# A Survey on Routing Metrics

TIK Report 262

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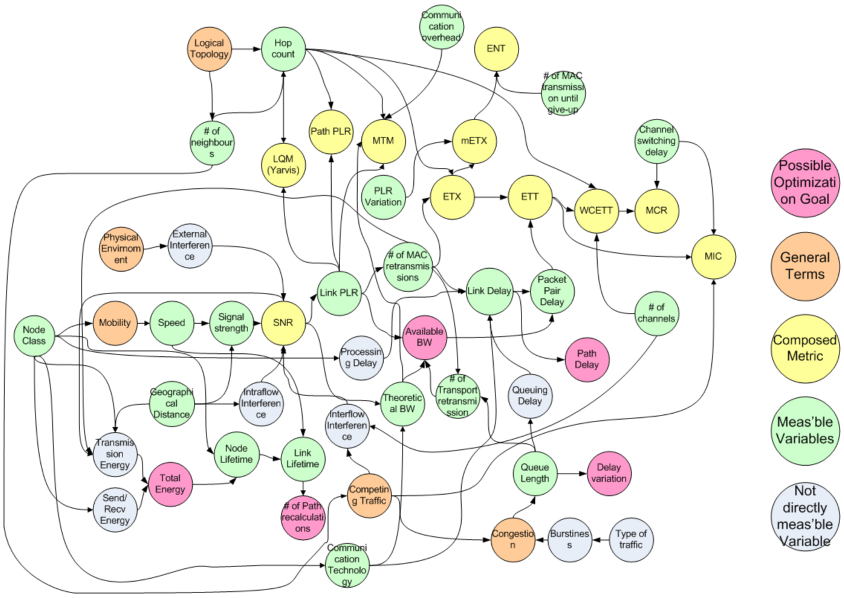

**Abstract**

Routing is the key functionality for directing communication over large networks. Optimal paths are determined based on routing metrics. In this report, we first develop a taxonomy for categorizing and classifying of routing metrics. Then, we give an extensive overview of routing metrics and apply our classification to them.

# 1 Introduction

Routing is the key functionality for directing communication over large networks. Optimal paths are determined based on routing metrics. In this report, we first develop a taxonomy for categorizing and classifying of routing metrics. Then, we give an extensive overview of routing metrics and apply our classification to them. The surveyy of metrics are arranged in five sections, based on their functional usage: Traffic-based, radio-related, topology-based, mobility-based and geographical, and finally energy-related metrics.

# 2 Taxonomy

In the following section, we propose a novel taxonomy for routing metrics. The purpose of this taxonomy is to bring structure into the complex area of routing metrics. It provides a decision-making aid for the choice of appropriate metrics for a given problem.

Our classification scheme consists of five different aspects under which a metric is investigated: Influence factors, mathematical properties, design goal of the metric, implementation characteristics and finally a qualitative evaluation of the metric. Each of these aspects consists of various sub-classifications.

## 2.1 Factors of Influence

The value of many metrics is governed by various different effects. Often, it is not trivial to identify all these factors. There are two different types of such factors: Environmental factors and network-immanent factors (see Figure 1).

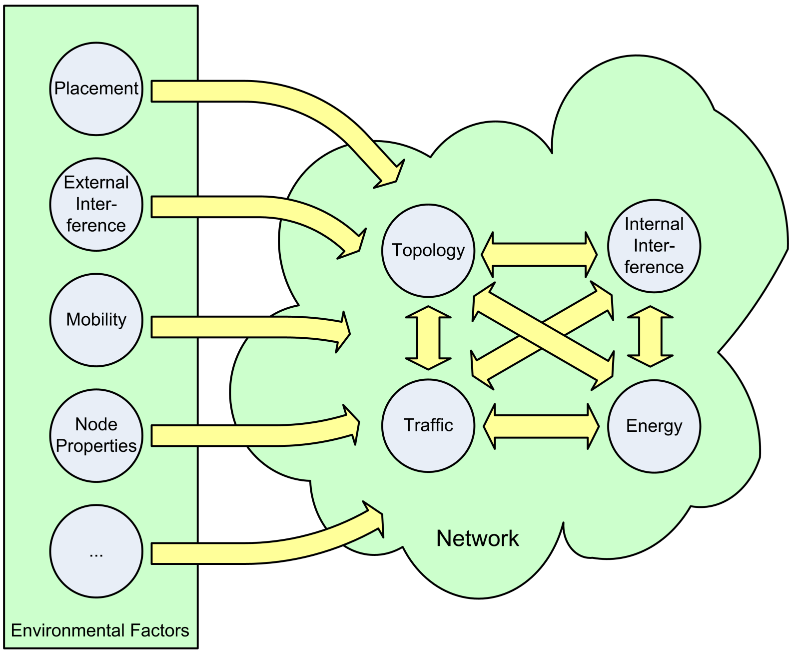

**Figure 1:** *Factors of influence: Environmental and network-immanent factors*

1. **Environmental Factors** are defined as factors that influence the metric, but are not affected by the network. With other words: Environmental factors are parameters that are not subject to feedback from the network. Examples for environmental factors are the placement and mobility of the nodes, their technical properties or external interference.

2. **Network-Immanent Factors** are defined as factors that depend directly or indirectly from the traffic within a network. Among these factors are congestion, internal interference (inter-flow and intra-flow interference), the consumed energy[1] and e.g. in IEEE 802.11 systems also the topology of the network[2].

In the survey, the influencing factors of a metric are described using flow diagrams.

## 2.2 Mathematical Properties

Metrics can be classified into a number of mathematical categories.

1. **Link Combination Operator:** Link metrics are aggregated and concatenated according to certain rules in order to attain the metric of a path. Each combination operator defines a class. While the concatenation operator is clearly defined for most metrics, the definition of the aggregation operator often is less straightforward.

2. **Dynamic vs. Static:** A metric is dynamic, if the value of the metric changes over time. This is the case for most metrics. Examples for static metrics are the number of interfaces of a node or the maximal energy capacity.

3. **Symmetric vs. Asymmetric:** Let $d_{i,j}$ be the metric value of the link from node $i$ to node $j$ and $d_{j,i}$ the link in the opposite direction. A metric is symmetric if $d_{i,j} = d_{j,i}$ holds for all links and all points in time.

4. **Single-Dimensional vs. Multi-Dimensional Metrics:** Multi-dimensional metrics are not of type real, but they are vectors. Wang and Crowcroft [94] use delay and bandwidth for the design of a two-dimensional metric. Iannone et al. [43] do the same for PLR, interference level and data rate. Sometimes, multi-dimensional metrics are also called *multiple metrics* because they can be decomposed into single-dimensional metrics.

   Wang and Crowcroft [94] prove that finding a shortest path in a network with multi-dimensional metrics is NP-complete, for multiplicative as well as for additive metrics, if it is done in the same fashion as in the single-dimensional case. Therefore, multi-dimensional metrics are not used in practise to the best of our knowledge.

## 2.3 Design Perspective

This aspect describes the design goals of a metric. We divide this aspect into two sub-classification dimensions:

1. **Target Platform:** What system was the metric originally designed for? Most metrics are laid out for standard Internet applications, QoS Internet applications, MANETs or WMNs.

2. **Optimisation Goal:** What is the optimisation goal of the metric? This can be e.g. “minimise energy”, “maximise node lifetime”, “maximise average end-to-end throughput”, “guarantee a minimal bandwidth” or “minimise delay”.

   We point out that a metric which is dedicated to a certain goal must not necessarily be able to fit this goal. For example, the delay metric originally was proposed to minimise delay. In many cases, however, it produces an end-to-end delay which is worse than the hop count metric. Please refer to Section 2.5 on evaluation criteria to read more about performance evaluation of metrics.

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[1] Of course, the amount of traffic influences the consumed energy. But topology can have an effect on energy, as well. In systems that adapt transmission energy, one long hops may consume more energy than a series of short hops (see Section 7.1).

[2] IEEE 802.11 systems adapt the communication radius according to the present interference. Therefore, the neighbourhood of a node changes in dependence of the competing traffic.

## 2.4 Implementation Characteristics

The implementation characteristics specify the properties of a metric which are related to practical implementation problems.

1. **Combined Metrics** are metrics that are mathematically combined from other metrics and do not base on own measurements. A typical example is the ETT metric (Section 3.10). This metric is calculated by multiplying bandwidth with the ETX metric (Section 3.8).

2. **Layer:** This property describes which OSI layer provides the required information. Traditionally, routing metrics are calculated only from information available directly on the network layer. Today, however, many researchers acknowledge the need for cross-layer approaches for designing routing metrics for MANETs and WMNs).

3. **Analytically vs Empirically-Defined Metrics:** Some network quantities – for example the available bandwidth – are very well suited for analytical description, but are rather complex to measure. Metrics that are defined using such properties are called *analytically-specified.* Other variables can be measured conveniently, but it is not trivial to interpret them analytically. This kind of metrics is termed *empirically specified* [77].

4. **Information Acquiring Method:** There are various ways how metrics acquire the information they need. We define the following classes:

   *Node-related:* Information for the metric is acquired from a node without high effort. This may be fixed values like the number of interfaces of a node, configured values like the financial communication costs or variable values like the length of input and output queues.

   *Passive Monitoring:* Information for the metric is gathered by observing the traffic coming in and going out of a node. In combination with other measurements, this can be used e.g. to estimate the available bandwidth.

   *Piggy-back Probing:* Measurements are done by including probing information into regular traffic or routing protocol packets without creating own packets for metric measurement. This is a common method to measure delay.

   *Active Probing:* For this technique, special packets are generated to measure the properties of a link. For more information on the problems of this technique, please refer to Section 3.1.1.

## 2.5 Evaluation

Qualitative and quantitative evaluation and comparison of metrics cannot be done in a simple manner. The assessment of a metric depends on various factors, among them are the applied performance goals, the utilized routing protocol and the postulated scenario in terms of placement, mobility and communication capabilities of the nodes. Thus, the evaluation criteria and the resulting grading of metrics are subject to assumptions of average cases which are not perfectly objective. A truly satisfying evaluation would only be possible by deploying all metrics in various application scenarios, embedded in various routing protocols, implemented in various simulators and even in hardware. Of course, this would be beyond the scope of this master's thesis. Nevertheless, it is possible to make qualitative statements on metrics using general assumptions and earlier studies on this topic. Hence, we tried to rate the metrics as thoroughly as possible and predict their performance as accurate as we could basing on all information and related studies that we disposed of.

In order to provide developers with a concise and fast decision help, we condensed the central evaluation criteria of metrics in six categories, each having four quality classes. Three categories rate the metric with respect to the performance indicators, two categories evaluate the ease of implementation (complexity and measurability) and one category specifies how widely used a metric is (see Fig. 2). An ovreview example is given in Fig. 3.

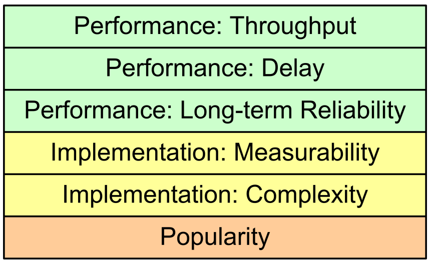
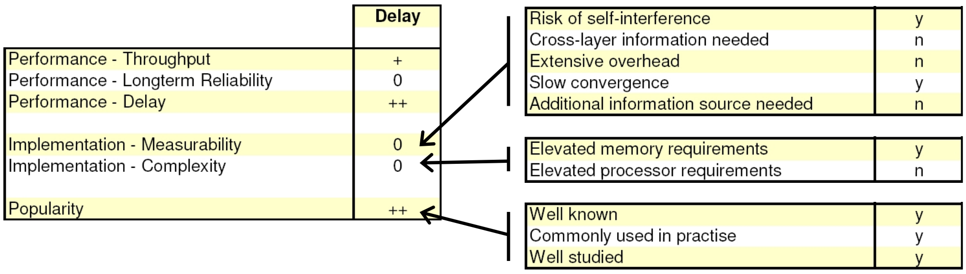


**Figure 2:** *Six Evaluation Criteria*



| | Delay |
|---|---|
| Performance - Throughput | + |
| Performance - Longterm Reliability | 0 |
| Performance - Delay | ++ |
| Implementation - Measurability | 0 |
| Implementation - Complexity | 0 |
| Popularity | ++ |

| | |
|---|---|
| Risk of self-interference | y |
| Cross-layer information needed | n |
| Extensive overhead | n |
| Slow convergence | y |
| Additional information source needed | n |

| | |
|---|---|
| Elevated memory requirements | y |
| Elevated processor requirements | n |

| | |
|---|---|
| Well known | y |
| Commonly used in practise | y |
| Well studied | y |

**Figure 3:** *Example of the Six Evaluation Criteria*

### 2.5.1 I-III Three Performance Criteria

Metrics are evaluated along three performance criteria that we identify as fundamental: Throughput, delay and long-term reliability. These criteria, first, are orthogonal i.e. independent from each other and, secondly, they describe the properties of a network which are of interest for the user of a communication network.

For the evaluation, we always suppose an optimal implementation which has been tuned perfectly. The four quality classes are defined as: (++) has a clearly positive effect, (+) tends to have a positive effect in certain situations, (0) neither positive nor negative effect can be anticipated and (-) negative effects will probably prevail.

### 2.5.2 IV Implementation – Measurability

The *measurement criteria* consists of five sub-criteria. If none of the sub-criteria applies, the metric is rated with (++), for one sub-criteria the rating is (+), for two is is (0). If more than two sub-criteria apply, the metric is rated with (-). The five sub-criteria are:

- Oscillation Stability: Is the metric vulnerable to self-interfering effects (see Section 3.1.2)?
- Cross-Layering: Does the metric need access to information provided by other layers?
- Overhead: Does the metric induce extensive measurement overhead? We define that a measurement overhead is extensive if more than one message exchange is performed per measurement. For example, a ping message is not considered extensive, whereas PATHCHAR or packet pair algorithms are.

- Freshness: Is there an inherent delay between the reaction of the metric to changes of the measured value? Are there transient effects?
- Additional devices: Is data from an additional data source (e.g. a geographical positioning system) needed?

### 2.5.3 V Implementation – Complexity

The better the *complexity criteria*, the less are the computation and memory requirements that are implied by the metric. In fact, there are almost no metrics with high processing demands[3]. We assume elevated memory requirements whenever a series of measurements has to be stored in order to compute the current value of a metric.

### 2.5.4 VI Popularity

The *popularity criteria* indicates how widely used a metric is and on how much experience one can build. This criteria is composed of three sub-criteria:

- Is a metric well known i.e. is it cited often in literature?
- Is it in practical use outside the academical world?
- Is it well studied in literature?

## 2.6 Summary

In the following table, the aspects and categories of our taxonomy are summarised. We give an example for each sub-classification in italics. We will use this table format throughout the survey.

| **Factors of Influence** | see Figure |
|---|---|
| **Mathematical Structure** | Concatenation operator: *Addition*<br>Aggregation operator: *Minimum*<br>Other mathematical properties: *Dynamic, asymmetric, one-dimensional* |
| **Design Goals** | Target Platform: *Internet, QoS protocols*<br>Optimisation goal: *Minimise average end-to-end delay* |
| **Implement. Characteristics** | Layer: *Measurement possible on L2-L7*<br>Information acquiring method: *Monitoring, piggy-back or active probing possible*<br>Other properties: *Empirically and analytically defined, not combined* |
| **Evaluation** | Performance: Throughput = +<br>Performance: Delay = ++<br>Performance: Reliability = 0<br>Implementation: Measurability = 0<br>Implementation: Complexity = 0<br>Popularity = ++ |

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[3] Theoretically, multidimensional metrics are np-complete and, therefore, require high processing efforts. However, we do not know of any practical implementations of multidimensional metrics.

# 3 Traffic-Based Metrics

When using wireless networks for Internet or other communication applications, many design goals are related to network traffic: High throughput, small delay, or limited variance of the connection quality. It is an obvious idea to incorporate traffic indicators into routing algorithms. Many metrics were proposed that attempt to do this. However, measuring traffic variables is a sophisticated challenge and the risk of obtaining unstable network behaviour is high.

Some implementation problems are common to all traffic-based metrics. In the first section, some general considerations regarding the measurement of traffic are presented. In the subsequent sections, single traffic metrics, their strengths, their limitations and their pitfalls will be discussed.

## 3.1 Traffic Measurement

### 3.1.1 Generating Probing Packets

Many metrics require some kind of probing messages in order to measure the quality of a link or a path. This technique entails different challenges.

Several authors point out that probing does not always reflect what a metric wants to measure. For example, routing traffic or ICMP packets, which both are used regularly for probing, often have higher priority in routing queues than normal traffic. These so-called *out-of-band* measurements may not reflect the network condition normal traffic is subject to. On the other hand, if the probing packets are interlaced with the regular traffic (so-called *intrusive* or *in-band* measurement), the probes themselves influence the amount of traffic. Ferguson and Huston [31] compare this effect with the Heisenberg Uncertainty Principle. Lundgren et al. [63] and later Zhang et al. [97] observed that the different properties of unicast and broadcast communication in IEEE 802.11 systems may lead to similar effects: Probes that are sent using the broadcast mechanism will report neighbours that are not reachable using unicast communication. Both papers call this phenomenon the *grey zone* problem.

Another problem are the intervals at which probing messages are generated. An overly small interval produces unnecessarily large amount of overhead, while the risk of missing important information increases with greater intervals. RFC 3432 [82] is dedicated to such considerations.

### 3.1.2 Oscillation Stability

Certain metrics tend to provoke oscillating traffic patterns. This effect can be explained as follows: Once a link is recognized as good, it attracts a lot of traffic. Consequently, the link becomes jammed and it is assigned with a worse metric value. As traffic starts to route around this link, its metric value increases again and the effects starts anew. This phenomenon, called *self-interference*, was observed already in the first Internet applications [51].

The level of oscillation stability may not only depend on the principal characteristic of a metric but also on the implementation details. In many cases, the risk of self-interference can be reduced by smoothing out short-term peaks in the value of a metric (see next section). However, this method conflicts with the goal that metrics should represent the current state of the network. Furthermore, the choice of parameters for smoothing is rather delicate.

### 3.1.3 Filtering Measurements

Some network parameters that are central for certain metrics are subject to high variation, e.g. delay or link loss ratio. Usually, it is desired that short-term variations do not influence the value of a metric, as this could cause disproportionate adaptations of the metric and would increase the risk of self-interference. Therefore, metric measurements should be filtered over time. Floyd et al. [32] propose three methods how this can be done by applying weighted averages of the measurements:

1. **Dynamic History Window:** An average is computed over a number of previous measurements. The size of the measurement window depends on the current transmission rate.
2. **Fixed History Interval:** An average is computed over a fixed number of previous measurements.
3. **Exponential Weighting Moving Average (EWMA):** Measurements are weighted with exponentially less the older they are. This can be stated with the following formula [6]. The current value is recalculated whenever a new sample of the delay measurements arrives.

   $$d_{new} = \alpha * d_{old} + (1 - \alpha) * d_{sample}$$

   with $\alpha \in [0, 1]$ being the weighting factor, $d_{sample}$ being the new sample, $d_{old}$ the current metric value and $d_{new}$ the newly calculated value. In fact, this calculation implements a discrete low pass filter [45].

Floyd et al. show that the Average Loss Interval method results in smoother TCP traffic in wired networks. Anderson et al. [6] confirm this finding for overlay networks. However, it is not clear whether this results can be translated to MANETs one-to-one (see e.g. Section 3.6 on packet loss metrics).

## 3.2 Delay

| **Name** | Delay, latency, transmission time |
|---|---|
| **Factors of Influence** | see Figure 4 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined (see following paragraphs)<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: QoS protocols, ARPANET<br>Optimisation goal: Minimise average end-to-end delay |
| **Implement. Characteristics** | Layer: Measurement possible on L2-L7<br>Information acquiring method: Monitoring, piggy-back or active probing possible<br>Empirically and analytically defined |
| **Evaluation** | Performance: Throughput = +<br>Performance: Delay = ++<br>Performance: Reliability = 0<br>Implementation: Measurability = 0<br>Implementation: Complexity = 0<br>Popularity = ++ |
| **Adaptations** | Expected Delay, Round-Trip Time |
| **Main References** | Draves et al. [27], Khanna et al. [51] |

The delay metric measures the time to send and receive a unicast packet from one node to another. There are three principal approaches on which this measurement may base: Active probing, piggy-back normal traffic or piggy-back routing information exchange messages.

Delay can be subdivided into six different phases, see Figure 5. The overall delay is composed from queuing delays ($Q_S$ and $Q_R$) , processing delays ($P_S$ and $P_R$), transmission delay $T$ and propagation delay $P$. Given a bandwidth $\rho$, the transmission delay for a packet of $b$ bits equals $b/\rho$. Thus, the overall delay $D$ follows the equation

$$D = P_S + Q_S + P + \frac{b}{\rho} + Q_R + P_R$$

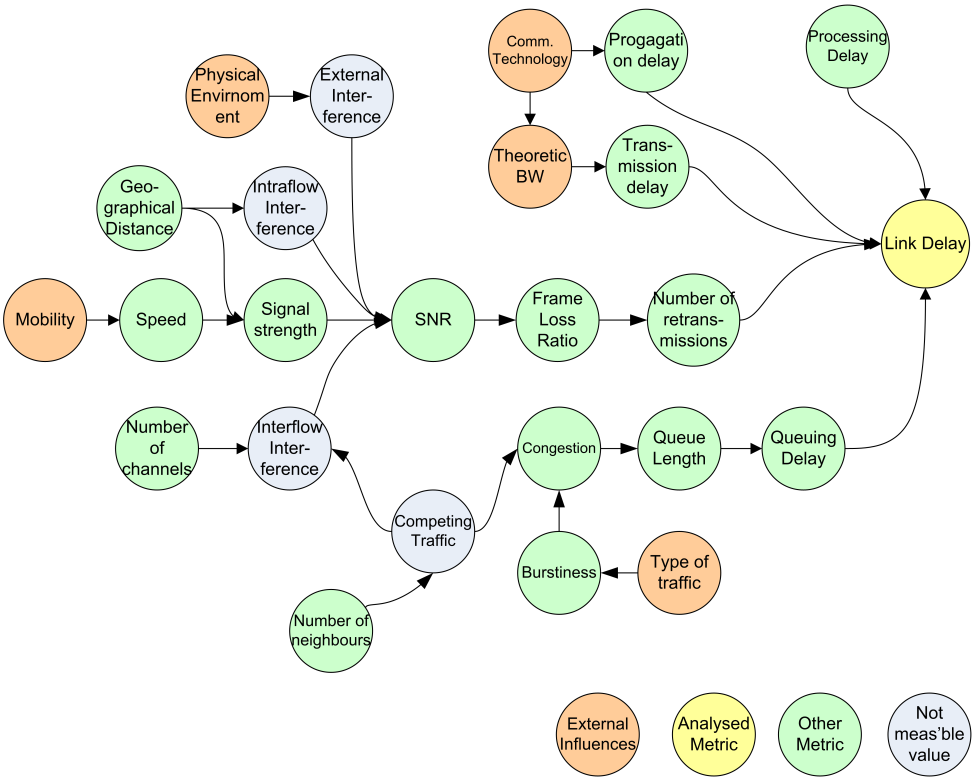

**Figure 4:** *Dependencies of the delay metric*

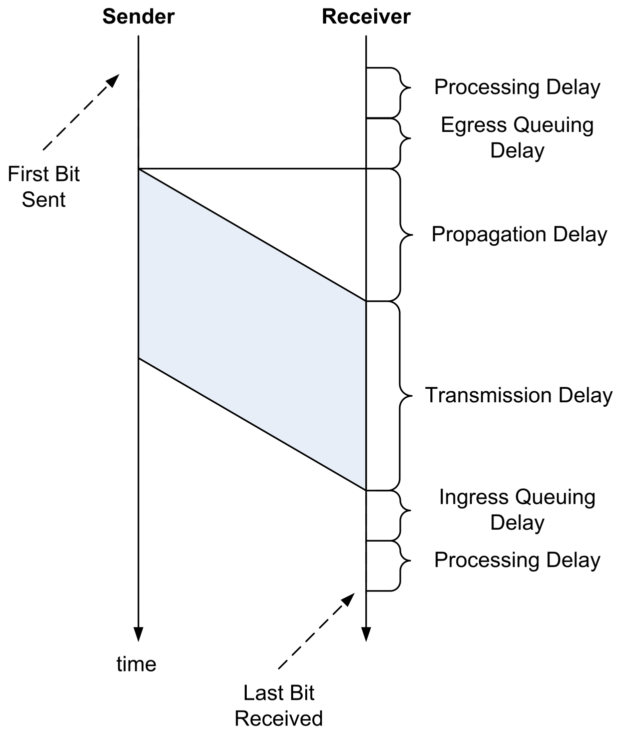

**Figure 5:** *Terminology of delay phases*

### 3.2.1 Moving Averages

The delay of a link normally is subject to considerable variance. For this reason, most protocols do not use only the currently measured value to determine the metric for a link, but they utilize a weighted average. Usually, an Exponential Weighting Moving Average (EWMA) is applied (see Section 3.1.3). For example, Gupta and Kumar [40] propose to use EWMA for their MANET routing algorithm, calling it *Expected Delay*. To the best of our knowledge, there was no evaluation published on how the EWMA parameter is set appropriately in MANETs or WMNs.

### 3.2.2 Unidirectional Delay

When a delay is measured only in one way, it is necessary to synchronise the internal clocks of the two involved nodes. Therefore, most protocols do not use unidirectional delays, but round-trip times. Nevertheless, IETF RFC 2679 [3] describes a one-way delay metric for IP traffic. Recently, Shalunov et al. [86] drafted another unidirectional delay measurement protocol for the Internet.

The Round-Trip Time (RTT) quantifies the bidirectional delay of a link: A probe carrying a timestamp is sent to a neighbouring node. This node returns the probe immediately. Thus, the time is measured for a packet to travel to the neighbouring node and back again.

Different factors have to be taken into account when the advantages and disadvantages of RTT and unidirectional delays are weighted against each other. In a scenario with many asymmetric links and a lot of unidirectional traffic, a unidirectional delay metric will represent the capacity of links better than an RTT metric. On the other hand, time synchronisation is not required when RTT is used, as only the timestamp of the probing node needs to be evaluated.

Round-Trip Time measurements often are implemented using ICMP echo-request (ping) messages or information from TCP[4]. A definition for a more sophisticated protocol is given in IETF RFC 2681 [5]. For a more general overview of probing, please refer to Section 3.1.1.

Adya et al. propose to use RTT for their “Multi-Radio Unification Protocol” [1].

### 3.2.3 Combination of Links

Unidirectional delay and RTT can be measured either for each link separately or for an entire path. The sum of the delay of concatenated single links will result in the costs of the entire path. When a multi-path routing algorithm is used, multiple probes travelling on different paths will report different delays. There is a number of ways, how this values can be aggregated: Minimal delay, maximal delay, medium delay et cetera.

### 3.2.4 Performance and Instabilities

The deployment of unidirectional delay metric as well as of RTT can lead to unstable routes or oscillating load allocation when links are heavily utilised: Links with low load are given an attractive metric value and subsequently are overflown with traffic, while other links starve and only receive a better metric value after a while. For example, the first versions of ARPANET suffered from this problem (see Khanna and Zinky [51]). Draves et al. [27] call this phenomenon *self-interference* (see Section 3.1.2. Draves [27] measured in a test-bed experiment that RTT performed 3 to 6 times worse than Minimal Hop Count, Packet Pair or ETX metrics in terms of TCP throughput. He also attributes this to self-interference problems.

In order to reduce this issue, the parameters of this metric (e.g. the EWMA weighting factor, see Section 3.1.3) must be carefully adjusted. Further, Draves et al. propose to deploy a Packet Pair Delay metric (see Section 3.5.3) to decrease the impact of this phenomenon.

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[4] IETF RFC 1323 [44] gives some important hints on this technique. For example, retransmitted packets should not be taken into account for RTT measurement, as these packets will produce a distorting effect.

## 3.3 Delay Variation

| | |
|---|---|
| **Name** | Delay variation, jitter |
| **Factors of Influence** | see Figure 6 |
| **Mathematical Structure** | Concatenation operator: Addition (with restrictions, see following paragraphs)<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: QoS protocols<br>Optimisation goal: Minimise delay of streams |
| **Implement. Characteristics** | Layer: Measurement possible on L2-L4<br>Information acquiring method: Monitoring or piggy-back probing possible<br>Empirically and analytically defined |
| **Evaluation** | Performance: Throughput = 0<br>Performance: Delay = +<br>Performance: Reliability = 0<br>Implementation: Measurability = +<br>Implementation: Complexity = 0<br>Popularity = 0 |
| **Adaptations** | |
| **Main References** | IETF RFC 3393 [25] |

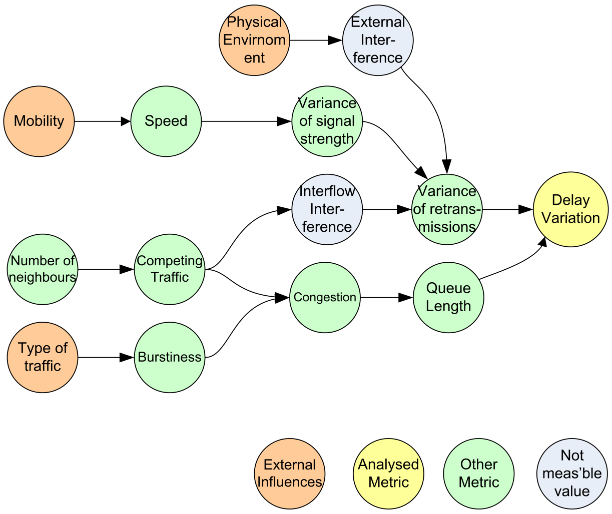

**Figure 6:** *Dependencies of delay variation metric*

*Delay variation* is the variation of a delay metric with respect to some reference value e.g. average delay or minimum delay (see IETF RFC 3393 [25]). In this section, we will assume that classical statistical variance[5] is used to describe the *delay variation*. Often – but not always – people utilize the term *jitter* interchangeably. As jitter is used also with slightly different meaning in other domains, we will avoid this term in this thesis.

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[5] The variance $Var(X)$ is defined as the expected value $E((X-\mu)^2)$ with $\mu$ being a mean value and $X$ a series of measurements.

The delay variation metric is of special interest for applications which are subject to some real-time restrictions, for example interactive voice or video communication. In such applications, the delay variation determines – among other things – the size of the buffers which are necessary to smooth the audio and/or video stream.

Like the delay metric, the delay variation can be measured either with active probing or piggy-back on normal or routing traffic. Unlike plain delay, delay variation is not reliant on time synchronisation, even for unidirectional measurements [25].

Due to the self-similarity ("burstiness") property of Internet traffic, delay variation will only converge in the long-term, if it converges at all. For more information on this topic, please refer to [59].

### 3.3.1 Combination of Links

When the delay variation is measured for a single-path routing algorithm on an entire path, the value is measured directly. But how do we calculate the metric for a path, if the Delay Variance is measured on each link separately? If the delay values of the concatenated links were uncorrelated, the sum of the single link delay variance measurements would represent the delay variance or the entire path. However, we claim that this is not the case. If one router is contented, the chances are high that two consecutive links will both report higher delays. Likewise, both delays will decrease simultaneously, as soon as traffic volumes become smaller.

When two links with the delay series $D_1$ and $D_2$ are concatenated, the resulting variance can be expressed with the following equation:

$$Var(D_1 + D_2) = Var(D_1) + Var(D_2) + 2 * Cov(D_1, D_2)$$

with $Cov(D_1, D_2)$ being the covariance of the delays of the two links. The calculations becomes more complicated when three or more links are involved. To the best of our knowledge, all systems that use delay variation measure the metric on the entire path and not on each link separately. Therefore, covariance does not play any role in these metrics. If we envision a system without the opportunity to measure delay variation on the complete path, but for each link separately, it is not clear how the covariance could be calculated.

## 3.4 Queue Length

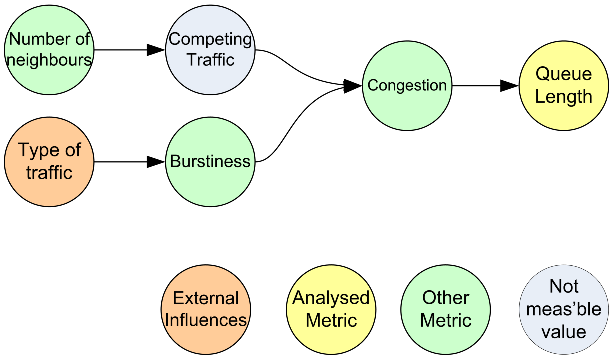

**Figure 7:** *Dependencies of queue length metric*

Every network node has an ingress and an egress queue. In these queues, incoming and outgoing packets are stored if the interface is not able to forward them immediately. The queue length gives an indication for the current state of the device: If the queue is empty, the device can process more traffic, if the queue is full, the interface is contented and cannot handle more packets.

| **Name** | Queue length |
|---|---|
| **Factors of Influence** | see Figure 7 |
| **Mathematical Structure** | Concatenation operator: Addition or minimum (see following paragraphs)<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: Internet, QoS<br>Optimisation goal: Minimise delay, load-balancing |
| **Implement. Characteristics** | Layer: Measurement on L3<br>Information acquiring method: Node-related<br>Empirically defined |
| **Evaluation** | Performance: Throughput = +<br>Performance: Delay = +<br>Performance: Reliability = 0<br>Implementation: Measurability = 0<br>Implementation: Complexity = 0<br>Popularity = + |
| **Adaptations** | |
| **Main References** | |

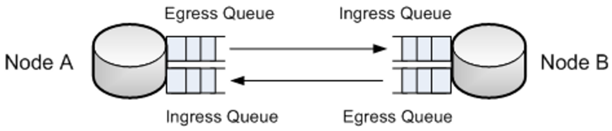

**Figure 8:** *Queuing in network nodes*

Usually, the queue length is limited to a few packets and routers start to drop packets when the queue is full. However, some other strategies were proposed to avoid congestion, most notably Random Early Detection [33].

Queue lengths are properties of network nodes. Though, we defined metrics to be properties of network links. There are three straightforward ways to map queue length to link metrics:

- Add the sizes of the ingress and egress queues at both ends of the link.
- Use the maximal value of the four queues.
- Use each queue size as one single metric.

### 3.4.1 Measurement

The most obvious and reliable method to obtain information on the status of remote queues are SNMP request messages. If this is not a viable solution for any reason, the queuing delay in congested nodes can be estimated with Packet Pairing (see Section 3.5.3).

### 3.4.2 Combination of Links

There are various ways how a path metric can be calculated when the metric values of the single links are known. When links are concatenated, we propose two options: *Adding* the values of the single links or taking the *minimum* value. The latter strategy focusses on the avoidance of bottleneck routers, while the first one minimizes the overall queue lengths.

### 3.5 Bandwidth, Capacity, Throughput

| **Name** | Bandwidth, capacity, flow capacity, throughput, transfer rate |
|---|---|
| **Factors of Influence** | see Figure 9 |
| **Mathematical Structure** | Concatenation operator: Minimum<br>Aggregation operator: Addition<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: Internet, QoS<br>Optimisation goal: Maximise Throughput, load-balancing |
| **Implement. Characteristics** | Layer: Measurement on L3-L7<br>Information acquiring method: Active probing<br>Analytically defined |
| **Evaluation** | Performance: Throughput = ++<br>Performance: Delay = +<br>Performance: Reliability = 0<br>Implementation: Measurability = -<br>Implementation: Complexity = 0<br>Popularity = ++ |
| **Adaptations** | |
| **Main References** | Lai and Baker [57], Carter and Crovella [15] |

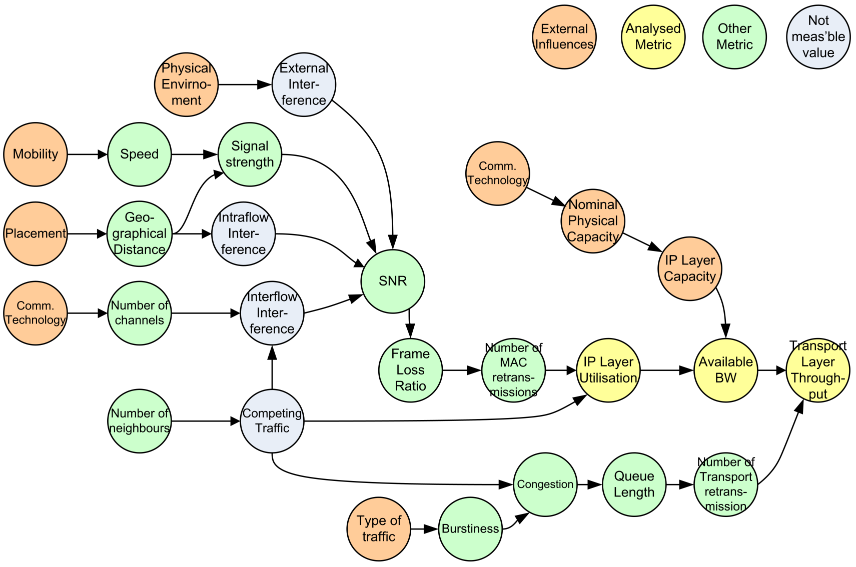

**Figure 9:** *Dependencies of the bandwidth metric*

Bandwidth and related routing metrics indicate the capacity of data which can be sent over a link within a given time. From the perspective of a node, this is equal to the transfer rate of a link. Many factors other than theoretical physical bandwidth have a significant effect on this metric, e.g. packet loss ratio [57]. Bandwidth metrics are quite popular, especially for QoS applications.

There is a considerable lack of clarity in the terminology of this area. In Table 1, we will shortly summarise the most important terms used in the relevant literature. If not stated otherwise, the definitions are adopted from Chimento and Ishac [21].

| | |
|---|---|
| **Nominal Physical Link Capacity** | The theoretical maximum amount of data that a link can support on the physical layer, without concurrent traffic and in a perfect physical environment. |
| **IP Layer Capacity** | The maximum number of IP layer bits that can be transmitted from a sending node and correctly received by a receiver over the link or path during the interval [T, T+I], divided by I, under the assumption that all network resources are free of contention. Some people use the terms *flow capacity*, *bottleneck bandwidth* [78] or *base bandwidth* in the same sense. |
| **IP Layer Usage** | The actual number of IP layer bits correctly transmitted from any source during the interval [T, T+I], divided by I. |
| **IP Layer Utilisation** | The IP Layer Usage divided by the IP Layer Capacity. |
| **IP Layer Available Capacity** | IP Layer Capacity * ( 1 - IP Layer Utilisation ). Often, the term *available bandwidth* is used [78]. |
| **Transport Layer Throughput** | The actual number of IP layer bits correctly transmitted from any source, as experienced by an application using the transport layer. Sometimes, this value is also called "goodput". |
| **Free slots** | Sometimes, the measurement of bandwidth is reduced to the determination of the number of free communication slots. Lin and Liu [61] use this approach in their QoS routing protocol with TDMA and CDMA slots. |
| **Bulk Transport Capacity (BTC)** | The expected long term average data rate of a single congestion-aware transport connection (e.g. a TCP connection) when big amounts of data are transferred [65]. |
| **Congestion Avoidance Capacity (CAC)** | The data rate of a fully specified implementation of a congestion avoidance algorithm, with the restriction that the retransmission time-out and slow-start algorithms are not invoked [65]. |
| **Maximum flow capacity of an IP cloud** | For a given entry and an exit point, the greatest transmission rate achievable, in bits per second, if we had all of the links and routers in the cloud at our disposal. A cloud is defined as a combination of links which may contain various disjoint and conjoint paths [65]. |

**Table 1:** *Bandwidth-related metrics: Definitions*

### 3.5.1 Combination

The bandwidth metric is concave, i.e. when the links of a path are concatenated, the minimal bandwidth determines the cost of the whole path [19, 16].

$$BW(path) = \min_i BW(link_i)$$

When a multipath routing protocol is used, the bandwidth of two parallel links can be aggregated additively.

### 3.5.2 Measuring Bandwidth

A vast number of bandwidth measuring techniques has been proposed. Often, TCP throughput is used to measure available bandwidth. This makes sense if we want to measure the current *Transport Layer Throughput*. However, this passive measurement method does not reflect the available bandwidth if the link is not fully loaded.

An active bandwidth measurement technique are PATHCHAR algorithms [46, 26]. This method tries to correlate round-trip times of probe packets with the Maximal Transfer Unit (MTU) of the single links of a path. To achieve reasonable accuracy, PATHCHAR needs to send up to 10 MB of test data [57], which is a prohibitively high burden for many networks – in particular for MANETs.

### 3.5.3 Packet Pair Delay

A third way to measure bandwidth is packet pairing. The packet pair method (sometimes called Packet Inter-Arrival Time method) was designed to measure the the queueing delays at intermediate nodes and the destination node of a packet. However, it also is possible to infer from the queueing delay to the bandwidth of a link, if packets of different sizes are examined.

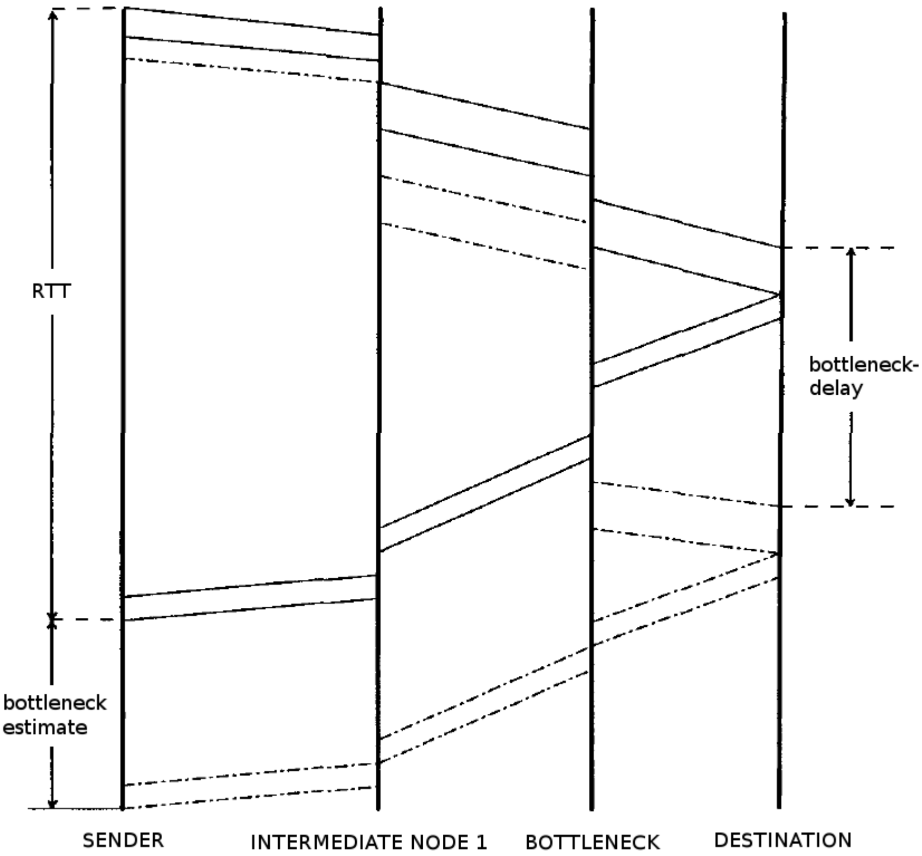

**Figure 10:** *Packet pair method. Solid line = first packet, dashed line = second packet. (Figure adopted from [50])*

To compute this value, a node sends out two consecutive packets to another node. The destination acknowledges the packets. If the packet encounters a bottleneck, the two packets are dispersed (see Figure 10). The delay between the arrival of the two packets can be used to estimate the time the packets were delayed due to queueing (see Keshav [50]).

Various research has been conducted on this topic. Carter and Crovella [15] present a thorough analysis of the problems that arise when applying packet pairing. They also synthesise two tools which are designed to measure base bandwidth as well as available bandwidth. Packet pairing suffers from the problem that the maximal amplitude of the measurable bandwidth is limited by the size of the probing packets. This effect becomes especially troublesome, when an asymmetric link is examined or when asymmetric traffic (e.g. HTTP connections) is used as piggy-back probes. Lai and Baker [57] propose a method to *detect*, at least, when this problem arises. Paxson [78] proposes two methods to search for Packet Bunch Modes (PBM) in order to find a robust bandwidth estimation: A sender-based method and a receiver-based one. Lai and Baker [57] propose a compromise between the two, which they call Receiver Only Packet Pair (ROPP).

Another implementation is described by Draves et al. [27]. They send first a small packet, then a large one, making the metric sensitive to bandwidth, as well. In contrast to other implementations, Draves et al. let the destination calculate the delay between the two packets and inform the sender about the delay instead of leaving this task to the sender.

Packet pair delay is unaffected by the egress queueing of the sending node. If the two packets are of the same size, the packet pair delay also is independent of channel loss rates. Apart from statistical variance, the packet pair metric is determined only by queue bottlenecks at intermediate nodes and the destination node. The packet pair metric is less susceptible to self-interference than e.g. RTT (see Section 3.2.4), but it is not completely immune against this phenomenon neither [27].

Compared to most other techniques, the packet pair method requires a relatively high quantity of overhead messages. There are a number of tools that are designed to measure packet pair delay in the Internet. A summary of such tools can be found in Lai and Barker [57].

### 3.5.4 Performance

Chang et al. [16] compared in a simulation experiment Minimal Hop Count with a bandwidth metric. They found that the throughput of the bandwidth metric was 20% higher the with hop count. However, it is not clear which technique Chang's metric uses to determine the capacity of a link.

## 3.6 Packet Loss Ratio

Packet Loss Ratio (PLR) is a crucial variable for all applications. A high loss ratio degrades the communication quality of non-reliable protocols (e.g. for voice or video applications). With reliable transfer protocols, it potentially forces a high number of retransmissions, slows down communication and reduces the usable bandwidth.

### 3.6.1 One-Way vs. Round Trip Loss Ratio

Similar to the delay metric, PLR can either be measured on a round-trip basis, or only one-way. On one hand, round-trip measurements imply less implementation effort. On the other hand, many applications produce asymmetric traffic, e.g. file transfer traffic, web traffic or multimedia broadcasts. For these tasks, one-way PLRs are of more interest than bi-directional metrics. Packet loss ratios, in fact, often are highly asymmetric due to asymmetric queuing. Therefore, one-way packets reflect better the network conditions to which packets are subject. IETF did only issue RFCs for one-way PLRs: RFC 2680 [4] and RFC 3357 [55]. When TCP is used, the round-trip loss ratio can be determined by counting the missing packets in the current receiving window [34]. A special case of symmetric PLR is the Expected Transmission Count metric (ETX) which is described in Section 3.8.

| **Name** | Packet Loss Ratio (PLR), delivery rate |
|---|---|
| **Factors of Influence** | see Figure 11 |
| **Mathematical Structure** | Concatenation operator: Multiplication<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: Wireless networks<br>Optimisation goal: Maximise throughput, minimise energy consumption |
| **Implement. Characteristics** | Layer: Measurement on L2-L4<br>Information acquiring method: Passive monitoring, piggy-back or active probing<br>Analytically and empirically defined |
| **Evaluation** | Performance: Throughput = +<br>Performance: Delay = +<br>Performance: Reliability = +<br>Implementation: Measurability = +<br>Implementation: Complexity = 0<br>Popularity = ++ |
| **Adaptations** | ETX, mETX (see Sections 3.8 and 3.9), LQM |
| **Main References** | RFC 2680 [4] |

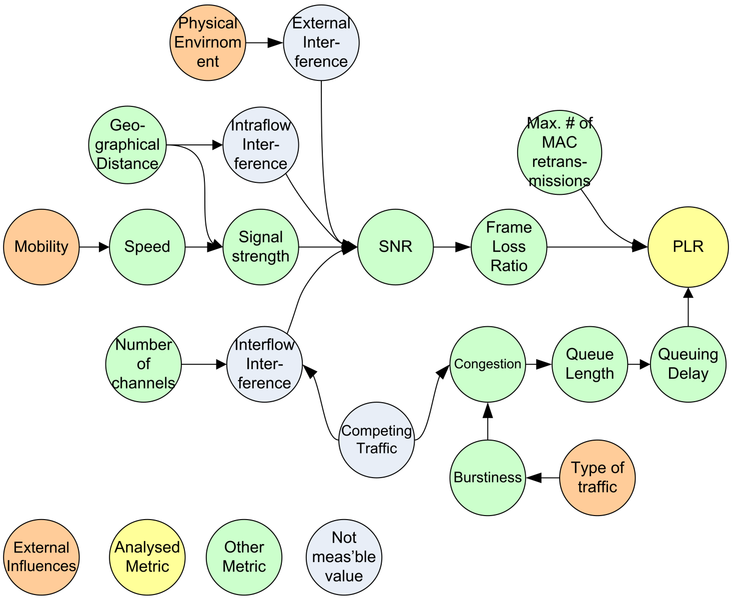

**Figure 11:** *Dependencies of the packet loss ratio metric*

### 3.6.2 Weighting

Andersen et al. [6] and Floyd et al. [32] all find that the unweighted average of losses for a given number of past packets is better suited for PLR metrics than EWMA (see Section 3.1.3). This can be attributed to the bursty nature of packet losses. RFC 3357 [55] proposes some definitions and statistical description methods for packet loss characteristics.

### 3.6.3 Combination

When links are concatenated, the likelihood of packet losses increases according to the laws of probability. Thus, the PLR of an entire path consisting of concatenated links $l$ is computed with the following formula [6]:

$$PLR_{path} = 1 - \prod_{l \in path} (1 - PLR_l)$$

The calculation of aggregated links cannot be defined in such a straightforward fashion. We propose to use the average of the link PLRs. This can be enhanced by weighting the links according to their link bandwidth.

### 3.6.4 Causes for Packet Loss

In wired Internet networks, the main cause for packet losses are overfull routing queues, routine maintenance, unexpected outages or router reboots. These losses mostly occur in bursts [14]. In wireless networks, physical reasons such as interference or node mobility emerge as other major causes for packet loss. It is vital to differentiate between the different causes, as the appropriate reaction to such losses may be fundamentally different.

A first method to distinguish between different loss causes is outlined by Biaz and Vaidya [12]. Fu et al. [34] improved this method and proposed to combine four different metrics heuristically in order to identify the network state. These four metrics are: Inter-packet delay difference (a synonym for packet pair delay, see Section 3.5.3), short-term throughput, Packet Reordering Ratio PRR (see Section 3.7), and PLR.

### 3.6.5 Link Quality Metric

Yarvis et al. [96] used a modified PLR metric: Every link is given a weight according to its PLR. However, this weights were not handled multiplicatively, but additively. In a real world experiment, they measured an improvement of 20 to 32% in terms of end-to-end loss rates. With growing networks size, the improvement reduced to 2 to 4%. However, it is probable that this decay is a result of the limited processing power of the devices they deployed.

## 3.7 Packet Reordering Ratio

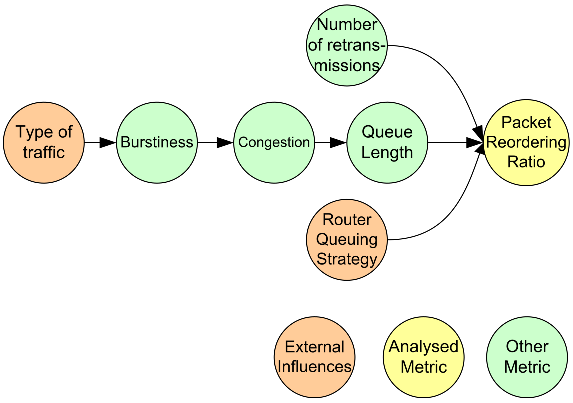

**Figure 12:** *Dependencies of the packet reordering ratio metric*

| **Name** | Packet Reordering Ratio (PRR) |
|---|---|
| **Factors of Influence** | see Figure 12 |
| **Mathematical Structure** | Concatenation operator: Multiplication<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: Internet, QoS<br>Optimisation goal: Minimise delay |
| **Implement. Characteristics** | Layer: Measurement on L3-L4<br>Information acquiring method: Passive monitoring, piggy-back or active probing<br>Analytically and empirically defined |
| **Evaluation** | Performance: Throughput = 0<br>Performance: Delay = ++<br>Performance: Reliability = 0<br>Implementation: Measurability = +<br>Implementation: Complexity = 0<br>Popularity = - |
| **Adaptations** | |
| **Main References** | Morton et al. [74] |

A packet is reordered if it arrives before its predecessor. The frequency of such reordering events can be interpreted as routing metric. This variable is of special interest for real-time applications or video and voice communication. For the latter tasks, the packet reordering ratio is one of the factors that determines the delay and delay variation experienced by the user.

The Packet Reordering Ratio (PRR) can be measured easily if the used transfer protocol uses incrementing sequence numbers. PRR always is higher or equal than Packet Loss Ratio by definition. Recently, Morton et al. [74] proposed a PRR standard for IETF.

## 3.8 Expected Transmission Count

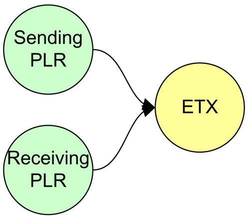

**Figure 13:** *Dependencies of the ETX metric*

Expected Transmission Count (ETX) probably was the first metric specifically designed for MANETs. Starting with the observation that minimal hop count is not optimal for wireless networks, De Couto et al. proposed a metric that bases on bidirectional loss ratios [23]. It aims to predict the number of transmissions (including retransmissions) required to send a packet over a link. This is an appealing concept: Minimizing the number of transmission does not only optimize the overall throughput, it does also minimize the total consumed energy if we assume constant transmission power levels [54].

Let $d_f$ be the expected forward delivery ratio and $d_r$ be the reverse delivery ratio i.e. the probability that the acknowledgement packet is transmitted successfully. Then, the likelihood that a packet arrives

| **Name** | Expected Transmission Count (ETX) |
|---|---|
| **Factors of Influence** | see Figure 13 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, symmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs<br>Optimisation goal: Maximise throughput |
| **Implement. Characteristics** | Layer: Measurement on L2-L4<br>Information acquiring method: Passive monitoring, piggy-back or active probing<br>Analytically defined, combined metric |
| **Evaluation** | Performance: Throughput = ++<br>Performance: Delay = +<br>Performance: Reliability = +<br>Implementation: Measurability = +<br>Implementation: Complexity = 0<br>Popularity = ++ |
| **Adaptations** | mETX, ENT (see Section 3.9) |
| **Main References** | De Couto et al. [23] |

and is acknowledged correctly is $d_f \cdot d_r$. De Couto et al. assume that each attempt to transmit a packet is statistically independent from the precedent attempt, independent of the packet size et cetera, i.e. the sending attempt can be considered a Bernoulli trial. Then, the expected number of transmissions is:

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

The delivery ratios are measured using broadcast probes at link-layer level. Therefore, ETX only makes sense for networks with link-layer retransmission, for example for 802.11b.

Although ETX bases on delivery ratios, which have a direct effect on throughput, ETX is independent from link load in a first approximation[6]. In other words: ETX does not try to route around congested links. On one hand, this is a disadvantage of this metric. On the other hand, ETX does not run the risk of self-interference because of this.

### 3.8.1 Combination

The ETX of a path is defined as the sum of the metric values of the links that form this path. De Couto et al. did not specify how link metrics should be aggregated.

### 3.8.2 Performance and Popularity

Measurements conducted by De Couto et al. [23] on a static test-bed network show that ETX performs up to two times better than minimal hop-count for long links in terms of throughput. This advantage reduces with increasing mobility of the nodes. ETX is one of the few non-hop-count metrics that has been implemented in practice in MANETs, namely in olsrd [62].

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[6] On the physical layer, however, the number of retransmissions depends on the interference that is caused by competing traffic as well as from interference stemming from the same data flow. It is not clear how substantial the impact of this effect is in an average communication setting.

### 3.9 mETX, ENT and EDR

| **Name** | modified ETX (mETX), Effective Number of Transmissions (ENT), Expected Data Rate (EDR) |
|---|---|
| **Factors of Influence** | see Figure 14 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, symmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs<br>Optimisation goal: Maximise throughput |
| **Implement. Characteristics** | Layer: Measurement on L2-L4<br>Information acquiring method: Passive monitoring, piggy-back or active probing<br>Analytically defined, combined metric |
| **Evaluation** | Performance: Throughput = ++<br>Performance: Delay = +<br>Performance: Reliability = +<br>Implementation: Measurability = +<br>Implementation: Complexity = 0<br>Popularity = - |
| **Adaptations** | |
| **Main References** | Koksal and Balakrishnan [54] |

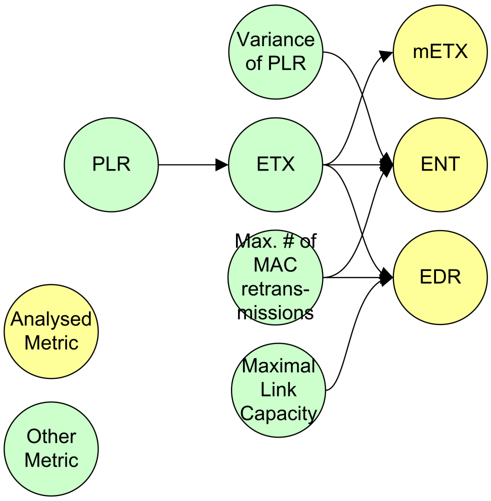

**Figure 14:** *Dependencies of the mETX, ENT and EDR metrics*

Packet loss can vary significantly over different orders of magnitude depending on the radio technology of a system. In fact, packet loss probability of 802.11 systems show significant long-term dependence. This can lead to poor performance when the average of the packet loss ratio is taken as basis for ETX. Koksal and Balakrishnan [54] propose two metrics that approach this problem:

**modified ETX** is defined as $mETX = exp(\mu + \frac{1}{2}\sigma^2)$, with $\mu$ being the estimated average packet loss ratio of a link and $\sigma^2$ the variance of this value. Like ETX, mETX is additive over concatenated links.

**Effective Number of Transmissions** is defined as $ENT = exp(\mu + 2\delta\sigma^2)$. The parameter $\delta$ depends on the number of subsequent retransmissions which will cause the link layer protocol to give up a sending attempt.

### 3.9.1 Expected Data Rate (EDR)

Park and Kasera [76] try take into account the non-optimality of IEEE 802.11 medium access scheduling in order to predict the capacity of a link. Their Expected Data Rate (EDR) metric uses ETX, the medium access contention window and the maximal capacity of a link.

## 3.10 Expected Transmission Time

| **Name** | Expected Transmission Time (ETT) |
|---|---|
| **Factors of Influence** | see Figure 15 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs<br>Optimisation goal: Maximise throughput |
| **Implement. Characteristics** | Layer: Measurement on L2-L4<br>Information acquiring method: Active probing<br>Analytically defined, combined metric |
| **Evaluation** | Performance: Throughput = ++<br>Performance: Delay = +<br>Performance: Reliability = -<br>Implementation: Measurability = -<br>Implementation: Complexity = 0<br>Popularity = - |
| **Adaptations** | Weighted Cumulative ETT (WCETT), Multi-Channel Routing metric (MCR), see Section 3.11 |
| **Main References** | Draves et al. [28] |

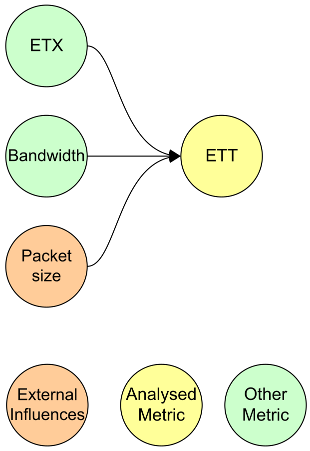

**Figure 15:** *Dependencies of the ETT metric*

Draves et al. [28] observed that ETX (see Section 3.8) did not perform optimal under certain circumstances. For example, ETX prefers heavily congested links to unloaded links, if the link-layer loss rate of congested links is smaller than on the unloaded links. Therefore, the Expected Transmission Time metric (ETT) has the goal to incorporate throughput into its calculation.

Let $S$ be the size of the probing packet and $B$ be the measured bandwidth of a link, then the ETT of this link is defined as follows:

$$ETT = ETX * \frac{S}{B}$$

Draves et al. propose to use packet pairing (see Section 3.5.3) to measure the bandwidth on each link. Of course, this sharply increases the measuring overhead. ETX is measured as described in Section 3.8.

## 3.11 WCETT and Other Interface-Dependent Metrics

| **Name** | Weighted Cumulative Expected Transmission Time (ETT), Multi-Channel Routing metric (MCR), Metric of Interference and Channel-switching (MIC), PARMA |
|---|---|
| **Factors of Influence** | see Figure 16 |
| **Mathematical Structure** | Concatenation operator: Addition / more sophisticated terms (see following paragraphs)<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs<br>Optimisation goal: Maximise throughput (by optimising channel usage) |
| **Implement. Characteristics** | Layer: Measurement on L1-L3<br>Information acquiring method: Node-dependent and active probing<br>Analytically defined, combined metrics |
| **Evaluation** | Performance: Throughput = ++<br>Performance: Delay = +<br>Performance: Reliability = -<br>Implementation: Measurability = -<br>Implementation: Complexity = 0<br>Popularity = - |
| **Adaptations** | |
| **Main References** | Draves et al. [28], Yang et al. [95] |

Many wireless technologies, including 802.11a/b/g, provide multiple non-overlapping channels. It is obvious that this property should be exploited by link layer protocols and just as obvious to devise metrics take advantage of this feature as well.

Draves et al. [28] propose a special technique to compose the single links of the ETT metric and call it Weighted Cumulative ETT (WCETT). They suggest to compute the path metric not just as the sum of the metric values of the links that form this path. When we simply sum over the link metrics, we neglect the fact that concatenated links may interfere with each other, if they use the same channel.

Draves et al. first assume that communication on the same channel always interferes. This forces the links to split up the bandwidth. Let $k$ be the total number of channels of a system. Then, the sum of

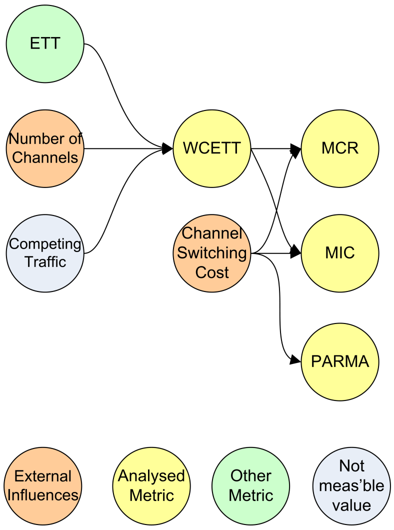

**Figure 16:** *Dependencies of the WCETT, MCR, MIC, PARMA metrics*

transmission times of hops on channel $j$ is:

$$X_j = \sum_{\text{Hop i is on channel j}} ETT_i \qquad 1 \leq j \leq k$$

The total path throughput will be dominated by the bottleneck channel, which has the largest $X_j$. Draves et al. propose to use a weighted average between the maximum value and the sum of all ETTs. This results in the formula:

$$WCETT = (1-\beta) * \sum_{i=1}^{n} ETT_i + \beta * \max_{1 \leq j \leq k} X_j$$

with $0 \leq \beta \leq 1$ being a tunable parameter. Draves et al. [28] describe different interpretation possibilities for this parameter.

WCETT has a serious drawback: It is not immediately clear if there is an algorithm that can compute the path with the lowest weight in polynomial time or less. If a traditional algorithm for finding the shortest path is applied, there might even be the risk of routing loops [95].

### 3.11.1 Performance

In their static test-bed implementation, Draves et al. measured that WCETT outperformed ETX by a factor of two and minimal hop count by a factor of four, when two different 802.11 radio cards per station were used.

### 3.11.2 Multi-Channel Routing Metric MCR

Kyasanur and Vaidya [56] extend WCETT so that it takes into account the cost of changing channels. Let $InterfaceUsage(i)$ be the fraction of time a switchable interface was transmitting on channel $i$ and let $p_s(j)$ be the probability that the used interface is on a different channel when we want to send a packet on channel $j$. If we assume that all the current interface idle time can potentially be used on channel $j$, we can estimate $p_s(j)$ as

$$p_s(j) = \sum_{\forall i \neq j} InterfaceUsage(i)$$

Let $SwitchingDelay$ denote the switching latency of an interface. This value can be measured offline. Then, the cost of using channel $j$ is measured as

$$SC(c_i) = p_s(j) * SwitchingDelay$$

Kyasanur and Vaidya want to prevent that paths are chosen which require frequent channel switching. Therefore, they include the switching cost into the ETT metric. This results in the following definition for their metric:

$$MCR = (1-\beta) * \sum_{i=1}^{n}(ETT_i + SC(c_i)) + \beta * \max_{1 \le j \le k} X_j$$

### 3.11.3 Metric of Interference and Channel-switching (MIC)

Independently from Kyasanur and Vaidya, Yang et al. [95] proposed another metric which incorporates the cost of switching channels. Furthermore, their metric takes also into account the influence of inter-flow interference. MIC of a path $p$ is defined as follows:

$$MIC = \alpha \sum_{\text{link l} \in \text{p}} ICU_l + \sum_{\text{node n} \in \text{p}} CSC_n$$

In this equation, $\alpha$ is a tunable weighting factor and $CSC_n$ refers to the cost for a node to switch from one channel to another. $ICU_l$ is the *Interference-aware Resource Usage*. This value is computed from the ETT of a link and the number of nodes which may interfere with a transmitted packet.

### 3.11.4 PARMA

A very similar concept is followed by the "PHY/MAC Aware Routing Metric for Ad-Hoc Wireless Networks with Multi-Rate Radios (PARMA)" proposed by Zhao et al. [98]. This metric is defined as follows for a path $p$:

$$PARMA(p) = \sum_{links \in p} (\frac{Packet\_Size}{Link\_Speed} + T_{access})$$

where $T_{access}$ is the the medium access time spent by the packet getting access to a link. Zhao et al. assume that this value is available from the MAC layer.

# 4 Radio Information

The physical layer of wireless networks is far more complex than its wired counterpart. Especially the phenomenon of interference turns out to be not only a challenge when developing the physical or MAC layers of network, but it should also be taken into account for routing purposes.

## 4.1 Signal strength, SNR

Many wireless technologies – among them IEEE 802.11 – use beacon packets in order to detect neighbouring hosts. Through these beacons, network devices can measure the signal strength at which a packet is received. Signal strength can be considered as an indication for the link quality and the distance between two nodes.

Dube et al. [29] use signal strength[7] for their Signal Stability-based Adaptive Routing protocol (SSA). By simulation, they found that the number of route reconstructions was up to 60% smaller with

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[7] In fact, an Exponentially Weighted Moving Average (EWMA, see Section 3.1.3) of the current signal strength value was used.

| **Name** | Signal Strength, Signal-to-Noise Ratio (SNR), Interference |
|---|---|
| **Factors of Influence** | see Figure 17 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs<br>Optimisation goal: Minimise transmission energy / Minimise interference |
| **Implement. Characteristics** | Layer: Measurement on L1<br>Information acquiring method: Passive monitoring or active probing<br>Analytically and empirically defined |
| **Evaluation** | Performance: Throughput = +<br>Performance: Delay = +<br>Performance: Reliability = +<br>Implementation: Measurability = ++<br>Implementation: Complexity = ++<br>Popularity = 0 |
| **Adaptations** | |
| **Main References** | Dube et al. [29] |

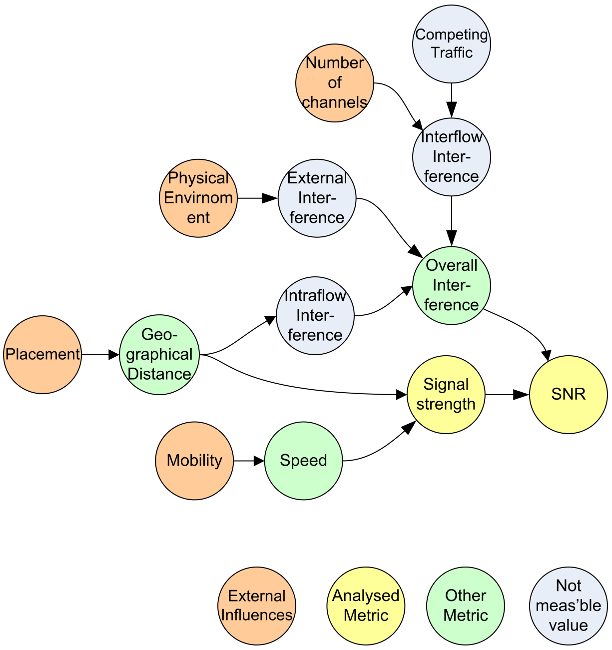

**Figure 17:** *Dependencies of the signal strength metric*

a signal strength-based metric than with a hop count metric. This was especially apparent in dense networks.[8] De Couto et al. [24] show that the signal strength of IEEE 802.11 systems does not correlate

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[8] Dube et al. found also that their SSA protocol performed significantly worse when they included location stability into their algorithm [29]. We suppose that this probably was caused by the simulation setting they used. Further, we suspect that the positive results that Dube et al. measured were due to the fact that signal stregth was a better predictor for link stability than the

with the delivery rate of a link, but only with the geographical distance of two communicating nodes.

### 4.1.1 Signal-to-Noise Ratio

The signal strength alone does represent the quality of a communication link only to a limited degree. The amount of information that can be transferred on a channel depends on the present noise as well. Usually, the Signal-to-Noise Ratio (SNR) is used as measure for channel quality. IEEE 802.11 systems, for example, adapt the sending speed according to the measured SNR value [8].

Although SNR is an excellent indicator for link capacity in theory, it is not the case in reality. Lampe et al. [58] show that SNR is an optimal predictor for packet error rate only when the occurring noise is solely additive white Gaussian noise. They propose to make use of supplementary information about the quality of a channel instead. Such information, e.g. the channel transfer function, is provided by some receiver architectures.

### 4.1.2 Interference Estimation

Iannone and Fdida [42] propose a method to predict the interference which is caused when a link is used, if this value is not directly available from the physical layer. They do not directly estimate the interference, but they use a heuristic instead which allows to compare the potential interference of different links with each other. This heuristic takes into account the current transmit power level $P$, the maximal power level of the device $P_{max}^2$, and the number of neighbours $N(P)$ which can be used at a certain power level.

$$I(P) = \frac{N(P)}{N(P_{max}) + \beta}\sqrt{\frac{P^2 + P_{max}^2}{2 * P_{max}^2}}$$

## 4.2 Medium Time Metric

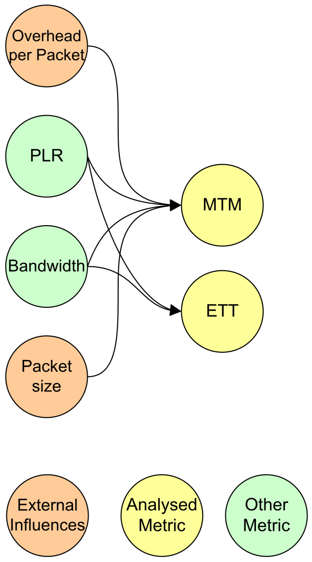

**Figure 18:** *Dependencies of the MTM and ETT metrics*

In wireless networks, individual links may interfere. Transmissions compete for the medium with other transmissions in the same geographical area. The longer the physical distance of a hop, the higher

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location stability metric they used (see Section 6.3).

| **Name** | Medium Time Metric (MTM), Estimated Transmission Time (ETT) |
|---|---|
| **Factors of Influence** | see Figure 18 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs<br>Optimisation goal: Minimise the time a packet occupies the medium |
| **Implement. Characteristics** | Layer: Measurement on L2-L3<br>Information acquiring method: Passive monitoring or active probing<br>Analytically defined, combined metric |
| **Evaluation** | Performance: Throughput = 0<br>Performance: Delay = +<br>Performance: Reliability = +<br>Implementation: Measurability = -<br>Implementation: Complexity = 0<br>Popularity = - |
| **Adaptations** | |
| **Main References** | Awerbuch [7, 8] |

is the energy necessary for the transmission and the more other hops are affected. Additionally, In IEEE 802.11a/b/g networks, the data rate is higher the closer two hosts are located. Traditional hop count metrics favour long links, which may be highly suboptimal in wireless networks. The Medium Time Metric (MTM) proposed by Awerbuch et al. [7, 8] aims at minimising the time during which the physical medium is consumed instead. The MTM of a packet $p$ on a path $\pi$ is defined as follows:

$$MTM(\pi, p) = \sum_{\forall e \in \pi} \tau(e, p)$$

where $\tau(e, p)$ is the time required to transfer packet $p$ over link $e$. This value is composed of the following components.

$$\tau(e, p) = \frac{overhead(e) + \frac{size(p)}{rate(e)}}{reliability(e)}$$

Link overhead can be computed from standards and specifications as well as from the type and configuration of the used wireless device. The packet size should be easily available through the routing protocol. Link transfer rate and reliability usually are known to the MAC layer. However, this information often is not accessible to higher network layers because the techniques used for auto-rate selection on the MAC layer is considered proprietary. It is possible to estimate the values for transfer rate and link reliability by probing. Though, this information produces unnecessary overhead and less accurate results than inter-layer communication would. Therefore, Awerbuch et al. [8] would favour that radio card manufacturers provide a standard interface in order to enable access to this information by higher network layers. Although we agree with them principally, one should not expect that all problems of measuring transfer rate or link reliability be solved at once thereby.

### 4.2.1 Performance

Awerbuch et al. [8] measured a en-to-end throughput which was equal to minimum hop count and ETX in short distances. When the distances were larger, minimum hop count and ETX found routes with a few hops. MTM selected multi-hop paths with more hops but higher capacity. For this reason, the resulting end-to-end throughput was up to 20 times higher with MTM than with the other metrics.

### 4.2.2 Similar Metrics

Although they base on different motivations, the MTM metric is basically the same as the Expected Transmission Time (ETT) metric described in Section 3.10. One difference is that MTM, unlike ETT, includes a term for communication overhead. Furthermore, ETT uses explicitly ETX as measurement for reliability while this is not defined for MTM.

Aguayo, Bicket et al. [2, 13] use again a very similar metric for their WMN implementation. However, in this metric, the size of a packet is assumed to be constant at 1500 Bytes and the overhead is neglected. Confusingly, they use the name Estimated Transmission Time (ETT) for their metric. Though it is very similar, this metric should not be mixed up with the *Expected* Transmission Time metric described in Section 3.10. The latter metric does not assume constant packet sizes and uses ETX as link reliability measure. For a link $e$, the Estimated Transmission Time metric is defined as follows:

$$\text{Estimated Transmission Time} = \frac{1}{reliability(e) * rate(e)}$$

# 5 Topology

Topology metrics base on an abstract concept of networks. They only take into account the presence or absence of links as well as the neighbourhood relations of the network nodes. Although this approach abstracts from a broad range of variables, it is widely used due to the simplicity it offers.

## 5.1 Number of Neighbours

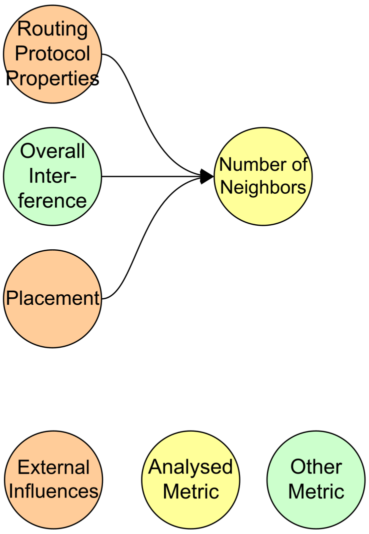

**Figure 19:** *Dependencies of the number of neighbours metric*

| **Name** | Number of neighbours |
|---|---|
| **Factors of Influence** | see Figure 19 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: Internet, MANETs<br>Optimisation goal: Minimise number of hops |
| **Implement. Characteristics** | Layer: Measurement possible on L2-L7<br>Information acquiring method: Monitoring, piggy-back or active probing possible<br>Analytically defined |
| **Evaluation** | Performance: Throughput = -<br>Performance: Delay = ++<br>Performance: Reliability = -<br>Implementation: Measurability = ++<br>Implementation: Complexity = ++<br>Popularity = - |
| **Adaptations** | |
| **Main References** | |

The Number of Neighbours metric is defined by how many other nodes can be reached from a node at a given moment. This idea is appealing because it might make it possible to benefit from the small world problem. This phenomenon was first described for social networks by Milgram [72] and later for computer networks (for example by Kleinberg [53]). The small world theory states that, in certain networks, there is always a short path between any two nodes. This is the case because in these “small world networks”, a class of highly interconnected nodes exists. These nodes play the role of wormholes and relate distant network regions. Such nodes typically are characterized by a high node degree i.e. a large number of neighbours. We suppose that in MANETs, this kind of topology will not occur usually. However, this structure is symptomatic for WMNs, where routers fulfil the function of wormholes the Internet.

We should be aware that neighbourhood not necessarily is reciprocal in wireless networks. If one node can contact another, this does not mean that this is also possible in the other direction. Therefore, the number of neighbours metric is unidirectional, i.e. the indegree not compulsorily equals its outdegree.

The number of neighbours is a property of a network node. However, we defined metrics to be properties of network links. Nevertheless, there are various ways how we can map indegree and outdegree of the two adjacent nodes of a link to the link itself.

### 5.1.1 Measurement

If the number of neighbours is not available from the MAC layer, the transport layer or the application layer, the degree of a node can be found by regular probing. The indegree can be measured by listening to the incoming probes. The outdegree can only be determined if probing messages are acknowledged. Probing brings along several problems, as stated in Section 3.1.1.

## 5.2 Number of Paths to a Node

Redundancy is a central criteria for MANET and WMN routing algorithm. Let there be one particular node with a special function in a network. Then, the number of disjoint paths to this node traversing a link can be considered as a metric for that link. In the case of WMNs, this metric could be defined as the number of paths to an Internet gateway. Many different paths to an Internet gateway means high tolerance against link failures. However, the number of paths to an Internet gateway should not simply be used as a single metric, because many paths to a gateway can also signify a long distance to the next gateway.

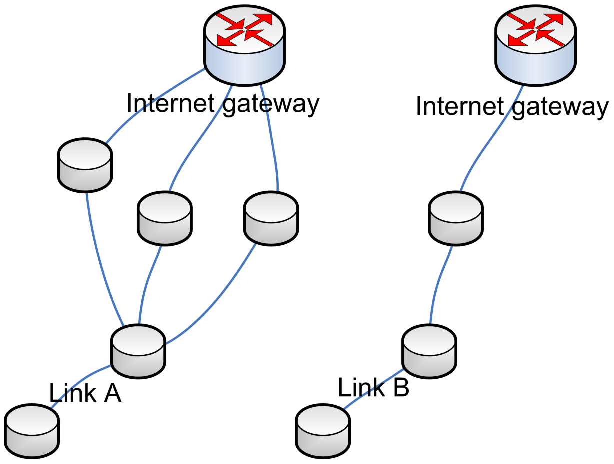

**Figure 20:** *Link A has lower cost than Link B, as more paths lead from Link A to an Internet gateway than from Link B.*

Surprisingly few reflections have been made in literature on the relationship between redundancy and metrics and many questions remain open. It is not trivial to determine the number of paths from one node to another and a number of considerations have to be kept in mind. For example, whether only completely disjoint paths should be counted or partly disjoint paths as well.

## 5.3 Hop Count

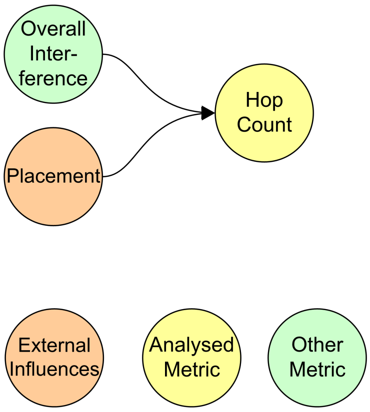

**Figure 21:** *Dependencies of the hop count metric*

The concept of the hop count metric is unbeatable in its simplicity: Every link counts as one equal unit, independent from the quality or other characteristics of the link. The ease of implementation made hop count to the most widely used metric for MANETs by far. It is implicitly or explicitly used e.g. in OLSR [22], DSR [49], DSDV [79] and AODV [80].

| **Name** | Hop count, minimal hop count |
|---|---|
| **Factors of Influence** | see Figure 21 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, symmetric, one-dimensional |
| **Design Goals** | Target Platform: Internet, MANETs<br>Optimisation goal: Minimise number of hops |
| **Implement. Characteristics** | Layer: Measurement possible on L2-L3<br>Information acquiring method: Piggy-back or active probing possible<br>Analytically and empirically defined |
| **Evaluation** | Performance: Throughput = 0<br>Performance: Delay = +<br>Performance: Reliability = 0<br>Implementation: Measurability = ++<br>Implementation: Complexity = ++<br>Popularity = ++ |
| **Adaptations** | Widest shortest path |
| **Main References** | |

### 5.3.1 Performance

De Couto et al. [24] as well as Yarvis et al. [96] observed in their tests on two different static test-bed environments using DSDV routing protocol, that using minimal hop count will not result in optimal performance. This is because the selection of minimum hop paths prefers long links. In multi-rate wireless networks, this typically results in paths with links operating at low rates [8]. Because of polynomial energy consumption in radio transmission, longer links are more expensive than several concatenated shorter ones in terms of energy. (Of course, this is only the case, if the used devices are able to adapt their transmission energy.)

But when nodes become mobile, things begin to look quite different. Draves et al. [27] compared hop count, RTT, packet pair, and ETX in a mobile test bed. They find that minimal hop count outperforms the quality-aware routing metrics under the presence of mobility and high channel variability. They attribute this finding to the quicker reaction of hop count to fast topology changes. ETX needs some time until a stable value for the packet loss ratios is determined. RTT and packet pair did not even find a stable state at all due to self-interference. However, it is not clear whether Draves et al. chose the probing technique for ETX, RTT and packet pair adequately (see Section 3.1.1).

Syrotiuk and Bikki [90] show that congestion and packet loss may have a big influence on the path found by the hop count metric. This problem can be reduced by giving higher routing priority than normal traffic to the probes that test links.

## 5.4 Widest Shortest Path and Shortest Widest Path

In many implementations, an arbitrary path is chosen, if there are several paths with minimal length that each have the same number of hops. Guerin et al. [37] propose to choose the path with the largest available bandwidth in this case, the so-called Widest Shortest Path. Wang and Crowcroft [94] propose a Shortest Widest Path algorithm i.e. from all paths with the highest bandwidth, the path with the fewest hops is chosen. However, Wang and Crowcroft show in their paper that it is not possible to find such a shortest widest path within polynomial time.

# 6 Mobility, Geography

The use of the geographical position of nodes is an often cited approach to simplify routing in ad hoc networks. In such systems, it is assumed that each node knows its physical location as well as the positions of its neighbours. this information can be acquired e.g. from a Global Positioning System (GPS).

Location information can be included into routing algorithms in various ways. To design a special metric is only one of these ways. For a survey on location-based routing – often called geocasting – please refer to [66].

## 6.1 Geographical Distance

| **Name** | Geographical distance |
|---|---|
| **Factors of Influence** | Only placement, no network-immanent factors |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, symmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs<br>Optimisation goal: Find “short” path |
| **Implement. Characteristics** | Information acquiring method: External position acquisition<br>Analytically and empirically defined |
| **Evaluation** | Performance: Throughput = +<br>Performance: Delay = +<br>Performance: Reliability = 0<br>Implementation: Measurability = +<br>Implementation: Complexity = ++<br>Popularity = + |
| **Main References** | |

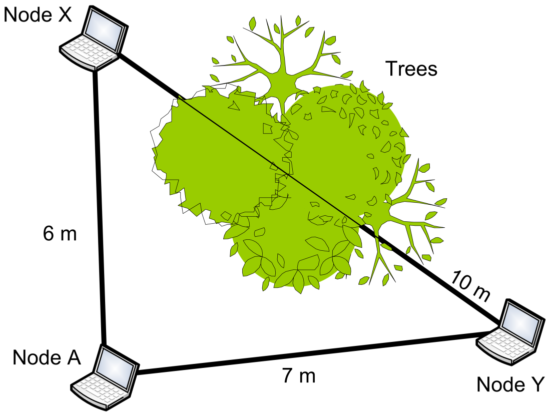

**Figure 22:** *Although the direct link from X to Y is less distant, it is probably more efficient to route traffic over A and accept a geographically longer path.*

The most straight-forward application of location information is to use the geographical distance as metric. However, this value does not represent a very useful information in many cases. Although distance has an influence e.g. on signal strength, other factors usually are more important. The quality of a link can be significantly decreased by obstacles such as walls or trees (see Figure 22). This is better reflected directly by a signal strength metric than by using the geographical distance.

### 6.1.1 Distance to Destination

Another way to use positioning information is to attribute the geographical distance to the destination as cost of a link instead of the distance between neighbours. In fact, this kind of rather reflects a special routing algorithm than a metric.

Several papers propose to combine geographical distance to destination with other metrics. Seada et al. [85] couple distance with packet reception rate. They find in their tests that this solution is especially apt for systems that use automatic repeat request (ARQ) techniques. Similarly, Zhang et al. [97] propose a metric that combines distance to destination with the expected latency. In their huge test bed implementation, they measure that their "expected MAC latency per unit-distance to the destination" metric (ELD) performed considerably better than Seada's metric and better than ETX in terms of latency, energy consumption and especially route stability.

## 6.2 Speed

| **Name** | Speed of nodes |
|---|---|
| **Factors of Influence** | Only placement, no network-immanent factors |
| **Mathematical Structure** | Concatenation operator: Addition or maximum<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric (symmetric for relative speed), one-dimensional |
| **Design Goals** | Target Platform: Highly dynamic MANETs<br>Optimisation goal: Find stable paths |
| **Implement. Characteristics** | Information acquiring method: External position acquisition<br>Analytically and empirically defined |
| **Evaluation** | Performance: Throughput = +<br>Performance: Delay = +<br>Performance: Reliability = 0<br>Implementation: Measurability = +<br>Implementation: Complexity = ++<br>Popularity = + |
| **Adaptations** | Relative speed of two nodes |
| **Main References** | |

Quality and stability of a link are highly dependent on the speed of a node. The faster a node moves, the higher is the probability that a link with this node will break within short time. One technique for measuring the speed of a node is to have information on the current position of a node. This can be acquired e.g. using a GPS system. alternatively, Basu et al. [11] propose to estimate the relative velocity of two nodes by measuring the alteration of the signal strength.

Johansson et al. [48] define a metric for the average relative speed. Let $l(N,t)$ be the position of a node $N$ at time $t$. Then, the relative velocity of the two nodes $X$ and $Y$ is

$$v(X,Y,t) = \frac{d}{dt}(l(X,t) - l(Y,t))$$

The mobility between a pair of nodes $X$ and $Y$ is defined by Johansson et al. as

$$M_{XY} = \frac{1}{T} \int_{t_0 \le t \le t_0+T} |v(x,y,t)|\, dt$$

## 6.3 Link Lifetime

| **Name** | Link lifetime, link longevity, link availability, connectivity |
|---|---|
| **Factors of Influence** | see Figure 23 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, symmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs<br>Optimisation goal: Maximise long-term reliability of a path, minimise number of path recalculations |
| **Implement. Characteristics** | Information acquiring method: Various techniques<br>Analytically defined |
| **Evaluation** | Performance: Throughput = 0<br>Performance: Delay = +<br>Performance: Reliability = ++<br>Implementation: Measurability = +<br>Implementation: Complexity = 0<br>Popularity = 0 |
| **Adaptations** | |
| **Main References** | Toh [93] (Associativity-Based Routing) |

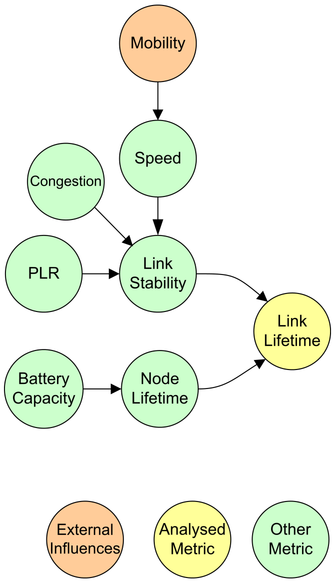

**Figure 23:** *Dependencies of the link lifetime metric*

A link exists as long as both communicating nodes are up and running and they have a radio connection that allows them to transfer data. In mobile wireless networks, finding routes that are stable over time is one of the most central challenges. The first routing algorithm which explicitly took into account the longevity of links was Associativity-Based Routing (ABR) proposed by Toh [93]. He based his routing algorithm on his observations of the movement of mobile communication devices in an office building. He found that mobile hosts (or rather the people who carried them) usually rest for several minutes before they start to move again. The longevity of these pauses varies heavily and seem to form a Pareto distribution (see Fig. 24). However, Toh did not investigate this any further.

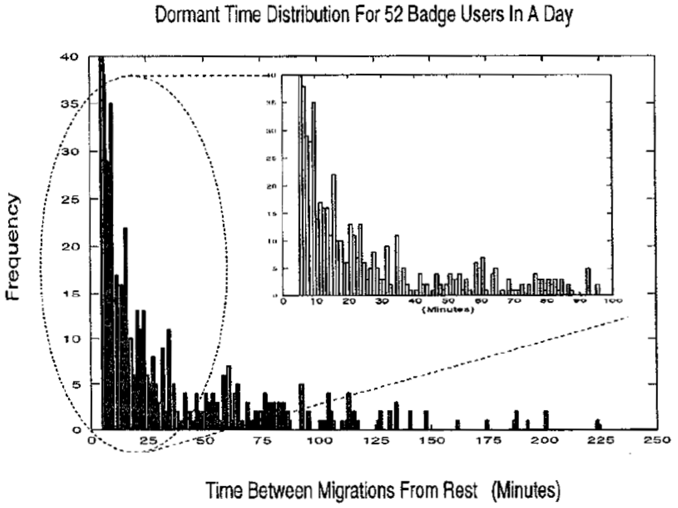

**Figure 24:** *Mobility distribution of mobile nodes in an office environment. Figure adopted from [92].*

Mcdonald and Znati [67] propose another routing metric, which defines a probabilistic measure of the availability of links that are subject to link failures caused by node mobility. They base their considerations on a random walk model. Each node is characterised by three values that describe the statistical distribution of the mean and variance of the speed of a node as well as an average interval time. Together with an estimated communication radius, Mcdonald and Znati derive a sophisticated function which estimates the expected availability of a link.

Various other metrics were proposed, based on other mobility models. Among them are the metrics described by Gerharz et al. [35] and Jiang et al. [47] that estimate the average residual lifetime of a link. However, all of these concepts base on the assumption that all nodes have similar mobility characteristics. In mesh networks, this obviously is not the case. For this kind of networks, we propose to devise special mobility metrics that use distinct node classes.

### 6.3.1 Connectivity

A simplified variety of link lifetime is the Connectivity metric. It has only two boolean values for a link, each of them indicating whether communication is possible in the one of the two directions at a given moment. A connectivity metric is described in IETF RFC 2678 [64].

## 6.4 Other Geographic Metrics

Punnoose et al. [81] propose to predict the propagation environment of a link using various information inputs. In particular, their protocol includes the use of terrain maps which is coupled with a location information system. Of course, this kind of prediction is only possible if accurate, detailed, up-to-date, three-dimensional map information is available. The cost for the acquisition of such data will be prohibitive in many cases, especially for indoor usage.

For large-scale applications, even weather forecasts could be used as input information. Like this, it would be thinkable to route traffic around thunderstorms, for example[9].

# 7 Energy-Based

Unlike in wired networks, energy efficiency is a major concern in mobile networks. Sensor networks as well as portable communication devices only have restricted battery lifetime. How the problem of restricted energy in a network can be approached has been subject to various work. Feeney [30], and Stojmenovic and Lin [89] give good overviews of this topic . In this section, we will first give a short introduction into the basic principles of energy-restricted networks, and then describe the metrics which were proposed in this context.

## 7.1 Fundamentals

The energy consumed for sending and receiving a packet over a path is influenced by various factors:

- The transmission energy of a packet over one link from node $i$ to node $j$ can idealisingly be modelled as

  $$e_{i,j} = h_{i,j}^{\alpha} + k \qquad 2 \leq \alpha \leq 4$$

  where $\alpha$ depends on the medium environment[10]. The variable $k$ models a fix processing overhead for sending and receiving the packet and $h_{i,j}$ stands for the geographical distance. The equation shows that it is necessary to find a balance between minimising the transmission power and minimising the number of hops. However, these considerations only apply, if the MAC layer of the used nodes provides adaptive power control.

- In the presence of interference – be it external, inter-flow or intra-flow interference – the energy necessary for successful transmission increases. As above, only devices with power control can take advantage of this opportunity to save energy.

- Every time a packet must be retransmitted, the energy consumption increases, of course. Retransmissions may be caused at various places of the reference layer model.

- Routing overhead should be minimised as far as possible. Some strategies were proposed how this kind of traffic can be reduced. One such strategy bases on the idea to select the links over which packets are sent, instead of broadcasting routing information to all neighbours. See e.g. Ramanathans and Rosales' [83] or Meng and Rodoplus [68] works on topology control.

- Due to overhearing, high density of a network can have a considerable deteriorating effect on energy consumption [52].

There are different goals energy based routing and the corresponding metrics may follow:

- To minimise overall energy consumption.

- To maximise the time until the first node runs out of energy. This is equivalent to keeping the energy load in all nodes as equable as possible.[11] However, this implies that all nodes of a network will fail at the same time and the network will collapse entirely all of a sudden.

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[9] For another aspect of the connection between weather data and wireless communication, please refer to [69].

[10] See Feeney [30]. A more detailed investigation is given by Heinzelman et al. in [41].

[11] A very striking example for such a scenario are sensor networks that are reloaded at daytime using solar cells and need to keep their service up over night.

- In certain scenarios, the goal can be that those nodes fail first which are not vital to the functioning of the network. In other words: The goal is to maximise the time until the first message cannot be transmitted due to a network partition. Li et al. [60] prove that it is not possible to find optimal paths in this sense within polynomial time.

## 7.2 Energy Consumed per Packet

| **Name** | Energy consumed per packet, transmission energy, Minimal Total Power metric (MTPR) |
|---|---|
| **Factors of Influence** | see Figure 25 |
| **Mathematical Structure** | Concatenation operator: Addition<br>Aggregation operator: Not defined (see following paragraphs)<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs, Sensor networks<br>Optimisation goal: Minimise the total power consumption |
| **Implement. Characteristics** | Information acquiring method: Node-related<br>Analytically and empirically defined |
| **Evaluation** | Performance: Throughput = 0<br>Performance: Delay = 0<br>Performance: Reliability = +<br>Implementation: Measurability = +<br>Implementation: Complexity = ++<br>Popularity = + |
| **Adaptations** | |
| **Main References** | Singh et al. [88], Scott and Bambos [84] |

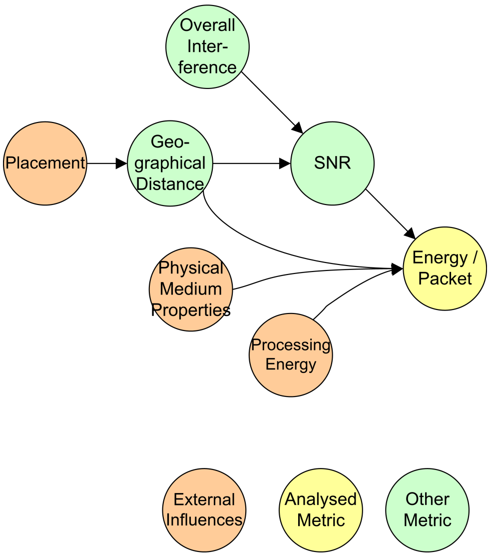

**Figure 25:** *Dependencies of the energy per packet metric*

Minimising the energy that is used per packet is the most basic approach for energy metrics. As this strategy minimises the overall energy consumption, too, this metric is called Minimal Total Power

Routing metric (MTPR) by Scott and Bambos [84]. Singh et al. [88] formalise the idea of this metric: Let $e_{i,j}$ denote the energy consumed for transferring and receiving a packet from node $i$ to the neighbouring node $j$. Then, the total energy required to send a packet from $s$ to $d$ is

$$E = \sum_{\text{all links on path n}} e_{n_i,n_{i+1}}$$

with $n_i$ being the nodes forming the path from $s$ to $d$. Thus, the concatenation operator of this metric is the addition. The aggregation operator is not clearly defined. We propose to take the average of the links, weighted by traffic distribution.

This metric will prefer multiple short hops over fewer longer hops. While this provides a minimal energy path and produce less interference, it occupies a big amount of other network resources.

A disadvantage of this metric is its lack of sensitivity for the remaining battery lifetime. This means that it is quite probable that some nodes will be burdened heavily with traffic and spend their energy much faster than others. Although, it might be sensible in some cases that specific nodes are loaded with more traffic, this must be done in well considered fashion.

In order to reduce the risk that bottleneck nodes are burdened to high, Michail and Ephremides [70] propose to weight the transmission energy with the number of free channels of a node at a given moment. Of course, this metric is appropriate for multi-channel systems only. Another approach to avoid the overload of some nodes is to take into account the remaining battery capacity of a node. This method is described in more detail in Section 7.3.

### 7.2.1 Measurement

Neither Singh et al. nor Scott and Bambos explain in detail how they envision to measure the energy used per transmission. However, it is clear that some information must be provided by the physical layer of a node. Combined with the model described in Section 7.1, an estimate of the consumed energy can be calculated.

## 7.3 Remaining Battery Capacity

| **Name** | Remaining battery capacity |
|---|---|
| **Factors of Influence** | see Figure 26 |
| **Mathematical Structure** | Concatenation operator: Addition (Minimum for MMBCR)<br>Aggregation operator: Not defined<br>Other mathematical properties: Dynamic, asymmetric, one-dimensional |
| **Design Goals** | Target Platform: MANETs, Sensor networks<br>Optimisation goal: Maximise the network lifetime |
| **Implement. Characteristics** | Information acquiring method: Node-related<br>Analytically defined |
| **Evaluation** | Performance: Throughput = 0<br>Performance: Delay = 0<br>Performance: Reliability = ++<br>Implementation: Measurability = 0<br>Implementation: Complexity = ++<br>Popularity = + |
| **Adaptations** | Energy cost per packet, MBCR, MMBCR, CMMBCR |
| **Main References** | Singh et al. [88], Chang and Tassulias [17], Kim et al. [52] |

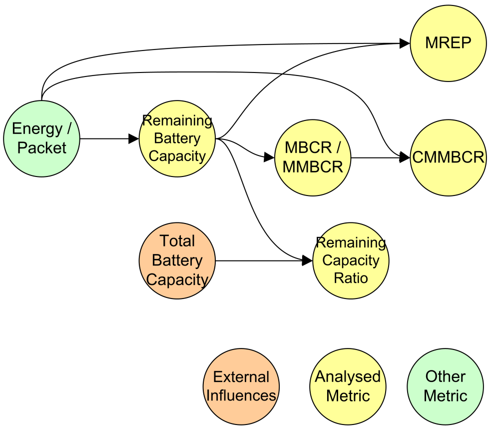

**Figure 26:** *Dependencies of the remaining battery capacity metric*

One approach to balance energy consumption over a network is to use the battery capacity of a node as basis for metrics. A metric that only bases on the current capacity of the node battery is used by Sheu et al. [87]. The *ratio of battery remaining capacity* $R_{brc}$ is defined as

$$R_{brc} = \frac{E_i}{E_{max}} = \frac{\text{Battery remaining capacity}}{\text{Battery full capacity}}$$

Singh et al. [88] propose to supply each node with a cost value $f_i(E_i)$ that depends on its current battery capacity $E_i$. Singh et al. call this strategy Minimum Battery Cost Routing (MBCR). They propose as one possible choice for $f_i$

$$f_i(E_i) = \frac{1}{E_i}$$

Gupta and Das [39] propose to define three levels of nodes: Nodes which dispose of less than 10 percent of their initial battery capacity are to be avoided whenever there is an alternative path. If an node has left 10-20 percent of battery capacity, it should not be used unnecessarily. Otherwise, a node is not treated specially.

### 7.3.1 Minimal Maximum Battery Cost Routing

Let $f_i(t)$ be a battery cost function for host $n_i$ and $E_i(t)$ the residual battery capacity at a given moment. The less energy remains in a node, the higher the cost function of this node should be. Singh et al. [88] propose to use $1/E_i(t)$ as cost function. Their Min-Max Battery Cost Routing (MMBCR) metric chooses the path with the least maximal such cost function. In other words, let $r_o$ be the chosen path and $r_*$ the set of all possible paths. Then the chosen path fulfils

$$Cost(R_o) = \min_{r_j \in r_*} \max_{\forall n_i \in r_j} f_i(t)$$

On one hand, MMBCR considers the weakest node over a path and thereby provides a balanced energy load. On the other hand, there is no guarantee that MMBCR minimises the total energy consumed over a path.

### 7.3.2 Combining Battery Capacity with Energy per Packet

Toh [91] merges MTPR and MMBCR into one single strategy called Conditional Max-Min Battery Capacity Routing (CMMBCR). First, CMMBCR searches paths using MTPR, with the restriction that all nodes need to have a remaining battery capacity that exceeds a threshold value $\gamma$. If there is no such path, MMBCR is used.

Chang and Tassulias [18] formulate an algorithm that takes into account remaining battery capacity and necessary transmission energy for their Maximum Residual Energy Path (MREP) algorithm. Let $e_{i,j}$ be the energy consumed to send one packet over the link from node $i$ to node $j$ and $E_j$ be the residual energy at node $j$. Chang and Tassulias define two metrics for the link from $i$ to $j$:

The remaining energy of a node:

$$d_{i,j} = \frac{1}{E_j - e_{i,j}}$$

and the residual capacity of a node in terms of packets that can be delivered with the remaining energy:

$$d_{i,j} = \frac{e_{i,j}}{E_j}$$

In a simulation with dynamically moving nodes, both metrics came quite close to a theoretically predicted average node lifetime[12]. However, Chang and Tassulias did not compare these two metrics to the hop count metric. This would have made it easier to estimate the benefit of their metrics.

Refining their work in [17], Chang and Tassulias proposed a more general formula:

$$d_{i,j} = e_{i,j}^{x_1} E_j^{-x_2} E_i^{x_3}$$

where $x_1$, $x_2$ and $x_3$ are adjustable parameters. In a simulation, Chang and Tassulias showed that with reasonable parameters, the theoretical maximal values for average lifetime, worst-case lifetime and transfer reliability can be reached.

A very similar metric is described by Michail and Ephremides [70]. However, they do not multiply the terms for transmission energy and residual battery capacity, but they add the two terms. We suppose that the effects are comparable.

Kim et al. [52] compare MTPR, MMBCR and CMMBCR. Their first finding was that considering overhearing does have a significant impact on the results of simulations. Further, they found that the intuitive speculation that MTPR is appropriate in dense networks (the overall energy consumption is minimised, redundant paths can be found easier), whereas it is more important to avoid network partition in sparse networks (and thus, MMBCR performs better). It would be interesting to compare those metrics to simple hop count, especially when overhearing is taken into account.

## 7.4 Other Energy-Based Metrics

### 7.4.1 Battery Prevention

Chiasserini and Rao [20] proposed a metric that takes into account the physical properties of batteries. This metric favours bursty traffic over constant traffic in order to optimise the long-term recharging ability of the battery. Although this is an interesting approach for some specific sensor network applications, bursty traffic should be avoided usually.

### 7.4.2 Packet Loss Ratio

Some authors propose to enhance energy-aware routing with packet loss information. Banerjee and Misra [9, 73] use the following metric:

$$d_{i,j} = \frac{e_{i,j}}{1 - p_{i,j}}$$

with $p_{i,j}$ being the packet loss ratio on the link from node $i$ to node $j$ and $e_{i,j}$ being the energy needed to transfer a packet from $i$ to $j$. This formula is useful if packets are retransmitted from node to node. It does not hold if the utilized transfer protocol supports only end-to-end retransmissions.

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[12] The maximal values were calculated using linear programming methods.

### 7.4.3 Interference

Michail and Ephremides [70] combine energy aspects with the attempt to reduce blocking of transmissions due to interference. Their Power and Interference-based Metric (PIM) is defined as:

$$d_{i,j} = \frac{e_{i,j}}{e_{max}} + \frac{|B_{i,j}|}{|B|}$$

where $e_{max}$ is the pre-determined maximal value for transmission energy, $|B_{i,j}|$ is the number of links that are blocked due to interference when node $i$ sends a message to $j$. $|B|$ is the overall number of links in the network.

# 8 Other Concepts

## 8.1 Security

The enforcement of security and cooperation is a basic need of WMNs. Often, game theoretic approaches are proposed for this aim. For example, Michiardi and Molva [71] propose a frameworks, which penalises non-cooperation with bad reputation. This bad reputation can be mirrored with a metric. Similar models can be found in [36] and in [75].

Another security related metric is mentioned in [77]: What is the average response time of the network administrator in case of a problem? Of course, this would be rather absurd for MANETs and WMNs.

## 8.2 Billing

In some networks, there might be links that can be used for free (e.g. open WLAN access points) and other links that are billed for (e.g. GSM). It is clear that cheaper links are preferred over more expensive links. This can be modelled using metrics as well.

## 8.3 Application-Specific Metrics

It is thinkable to construct metrics basing on information provided by the application layer. With this concept, task similar to the applications of overlay networks (see Andersen et al. [6]) could be devised. To the best of the authors's knowledge, this has not been investigated up to now.

## 8.4 MTU

The Maximum Transmission Unit (MTU) refers to the largest size of a packet a link can pass onwards. In most Ethernet LANs, the MTU is 1500 bytes. The MTU of a path is the minimal value of the MTUs of the links the path consists of. If IP packets with larger size are sent over this path, they are fragmented.

## 8.5 Node Resources

Metrics can be devised from the information on the capability of a node. Such capabilities can be the available memory of a node, the available processing resources or the number of interfaces. In WMNs, the most central property of a node is to which of the three classes (gateway, router and mobile node) it belongs.

### 8.6 Learning Networks

A completely different approach to assign link costs is intelligent learning. Barolli et al. [10] propose genetic learning algorithms. In fact, a network can be considered as an artificial neural network. The link weights represent the weights of the neural networks. A global target function for the optimisation of the network can be chosen according to the needs of the network. Thus, any kind of learning technique for neural networks can be used to choose optimal weights for each link. Güneş [38] describes a similar routing algorithm that bases on the methods that ants used to find optimal paths from the ant-hill to their nourishment sources.

At the moment, all theses techniques have not yet been tested in practise. However, we assume that they are only suited for very static networks.

## 9 Combination Operators

Metrics can be characterised by the mathematical operator that is used to compute the metric value of the concatenation or aggregation of links. In the following, an overview on the combination operators of various metrics is given.

### 9.1 Concatenation Operators

### 9.2 Aggregation Operators

Unlike the concatenation operator, the aggregation operator is explicitly defined only for a small number of metrics. For all other metrics, the aggregation operator has to be chosen according to the requirements of the routing algorithm.

| Metric | **Proposed Concatenation Operator** |
|---|---|
| **Delay, RTT** | Addition |
| **Delay Variation** | Addition or Addition and Covariance |
| **Queue Length** | Addition or Minimum |
| **Bandwidth** | Minimum |
| **Packet Loss Ratio** | Multiplication |
| **Link Quality Metric (LQM)** | Addition |
| **Packet Reordering Ratio** | Multiplication |
| **ETX** | Addition |
| **mETX, ENT, EDR** | Addition |
| **ETT** | Addition |
| **WCETT, MCR** | Addition and Maximum |
| **MIC** | Addition |
| **PARMA** | Addition |
| **Signal Strength, SNR, Interference** | Addition |
| **MTM, ETT** | Addition |
| **Number of Neighbours** | Addition |
| **Number of Paths** | Addition |
| **Hop Count** | Addition |
| **Widest Shortest Path / Shortest Widest Path** | Addition and Minimum |
| **Geographical Distance** | Addition |
| **Speed / Relative Speed** | Addition or Maximum |
| **Link Lifetime** | Addition or Multiplication or Minimum |
| **Connectivity** | Minimum |
| **Map Information** | Addition |
| **Energy per Packet / MTPR** | Addition |
| **MBCR** | Addition |

**Table 2:** *Concatenation operators, Part I*

| Metric | **Proposed Concatenation Operator** |
|---|---|
| **MMBCR** | Minimum |
| **CMMBCR** | Addition and Minimum |
| **MREP** | Addition |
| **Battery Prevention** | Addition |
| **MTPR with Packet Loss Ratio** | Addition |
| **MTPR with Interference** | Addition |
| **Security** | undefined |
| **Billing** | Addition |
| **Application-Specific** | Addition |
| **Node Resources** | Addition or Minimum |
| **Learning Networks** | Addition |

**Table 3:** *Concatenation operators, Part II*

| **Metric** | **Proposed Aggregation Operator** |
|---|---|
| **Delay, RTT** | Weighted Average |
| **Bandwidth** | Addition |
| **Packet Loss Ratio** | Addition and Multiplication |
| **Energy per Packet** | Weighted Average |

**Table 4:** *Aggregation operators*

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