Interference-Aware Routing Metric for Improved Load Balancing in Wireless Mesh Networks

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***Abstract*—Multihop wireless mesh networks are an attractive solution for providing last-mile connectivity. However, the shared nature of the transmission medium makes it challenging to fully exploit these networks. Nodes interfere with each other, resulting in packet loss and degraded network performance. In this paper, a routing metric specifically designed for WMNs is proposed. The Interference-Aware Routing metric (IAR) uses MAC-level information to measure the share of the channel that each link is able to utilize effectively. As a result, paths are selected that exhibit the least interference. Simulations show that utilizing this metric provides significant performance improvements in terms of end-to-end delay compared to several existing metrics.**

I. INTRODUCTION

In response to the increasing demand for ubiquitous low latency, high volume communication, the deployment of Wireless Mesh Networks (WMNs) has become an attractive alternative to wired solutions, 3G cellular systems, and WLANs. WMNs can offer high levels of service coverage, while requiring relatively inexpensive deployment costs. Initial deployments [11] [12] [13] have demonstrated WMNs' tremendous potential and market value. WMNs have been utilized to inexpensively share Internet connections in low-income community networks [9], and for deploying coverage across university campuses (e.g. MIT, University of Arkansas). As a result, several companies including Nokia [10], Microsoft [8], Motorola [1], and Intel [6] are actively promoting full IP-based solutions for WMNs.

Nonetheless, these are first-generation systems. They lack adequate resource management and service provisioning mechanisms, without which WMNs are unable to meet consumers' increasing demand for QoS guarantees. Creating the necessary resource management framework starts with an effective routing protocol including an adapted routing metric. In actual implementations, the choice of metrics has been influenced by the network specifics. However, previous experiments conducted in [4] have shown that currently implemented metrics (Hop Count, Expected Transmission Count, Expected Transmission Time) perform similarly. This suggests that the metrics do not consider the appropriate factors, and are essentially equivalent. In fact, only Hop Count, the simplest metric, distinguishes itself in mobile networks, as the other metrics do not adapt quickly enough to topology changes [3].

In response to this, we propose a routing metric that evaluates each link's effective share of the medium. The Interference-Aware Routing metric (IAR) MAC-level measurements determine the percentage of time each transmission wastes due to interference from other nodes. This wastage occurs in the form of backoff and waiting time, as well as failed transmissions. Routing using IAR therefore selects links that experience the least interference. We demonstrate through simulations that IAR produces improvements to end-to-end delay.

The remainder of this paper is organized as follows: in Section II, we consider the requirements of a WMN routing metric, and present an overview of some existing metrics currently used in WMNs. The characteristics of each metric is discussed, in order to evaluate their suitability for WMNs. Based on these discussions, Section III describes IAR, our new routing metric. Section IV presents a simulation-based evaluation of IAR, in comparison to three existing metrics, along with our analysis of the results. Finally, we conclude the paper in Section V.

II. BACKGROUND AND RELATED WORKS

Depending on the application requirements, the routing protocols can focus on optimizing one or more routing metrics. To motivate the need for a new routing metric, we define a set of criteria that we regard as important in the choice of a routing metric for WMNs and compare some existing routing metrics against them. Although many routing metrics have been proposed for WMNs, we only focus on the most commonly adopted. We first describe the criteria we chose and analyze how each of the selected routing metrics addresses these criteria.

A. Routing Metrics: Comparison Criteria

In order to assess the suitability of a routing metric for mesh networks, we select the following criteria as comparison factors:

- *Bandwidth*: In a wireless network, not all the links support the same transmission rate. These variations can be the result of technical limitations or environmental noise. The use of lower bandwidth links not only increases the

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end to end delay but also reduces the achievable rates of neighboring transmissions due to higher interference.
- *Path Length*: As the number of hops increases, the throughput decreases (self-interference) and the end-to-end delay increases. Path length constitutes therefore an important differentiation parameter.
- *Interference*: Due to the shared nature of the transmission medium, nodes transmitting on the same channel can interfere with each other if they are located in the same geographical area. Integrating interference in the design of the routing metric can therefore help combatting network congestion and increasing the overall network performance.
- *Packet Loss*: Channel quality can be assessed by estimating the number of retransmissions necessary for a transmission to be successfully performed.
- *Effective Link Share*: As access to the transmission medium is shared among the nodes located in the same area, a communication on a particular link is affected by the transmissions on neighboring links. It follows that a node may have to wait for concurrent communications to complete before to be able to send its own data. To obtain an estimate of the channel occupation (consequently of the congestion level) is a quality measure of interest.

Given the possibility to embed multiple interfaces in a node and to use different frequency bands (3 for IEEE802.11b and 12 for IEEE802.11a), integrating channel diversity in the routing decision is also an important decision criterion. Although we include it as part of the comparison criteria for completeness, this is not the focus of this work. We however provide some suggestions on how to enhance our metric to account for channel diversity based on works already done on this particular issue. We intend to investigate this problem in future works.

B. Metrics Description

1) Hop Count: Hop count is the most commonly used metric in wireless multihop networks. Indeed, it was chosen for ad hoc networks due to its easiness of computation as it only considers the route length as differentiation criterion. On the downside, this routing metric fails to account for the specifics of wireless environments (links may have different transmission rates, loss ratios, etc.) and it does not consider the congestion level resulting from the shared use of the transmission medium.

2) Expected Transmission Count (ETX): Expected Transmission Count is defined as the number of transmissions required to successfully deliver a packet over a wireless link [2]. The ETX of a path is then defined as the sum of the ETX of each link along the path. Let p_f and p_r be the packet loss probability in the forward and reverse directions. The probability p of an unsuccessful transmission is:

$$p = 1 - (1 - p_f)(1 - p_r)$$

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

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

The delivery ratios are measured using 134-byte probe packets. One probe packet is sent every second. The number of packets received over a predetermined period of time (set to 10 seconds in the experiments) will allow to determine the packet loss ratio.

ETX favors paths with higher throughput and lower number of hops as longer paths have lower throughput due to increased self-interference. However, this metric does not consider differences in transmission rates. It also does not give any information on the effective link share.

3) Expected Transmission Time (ETT): ETT is an improvement over ETX as it includes the bandwidth in its computation [3]. Let S be the packet size and B the bandwidth of the link considered, then ETT is computed as follows:

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

Similar to ETX, the expected transmission time of a path is computed as the sum of the links' ETX along the path. The main drawback of ETT is that channel diversity is not accounted for.

The authors later improved over ETT by proposing Weighted Cumulative ETT (WCETT) [3]. This metric was designed to favor channel-diverse paths. For a path P, WCETT is defined as follows:

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

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

Nonetheless, this metric still suffers from the same limitations as ETT by not estimating the effective link share.

C. Discussion on the choice of the routing metric

Table I summarizes the characteristics of each metric discussed previously. Although ETT (and its extension WCETT) satisfies most of the criteria that we identified as important for WMNs, they still fail to provide any information on the effective link share.

In this paper, we address this issue by proposing a novel routing metric based on the evaluation of the effective link share. We discuss its implementation when a single channel is used and describe how to extend this metric to integrate multiple channels. As our work is solely focused on wireless mesh networks that are characterized by a fixed backbone, we are not concerned with nodes' mobility.

TABLE I
COMPARISON OF ROUTING METRICS

	Bandwidth	Path length	Interference	Packet Loss	Effective Link Share	Multi Freq
Hop Count		X				
ETX		X	X	X		
ETT	X	X	X	X		
WCETT	X	X	X	X		X

III. INTERFERENCE-AWARE METRIC

A. Motivations and Design Choices

The impact of interference on the network performance is a parameter difficult to estimate. In order to have an accurate view of the channel state, it is necessary to factor in not only indicators of the channel quality such as nominal throughput or packet loss, but it is also critical to estimate the transmission delay resulting from concurrent data transmissions. The broadcast nature of the wireless medium forces the nodes at interference range of a given source and destination to wait for the medium to be cleared before to have access to it. Consequently, a routing metric properly tailored for WMNs that accounts for these different factors can improve the network performance by avoiding lossy links and congested zones. In particular, a routing metric specifically designed for WMNs should integrate the following characteristics:

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

B. Metric Computation

By estimating the actual waiting time between the initiation of a transmission and its completion, a more accurate view of the channel utilization can be obtained. In order to compute this time, we first need to identify the different states of a node. We identified five distinct states:

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

The period of time between the moment where a node generates a packet (or receives a packet it then has to relay) and the moment it successfully transmits the packet to the next hop node (possibly the destination of the packet) is a succession of *Success*, *Collision*, *Wait* and *Backoff* states (Fig. 1).

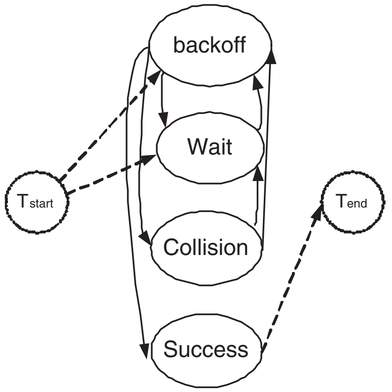

Fig. 1. Communication states

Our metric, *Interference-Aware Routing metric* (IAR), is therefore designed as follows. Let $T_{Success}$, T_{Wait}, $T_{Collision}$ and $T_{Backoff}$ be the time spent respectively in the *Success*, *Wait*, *Collision* and *Backoff* states. The communication cycle is defined as the period between the generation of a packet up to its successful transmission. For each link, we calculate the *unproductive busyness* α_{ub}, that is to say the percentage of time spent in states in which the node can not transmit any data.

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

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

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

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

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

$$IAR(p) = \sum_{l \in p} IAR(l) \tag{2}$$

The amount of time spent in each of these states can be determined by passive measurements using the actual traffic in transmission or by active probing.

Similar to ETT, IAR can be modified to handle the multi-channels scenario with the addition of a switching channel cost factor (cf. the computation of WCETT).

IV. IMPLEMENTATION

To evaluate the performance of our routing metric, we implemented various test scenarios using the network simulator NS2 [5] for different network topologies and traffic characteristics. Information on the link status are obtained via the implementation of an active probing mechanism. Unicast packets are sent periodically over each link in order to determine its utilization. To alleviate the cost incurred by the additional transmission of control packets that necessarily consume network resources and can potentially impact users transmission delay, load-adaptive probing mechanisms similar to the ones proposed in [7] can be implemented. For illustration purposes, we first run a series of simulations with a regular grid network topology We then extend our simulations scenarios to more general cases by considering random topologies. AODV is chosen as the underlying routing protocol. We compare our metric to three other metrics namely Hop Count, ETX (Expected Transmission Count) and ETT (Expected Transmission Time).

A. Grid Topologies

Let us consider the following grid topology composed of 25 nodes spaced by 200m. The interference range is set by default at around 500m and the data rate at 2Mb/s. RTS/CTS has been disabled.

We set up two flows from Node0 to Node4 and from Node5 to Node9. Theoretically, given the interference characteristics, $Link_{1-2}$ would be one of the bottlenecks as it would interfere with all the links along each path (Figure 3). Therefore, the maximal achievable throughput would be in the order of $B/8$ (B is the maximum achievable throughput at the MAC Layer).

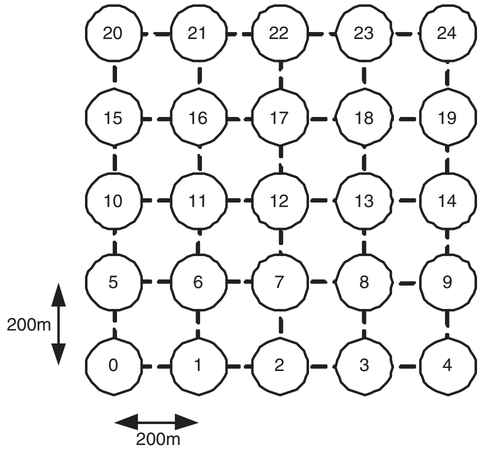

Fig. 2. Grid topology

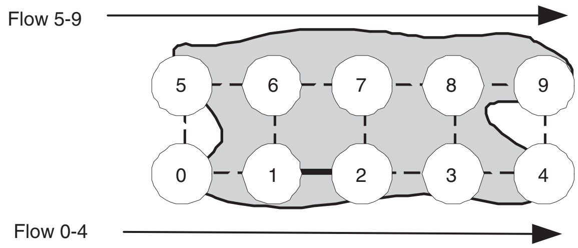

Fig. 3. Collision domain with 2 flows

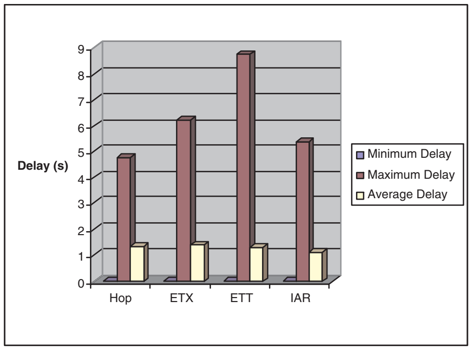

Fig. 4. End-to-end delay for 2 flows in a 25-node grid topology

When we analyze the results of the simulations, we can observe that IAR outperforms all the other metrics in terms of average end-to-end delay (Fig. 4). This result is a direct consequence of the design of our metric that favors longer paths less subject to interference over shorter paths but that might cross congested areas. This also explains that in some cases (in particular at the beginning of the flow transmission), the end-to-end delay achieved with IAR can be greater than the one achieved with Hop Count.

B. Random Topologies

After assessing the advantages of our metric for a simple topology, we ran additional test for random topologies, in which the source and destination nodes are also randomly chosen. We only enforce that the topologies be connected in order to guarantee that a path exists between any source-destination pair. The transmission range has been set to 250m. The traffic flows are CBR traffic with UDP as transport protocol. The packet size is fixed to 1000 bytes.

The settings of our tests are as follows. 4 flows are sent across the network at a rate of 0.05 packets per second. Source and destination nodes are randomly chosen. We can observe some distinct performance variations in terms of end-to-end delay (Fig. 5). Even though the interference-avoidance strategy of our metric usually results in longer paths, the paths chosen are less prone to packet loss and therefore result in a better end-to-end delay. The same observation can be made when there exists only one destination node as congestion is most likely to happen around this node.

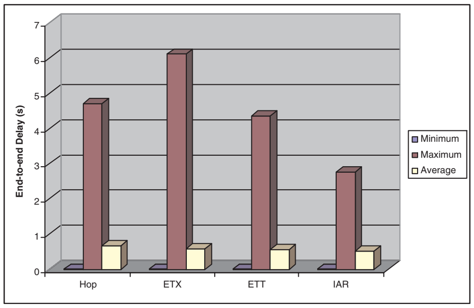

Fig. 5. End-to-end delay for 5 flows for random topologies - Network not congested

In scenarios where the network reaches congestion, IAR still outperforms the other metrics by allowing a better traffic distribution consequently resulting in a better end-to-end delay (Fig. 6). This is a direct consequence of the design of the metric that favors less congested zones and allows for a better traffic distribution.

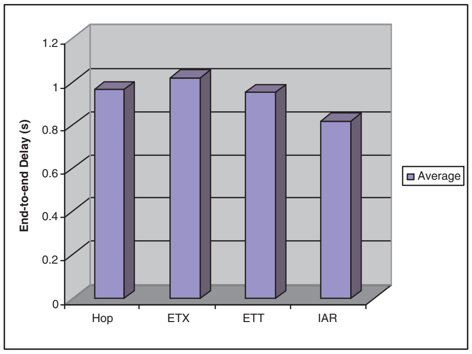

Fig. 6. End-to-end delay for 5 flows for random topologies - Network congested

V. CONCLUSION

With the rise of user expectation of anywhere connectivity and quality of service guarantees, new wireless technologies are sought after for their versatility, ease of deployment, and low cost. Wireless mesh networks present a promising solution by extending network coverage based on mixture of wireless technologies through multi-hop communications. WMNs exhibit several prominent characteristics that make them stand apart from traditional wired or wireless networks, and hence call for new resource management techniques.

Routing in multi-hop wireless networks is a challenging research issue, as paths self-interfere and interfere with concurrent transmissions. The medium quality can also be responsible for packet loss and trigger retransmissions that consequently impact the network performance.

To address the above issue, we have proposed a novel Interference-Aware Routing metric (IAR) that estimates the effective link share through local measurements. This approach allows to account for intra-flow and inter-flow interference as well as packet loss resulting from poor channel quality. We showed through simulations that significant improvement in terms of throughput and end-to-end delay can be achieved compared to those obtained with existing metrics.

As part of future works, we intend to investigate how accurately the channel quality can be evaluated via measurement and its impact on the network performance. We will also study more thoroughly the efficiency of existing approaches in terms of support for channel diversity and how to include it in our IAR metric.

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