlamtac, and B. Prabhakaran. A Survey of Quality of Service in IEEE 802.11 Networks. *IEEE Wireless Communications*, 11(4):6–14, Aug 2004.

[28] A. E. Zonouz, L. Xing, V. M. Vokkarane, and Y. L. Sun. Reliability-Oriented Single-Path Routing Protocols in Wireless Sensor Networks. *IEEE Sensors Journal*, 14(11):4059–4068, Nov 2014.