Routing Metrics for Multi-Radio Wireless Mesh Networks

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Abstract—**Multi-radio wireless mesh networks provide a great improvement over traditional mobile ad-hoc networks and are able to provide increased capacity and scalability. Routing metrics for multi-radio wireless mesh networks must cater to the specific characteristics that these networks exhibit and attempt to exploit these to maximize performance. Many routing metrics were designed for single-radio ad-hoc networks and hence do not perform well in multi-radio mesh networks. In this paper, we provide a survey of recently proposed routing metrics for multi-radio mesh networks. We also provide an overview of the most relevant single-radio metrics, since they typically form the basis of multi-radio metrics. For our survey, we identify the key components from which multi-radio metrics are constructed. We also provide a list of key criteria, which forms the basis of our qualitative comparison of routing metrics for multi-radio mesh networks.**

Keywords: routing metrics; multi-radio; wireless mesh networks

I. INTRODUCTION

Wireless mesh networks have, in recent years, increased in popularity due to their properties of self-configuration, self-healing and robustness. The motivation to build high-throughput mesh networks has been fuelled by the relatively low cost of network hardware. This has allowed routers to incorporate two or more radio interfaces on a single node in order to increase throughput and tackle the problems of co-channel interference in dense networks.

Wireless mesh networks can be categorized into three basic types according to architecture and topology [1]:

Client Mesh Networks are essentially the same as traditional Mobile Ad-hoc Networks (MANET) [2], in which the entire network consists of mobile client devices which implement routing and forwarding functionalities themselves.

In *Infrastructure Mesh Networks*, dedicated infrastructure nodes (Mesh Routers) provide a multi-hop wireless backbone infrastructure. Mesh Routers are typically equipped with multiple radio interfaces and are generally less resource constrained than client devices (Mesh Clients). In an Infrastructure Mesh Network, client devices do not perform any routing or forwarding functionality, and simply access the network via the nearest Mesh Router.

Hybrid Mesh Networks blend features from Client Mesh and Infrastructure Mesh Networks. Mesh Routers in Hybrid Mesh configurations still form the backbone of the topology and may provide backhaul access to external networks. However, in order to increase the reach of the network, client devices can be involved in routing. For example, if a client is not within communication range of a Mesh Router, another client device can act as a relay to the nearest router.

Recently, a lot of research effort has been focused on multi-radio wireless mesh networks. Due to the relatively low cost of commodity wireless hardware such as radio interfaces based on IEEE 802.11 standards, it is now feasible to include multiple radios on a single node. By operating these interfaces on orthogonal channels, the capacity of a Mesh Router can be significantly increased, and overcomes the limitation of half-duplex operation of single-radio nodes [3]. However, routing protocols must be designed to take advantage of the availability of multiple interfaces efficiently.

Routing protocols are at the heart of Wireless Mesh Networks and control the formation, configuration and maintenance of the topology of the network.

Much of the development of protocols for wireless mesh networks has been derived from protocols developed within the IETF MANET [2] working group. As the MANET protocols are designed for highly dynamic scenarios and therefore provide self-healing and self-configuring capabilities, they are also highly desirable in the context of wireless mesh networks.

Routing metrics are a key element of any routing protocol since they determine the creation of network paths.

Previous work published in [3, 4] have provided a discussion and comparison of some routing metrics for wireless mesh networks. In [4], the authors compare single-radio wireless network metrics by means of test-bed measurements. In [3], the authors identify several characteristics which they believe integral to the design of a good routing metric for wireless mesh networks. The authors then discuss various single- and multi-radio metrics and compare performance results via simulations.

In this paper, we provide an extensive qualitative comparison of the most relevant routing metrics for multi-radio wireless mesh networks, including recent proposals not included in [4] and [5]. For this purpose, we first identify the

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basic components or elements from which routing metrics can be constructed. We further discuss a set of key criteria for routing metrics, which will serve as the basis of our evaluation.

We then discuss various single-radio metrics, leading to the presentation of several prominent multi-radio metrics. We provide a qualitative comparison of these metrics according to our chosen criteria.

The rest of this paper is organized as follows: Section II provides a breakdown of critical components we believe metrics should be composed of. Section III describes a set of characteristics we have identified in order to compare various routing metrics. In Section IV, we provide a breakdown of some basic routing metrics as well as the most common metrics usable in multi-radio wireless mesh networks. In Section V, we discuss our classification scheme as applied to the selected routing metrics and provide a tabulated comparison of these metrics.

II. METRIC COMPONENTS

In this section, we identify and discuss the key components that can be utilized to compose a routing metric for multi-radio wireless mesh networks.

A. Number of Hops

Hop count can serve as a routing metric in itself, such as in most MANET routing protocols, but can also be a component in a more complex metric. Hop count as a routing metric for wireless mesh networks has significant limitations. It has been shown in [5] that a path with a higher number of high-quality links demonstrates significant performance improvements over a shorter path comprised of low-quality links. Additionally, the authors of [6] found that hop count tends to route through a few centrally-located nodes, leading to congestion and hot spots.

B. Link Capacity

Measuring the link capacity gives the metric a view at the current throughput capability of a link. There are a few ways this can be done, from actively probing the link to measuring transfer speeds, to relying on the radio interface's current rate. Furthermore, as most radio interfaces have the ability to automatically lower their transmission speeds in order to deal with lossy links, finding links with higher capacity will lower medium access time and increase the performance of the topology [7].

C. Link Quality

Finding high-quality links will greatly improve the overall performance of a path through higher transfer speeds and lower error rates. Link quality can be measured in a number of ways. The most common metrics are Signal to Noise Ratio (SNR) and Packet Loss Rate (PLR). This information is typically available from the device driver of a wireless interface. Alternatively, the PLR value can be determined through active probing [8].

D. Channel Diversity

Using the same channel on multiple consecutive hops of a path results in significant co-channel interference, and in a reduction of overall throughput. Ideally, all links of a path within interference range of each other should be operating on non-overlapping channels, resulting in significant performance gains [9, 10]. The extent to which this can be achieved can be expressed as *channel diversity*. Obviously, channel diversity is only relevant for multi-radio networks, since in single-radio networks all interfaces are required to operate on the same channel to guarantee connectivity.

III. METRIC CHARACTERISTICS

We have identified a number of criteria with which to compare the metrics we will describe. Note that not all criteria must necessarily be met in order for a metric to choose better routes as some metrics are specifically designed to ignore some criteria in favor of efficiency.

A. Intra-Flow Interference

Intra-flow interference occurs when the radios of two or more links of a single path or flow operate on the same channel. Intra-flow interference can be reduced by increasing channel diversity [10], i.e. by selecting non-overlapping channels for adjacent hops of a path. Intra-flow interference is not limited to neighboring links and can be experienced over multiple hops. This is due to the fact that the interference range of a node is typically bigger than a single hop [11].

B. Inter-Flow Interference

Inter-flow interference is the interference caused by other flows that are operating on the same channels and are competing for the medium. Inter-flow interference is harder to control than intra-flow interference, due to the involvement of multiple flows and routes.

C. External Interference

External interference occurs when a link experiences interference outside of the control of any node in the network. This type of interference can be further divided into two distinct types, as defined in [12]: *Controlled Interference* occurs when other nodes external to the network use networking technologies that overlap with those used by the network. Due to the broadcast nature of the wireless medium and the MAC back-off mechanisms of 802.11- based radios this creates contention at the MAC layer, resulting in reduced throughput. The second type of external interference is *uncontrolled interference* and is caused by any other source of radio signals emitted in the same frequency range, but not participating in the same MAC protocol. Examples include cordless phones, microwave ovens or Bluetooth [13]. Both of these types of external interferences can influence link quality and can seriously affect network performance and throughput [14].

D. Locality of Information

Some metrics require information such as channels used on previous hops of a path, or other metrics observed on other nodes of the networks, such as packet delivery rate or noise levels. This non-local information can be part of routing metric and can be used to make more optimal routing decisions. If the metric requires a lot of information from nodes external to itself, the result can be the following two problems. The first is that the control packets used to acquire this information may become excessively large and frequent, therefore increasing the routing overhead in the network. Secondly, the increased processing overhead might result in larger route establishment delays.

E. *Load Balancing*

The ability of a metric to balance load can provide fairer usage of the network's distributed resources. A metric can be greedy and attempt to maximize the throughput of the individual path that is being established, without regard for the overall performance of the network. This can occur because the metric only considers local measurements to form routes or because the metric attempts to use the highest capacity links without regard to their current loads. On the other hand, a metric can utilize information learned from neighboring nodes to make informed decisions that will attempt to alleviate load on highly loaded nodes. This can be accomplished by either attempting to minimize the impact on neighboring nodes, for example by attempting to find routes through links which have the most residual link capacity as in [15].

F. *Agility*

The agility of a metric refers to its ability to respond quickly and efficiently to changes in the network in terms of topology or load. In order for a metric to be considered *agile*, the rate at which measurements are taken should be higher than the rate of change in the network. If the rate of change exceeds the rate of measurement, then the metric is no longer providing a true picture of the state of the network and is therefore no longer accurate. This is shown in [4], where the hop count metric is able to outperform other, more sophisticated metrics. In contrast to other, more complex metrics, which require sampling and time averaging of multiple network parameters, the hop count can be determined instantaneously at route establishment time, which allows it to out-perform more complex metrics in highly dynamic network scenarios, i.e. networks with high mobility.

G. *Isotonicity*

In simple terms, the isotonic property of a routing metric means that a metric should ensure that the order of the weights of two paths are preserved if they are appended or prefixed by a common third path. This is described in more detail in [3]. Isotonicity is the necessary and sufficient condition of a routing metric for the existence of efficient algorithms to find minimal weight paths, such as Bellman-Ford or Dijkstra's algorithm.

If a routing metric is not isotonic, only algorithms with exponential complexity are able to find minimal weight paths. In some situations, isotonicity is also required to guarantee the establishment of loop free routes [3].

H. *Stability*

As described in [3], the metric of a link should not vary too greatly over time. Abrupt changes in the metric can trigger a protocol to send out route updates and may cause the protocol's overhead to become extremely high. Yang et al. [3] and Draves et al. [4] both mention that load-sensitive metrics may cause a metric to fluctuate greatly. The authors of [3] also point out that topology-dependent metrics vary much less and are much more stable, especially in low-mobility scenarios.

I. *Throughput*

In general, a metric should be able to select routes with greater throughput consistently. This is beneficial for a number of reasons. Firstly, as described in [7], traffic on a link with a faster transmission rate and greater throughput will occupy less air time, and it will therefore allow other nodes greater use of the medium. Secondly, a path that has greater throughput will transmit data with less delay and hence provide improved performance and quality of service.

IV. ROUTING METRICS

In this section, we will describe the major routing metrics for multi-radio mesh networks. We will begin by describing some metrics applicable to single-radio mesh networks as much of the later work is based on these metrics.

A. *Hop Count*

This is the base metric used in most MANET [2] protocols and is a simple measure of the number of hops between the source and destination of a path.

However, hop count maintains a very limited view of links, ignoring issues such as link load and link quality. De Couto et al. [5] showed that a route with a higher number of short links can outperform a route with a smaller number of long distance and therefore lower quality links.

This can lead the hop count metric to choose paths with low throughput and cause poor medium utilization, as slower links will take more time to send packets.

Furthermore, hop count tends to select long distance links with low quality, which typically already operate at the lowest possible rate, due the link layer's autorate mechanism. This leaves the autorate mechanism no further flexibility in dealing with channel quality fluctuations, resulting in reduced link and path reliability [7].

Hop count does not take into account link load, link capacity, link quality, channel diversity or other specific node characteristics. Neither does it consider any form of interference.

While it has been shown that the hop count is not necessarily an optimal metric to establish high throughput paths [8], comparisons have demonstrated that under scenarios of high mobility, hop count can out-perform other load-dependent metrics [4]. This is mostly a result of the metric's agility.

Hop count is also a metric with high stability, and further has the isotonicity property, which allows minimum weight paths to be found efficiently.

B. *ETX*

Expected Transmission Count (ETX) [8] is a measure of link and path quality. It simply considers the number of times unicast packets need to be transmitted and re-transmitted at the MAC layer to successfully traverse a link.

The ETX path metric is simply the sum of the ETX values of the individual links.

ETX considers the number of transmission in both directions of a link, since the successful transmission of a unicast frame requires the transmission of the frame in one direction plus the successfully transmission of an acknowledgement in the reverse direction.

The ETX metric for a single link is defined as shown below, where d_f is the measured rate or probability that a packet will be successfully delivered in the forward direction and d_r denotes the probability that the corresponding acknowledgement packet is successfully received. Assuming these two probabilities are independent, we can say that the probability of a successful transmission, including acknowledgement, is $d_f * d_r$. By utilizing the inverse of this value, the ETX calculation, defined below, provides a minimum-weight cost to higher quality links:

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

ETX is mostly determined by means of active probing, in which the number of successfully received packets is compared with the number of packets sent in a given time window, which is typically around 10 seconds [8].

While ETX outperforms hop count in single-radio and single-rate networks, it does not perform well in multi-rate and multi-radio networks due to its lack of knowledge of co-channel interference and its insensitivity to different link rates or capacities [16]. As a consequence, ETX tends to select links with lower rate. Links with lower transmission rates take up more medium time to transmit data and forces neighboring nodes to back off from their own transmissions. This phenomenon leads to poor medium fairness in the network [7].

Additionally, ETX does not consider the load of a link and will therefore route through heavily loaded nodes without due consideration, leading to unbalanced resource usage. ETX does not discriminate between node types and makes no attempt to minimize intra-flow interference by choosing channel-diverse paths. It has been shown in [4] that in highly-mobile single-radio environments, ETX demonstrates poor agility due to the long time window over which it is obtained. However, ETX does deal with inter-flow interference indirectly, through the measurements of link-layer losses. Links with a high level of interference will have a higher packet loss rate and therefore a higher ETX value. EXT is isotonic, and therefore allows efficient calculation of minimum weight and loop-free paths.

As many implementations of ETX [8] utilize small broadcast probe packets to detect losses there lies an issue where the measurements do not accurately reflect the loss rate of actual traffic due to the smaller size of the probe packets compared to the average packet size of network traffic.

These effects could be mitigated by utilizing a cross-layer approach and directly obtaining the number of retransmissions from the link layer.

C. ETT

The Expected Transmission Time (ETT) metric [10] is designed to augment ETX [8] by considering the different link rates or capacities. This allows ETT to overcome the limitation of ETX that it cannot discriminate between links with similar loss rates but have a massive disparity in terms of bandwidth. This is particularly useful in multi-rate networks. ETT is simply the expected time to successfully transmit a packet at the MAC layer and is defined as follows for a single link:

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

S denotes the average size of a packet and B the current link bandwidth. The ETT path metric is obtained by adding up all the ETT values of the individual links in the path.

ETT retains many of the properties of ETX, but can increase the throughput of the path through the measurements of link capacities, and therefore increase the overall performance of the network.

However, ETT still does not consider link load explicitly and therefore cannot avoid routing traffic through already heavily loaded nodes and links.

ETT was not designed for multi-radio networks and therefore does not attempt to minimize intra-flow interference by choosing channel diverse-paths.

D. WCETT

The Weighed Cumulative ETT (WCETT) metric [10] has been designed to improve the ETT metric by considering channel diversity. The WCETT metric of a path p is defined as follows:

$$WCETT_p = (1-\alpha) \times \sum_{i \in p} ETT_i + \alpha \times \max_{1 \le j \le k} X_j$$

X_j is the sum of the ETT values of links that are on channel j in a system that has k orthogonal channels and α is a tunable parameter within the bounds $0 \le \alpha \le 1$, that allows controlling the preference over path length versus channel diversity.

The first term of the equation simply adds up the individual link ETTs, and therefore generally favors shorter, high quality paths. The second term of the equation adds up the ETTs of all links of a given channel, and then takes the maximum over all channels. A path with a large number of links operating on the same channel will therefore have a high value. As a result, the second term favors paths with a high level of channel diversity, and therefore low intra-flow interference.

However, one of the problems of WCETT is that is simply considers the number of links operating on the same channel and their respective ETTs, but ignores the relative location of these links. For example, two links that are operating on the same channel, but that are outside of each other's interference range, do not create any interference and do not have a negative effect on throughput. WCETT simply assumes all links of a path operating on the same channel interfere [3], which can lead to the selection of non-optimal paths.

The second term of WCETT that allows controlling of channel diversity is responsible for the fact that WCETT is not isotonic, which makes this metric very difficult to use with link-state routing protocols, where algorithms such as Bellman Ford or Dijkstra are typically used to find minimal weight paths [3].

As WCETT is based on ETT to measure link capacity and loss ratios, it inherits many of the properties of both ETT and ETX, with the key improvement of considering channel diversity.

However, WCETT manages to improve the performance of multi-radio, multi-rate wireless networks when compared to simpler metrics such as ETT, ETX and Hop count [10, 12].

Finally, WCETT still does not explicitly consider the effect of inter-flow interference. As a result, WCETT may establish routes via nodes in dense areas of the network, suffering from high levels of interference and potentially leading to starvation of nodes [3, 12].

E. MIC

The Metric of Interference and Channel switching cost (MIC) was designed to support load-balanced routing and to consider intra-flow and inter-flow interference, in addition to being isotonic [3]. The metric for a path *p* is defined as follows:

$$MIC(p) = \alpha \sum_{l \in p} IRU_l + \sum_{i \in p} CSC_i$$

p represents a path in the network, *l* is a link in *p*, and the parameter *i* is a node in the path. α is a tunable parameter that allows to vary the weight given to the two components of MIC. These two components are: Interference-aware Resource Usage (IRU) and Channel Switching Cost (CSC). IRU considers inter-flow interference and CSC represents the level of intra-flow interference.

The IRU component of a link between nodes *i* and *j* is defined as follows:

$$IRU_{ij}(c) = ETT_{ij}(c) \times \left| N_i(c) \bigcup N_j(c) \right|$$

$N_i(c)$ is the set of neighbors which node *i* would interfere with if it transmits on channel *c,* and $| N_i(c) \cup N_j(c) |$ is the total set of neighbor nodes which would be interfered with by the link *ij* operating on channel *c*. By multiplying this with the corresponding ETT value, the IRU metric captures the total channel time of the neighbors that is affected by the transmission between *i* and *j*, which represents the level of inter-flow interference that the flow inflicts on the network.

The Channel Switching Cost (CSC) of a node *i* is defined as follows:

$$CSC_i = \begin{cases} w_1 & if \quad CH(prev(i)) \neq CH(i), \\ w_2 & if \quad CH(prev(i)) = CH(i), \end{cases}$$
$$0 \leq w_1 < w_2$$

CH(prev(i)) is the channel used by the previous hop to node *i* and *CH(i)* is the channel used for the next hop at node *i*. The metric tries to avoid consecutive hops in a path operating on identical channels, by giving it a higher cost.

MIC tries to overcome the limitations of WCETT by directly considering intra-flow and inter-flow interference.

The IRU component of MIC attempts to quantify the effects of transmitting a flow from a node on its neighbors. This approach shows some promise at first glance but has been shown to have a major flaw: the IRU metric makes the assumption that a link will always contend with neighboring nodes regardless of their current activity. This can lead to a scenario where MIC will start routing around the edge of the topology where nodes have fewer neighbors and hence create longer, slower paths [12].

The authors of [3] have also recognized that their approach to measuring intra-flow interference does not capture the exact phenomenon of carrier sense on wireless links. They offer some ideas to address this, but conclude that the benefit gained is not worth the extra complexity.

MIC can be made isotonic, if it is decomposed into virtual nodes when applying minimum weight path-finding algorithms such as Dijkstra's algorithm. Additionally, nodes do not need to communicate channels used between neighbors if MIC is used in its original state and hence does not increase routing overhead. In order to combat unstable route selections, MIC does not consider link loads.

F. iAware

The Interference Aware (iAware) metric [12] attempts to overcome some of the limitations of MIC by using a more accurate interference model. In contrast to MIC, iAware considers the amount of traffic generated by interfering nodes. The iAware metric is defined as follows:

$$iAWARE(p) = (1-\alpha) \times \sum_{i=1}^{n} iAWARE_i + \alpha \times \max_{1 \leq i \leq k} X_j$$

The X_j component is the same as in WCETT [10]. Instead of the ETT values used in WCETT, the *iAWARE* values are used. The *iAware* value of a link *j* is defined as follows:

$$iAWARE_j = \frac{ETT_j}{IR_j}$$

The value of IR_j for a link *j* between two nodes *u* and *v* is defined as follows:

$$IR_j = \min(IR_j(u), IR_j(v))$$

Finally, the Interference Ratio (IR) value at a single node *u* for a link *i* is defined as follows:

$$IR_i(u) = \frac{SINR_i(u)}{SNR_i(u)}$$

$SINR_i(u)$ [12] is the Signal to Interference Noise Ratio and $SNR_i(u)$ is the Signal to Noise Ratio at node u for link *i*. In contrast to SNR, SINR specifically considers the signal power received from interfering nodes and adds it to the general background noise. For a practical implementation, *iAware* relies on the radio to provide the necessary power levels.

The iAware metric exploits the fact that when there is little interference in the network, the ETT metric captures link quality quite well. If a node experiences no interference, then the iAware metric simply becomes ETT as the IR approaches 1.

The iAware metric retains many of the properties of the WCETT metric with the exception of its handling of inter-flow measurements. Following the design of the MIC metric, iAware directly measures the average interference generated by neighboring nodes. This approach overcomes the flaw in MIC where flows would be eventually forced to the outer edges of the topology.

TABLE I. Metric Components

	Hop	ETX	ETT	WCETT	MIC	iAware
Number of Hops	✓	×	×	×	×	×
Link Capacity	×	×	✓	✓	✓	✓
Link Quality	×	✓	✓	✓	✓	✓
Channel Diversity	×	×	×	✓	✓	✓

TABLE II. Metric Characteristics

	Hop	ETX	ETT	WCETT	MIC	iAware
Intra-Flow Interference	✓	×	×	✓	✓	✓
Inter-Flow Interference	×	✓	✓	✓	✓	✓
External Interference	×	×	×	×	×	✓
Locality	×	×	×	×	×	✓
Load Balancing	×	×	×	✓	×	✓
Agility	✓	×	×	×	×	×
Isotonicity	✓	✓	✓	×	✓	×
Stability	✓	×	×	×	×	×

V. Discussion

Table I gives an overview of the components that the various metrics are built from. Table II shows which of the criteria identified in Section III are met.

It is important to note that in order for a metric to perform well, it is not necessarily required for it to meet all of the criteria. Many metrics take deliberate design decisions and ignore certain criteria in favor of others.

The hop count (HC) metric ignores parameters such as interference and link quality, resulting in limited performance in wireless mesh networks. Due to its simplicity, HC does not require any external information, has a high level of agility, and is also isotonic.

The ETX metric builds on the HC metric but attempts to also consider link quality. It is designed to gracefully degrade as the number of hops increase in order to still choose shorter routes, but is unable to capture varying link capacities in multi-rate networks. Due to the active probing method in which the ETX metric is typically measured, and the corresponding large time window in which this is done, ETX is not very agile. Also, ETX does not consider link capacity and link load, and can therefore not perform load balancing.

The ETT metric extends ETX by consider link capacity. As mentioned previously, in the absence of interference, ETT captures link quality quite well. Unfortunately, ETT does not directly measure interference and hence will suffer in dense networks. As ETT does not measure intra-flow interference, it is poorly suited for multi-radio mesh networks.

The WCETT metric retains many of the characteristics of the ETT metric. In addition, it specifically considers intra-flow interference. By favoring links with high channel diversity, WCETT attempts to increase throughput. One of the limitations of WCETT is its insensitivity to inter-flow interference.

MIC tries to overcome the limitations of WCETT by directly considering intra-flow and inter-flow interference. We have discussed MIC's limitation in terms of its characterization of intra-flow interference. Since MIC does not consider link load, it is not able to balance the load among the nodes of a network.

Finally, iAware attempts to overcome some of the limitations of MIC by recognizing that even though a neighbor has the potential to interfere with other nodes, it does not do so if no traffic is generated.

VI. Conclusion

In this paper, we have presented a qualitative evaluation and comparison of routing metrics for multi-radio wireless mesh networks. We have identified key components of the metrics and a set of criteria that served as the basis of our comparison. However, much more work is required to further quantitatively evaluate these metrics in terms of their performance for a range of network topologies and scenarios.

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