MAC-Aware Routing in Wireless Mesh Networks

Vivek P. Mhatre, Henrik Lundgren, Christophe Diot

THOMSON - Paris Research Lab,
46 Quai A. Le Gallo, 92648 Boulogne, FRANCE
Email: {vivek.mhatre, henrik.lundgren, christophe.diot}@thomson.net

***Abstract*— We propose *Expected Throughput, ETP*, a new and improved routing metric for wireless mesh networks. In contrast to previously proposed routing metrics, ETP takes into account the bandwidth sharing mechanism of 802.11 DCF. In this mechanism, contending links with lower nominal bit rate degrade the throughput of faster links. It is evident that this MAC layer interaction impacts the link quality, and subsequently, the route quality. We develop an analytical model to capture the above interaction, and use it to define ETP. ETP is therefore expected to yield more accurate throughput estimations than existing routing metrics. Furthermore, ETP is suitable as a routing metric in multi-rate as well as multi-channel mesh networks.**

I. INTRODUCTION

Wireless Mesh Networks provide a cost-efficient avenue to extend the coverage of WiFi networks by using multi-hop communication. While significant advances have been made on routing in wired networks, the metrics used for routing in wired networks, such as link capacity, cannot be directly extended to wireless networks due to the following reasons. First, unlike the wired links, wireless links often have very high packet error rates [1]. Second, the wireless medium is broadcast in nature. Hence, a wireless link has to contend with other wireless links in its neighborhood for transmission opportunities. Such contention can lead to poor throughput performance as observed in [2]. Several recent proposals on routing in mesh networks therefore attempt to capture the above distinctive features of wireless networks.

In [2], [3], and [4], routing metrics have been proposed by taking into account (i) the link quality in terms of the nominal bit rate, (ii) the packet loss rate, and (iii) the MAC layer contention experienced by a link. However, none of the above approaches accurately captures the bandwidth sharing mechanism of 802.11 DCF. When wireless links contend for channel access, the 802.11 DCF mechanism tries to provide fair bandwidth sharing to all the contending links. The notion of fairness as per 802.11 DCF is to allocate equal number of transmission opportunities to all the contending links. Previous studies [6], [7] has shown that this results in the slow links (low nominal bit rate) occupying the wireless channel for long duration, and thereby leading to throughput reduction of the neighboring fast links (high nominal bit rate).

In this work, we use an analytical model of the bandwidth sharing mechanism of 802.11 DCF to determine the expected throughput of a link. Based on this analytical model, we propose a new MAC-aware routing metric called *Expected Throughput, ETP*. ETP takes into account the nominal bit rates of the contending links in the neighborhood of a given link, and thus explicitly accounts for the fact that slow links lower the throughput of neighboring fast links. This aspect of 802.11 bandwidth sharing is not captured by previously proposed metrics such as ETX [2], ETT [3], and EDR [4]. We are currently developing a mesh network testbed over which we will prototype the proposed ETP routing metric.

We also discuss the interdependence between the following important issues in wireless mesh networks: (i) determining high throughput routes by accounting for MAC interaction between the active links, and (ii) evaluating the quality of a wireless link by taking into account MAC contention from *all the active links* in the network. We argue that a *cross-layer* approach is necessary to determine optimum routes, since MAC and routing directly impact each other in a wireless mesh network.

The rest of the paper is organized as follows. In Section II, we motivate the need for a MAC-aware routing metric and discuss the related work. The analytical model for ETP and its implementation details are discussed in Section III. In Section IV, we discuss the generic problem of cross-layer interactions between MAC and routing in mesh networks. Finally, we conclude in Section V.

II. MOTIVATION AND RELATED WORK

A fundamental difference between wired and wireless networks is that the wireless links share a common wireless channel. Hence, in order to avoid packet collisions, the transmission of packets on neighboring links need to be co-ordinated via a MAC protocol. The manner in which the MAC protocol operates has a significant impact on the throughput of all the links. Past work [6], [7] has shown that the presence of slow links lowers the throughput of all the links in the neighborhood. For example, consider two contending co-channel wireless links, i.e., links such that a transmission on one link precludes a transmission on the other link due to carrier sensing. Assume that there are no other co-channel links, and that the links always have packets to send. Let the nominal bit rates of the links be r_1, r_2, and assume that the links have zero packet error rate. The 802.11 DCF mechanism ensures that on an average, both the links get equal number of transmission opportunities. Let m be the number of transmission opportunities that each of the links gets over a duration of t seconds. Assume that both links use a fixed and common packet size, L. Thus, the throughput of each of the links is $b_1 = b_2 = b = \frac{mL}{t}$. The respective durations for which the links occupy the wireless channel are $\frac{mL}{r_1}$ and $\frac{mL}{r_2}$. Thus,

$$t = \frac{mL}{r_1} + \frac{mL}{r_2} \quad \Rightarrow \quad \frac{mL}{b} = \frac{mL}{r_1} + \frac{mL}{r_2}$$
$$\Rightarrow \quad b = b_1 = b_2 = \frac{1}{\left(\frac{1}{r_1} + \frac{1}{r_2}\right)} \tag{1}$$

If $r_1 = 54$Mbps and $r_2 = 1$Mbps links, each link gets a throughput of 0.98Mbps. Thus, a slow link leads to throughput reduction of a faster neighboring link. This shows that while the nominal bit rate and packet error rate of a link are important indicators of its quality, the nominal bit rates of the *contending links* also have significant impact on the link quality. As we discuss in the rest of this section, the past work does not take the above dependence into account when defining a routing metric.

In [2], the authors define the routing metric for a link to be the *Expected Transmission count, ETX*, which is the expected number of transmissions required for delivering a packet over that link. The routing metric for a path is then defined as the sum of ETX of all the links on that path. The metric is designed to avoid paths with lossy links. As the authors themselves point out, by summing up the transmission counts of all the links for determining the transmission count of the entire path, they implicitly assume that all the links of the path contend with each other. While this assumption is true for paths of 3-4 hops, it is not applicable for longer paths. Longer paths have multiple links that can transmit concurrently, since they are not in each others' contention domain. When this spatial reuse is taken into account, the actual transmission cost of a path is *lower* than the sum of the transmission counts of all the links of the path. Thus, adding the ETX of all the links of a path, unfairly increases the cost of a long path.

Another key limitation of the ETX metric is that it does not take into account multi-rate links. In [3], the authors generalize the definition of ETX to *Expected Transmission Time, ETT*, so as to account for multi-rate links. The routing metric of a path is then defined as the sum of the ETTs of all the links of that path. Similar to ETX, the ETT metric assumes that all the co-channel links on a path contend with each other. Both these metrics therefore make conservative estimates for paths longer than 3-4 hops.

In [4], the authors attempt to overcome the above limitation by incorporating time-sharing effects of MAC in the routing metric. They define a quantity called the *Transmission Contention Degree*, $TCD(k)$ of link k as the average fraction of the time for which the outgoing queue of the transmitter of link k is non-empty. Whenever the outgoing queue of a link is non-empty, it contends with other links in its neighborhood for channel access. For a given path on which link k lies, the authors define a quantity $I(k)$ which is the sum of the TCDs of all the links on that path, that contend with link k. Note that $I(k)$ also includes $TCD(k)$. A routing metric for link k, referred to as *Expected Data Rate, EDR* is then defined as:

$$EDR(k) = \frac{\Gamma}{ETX(k) \cdot I(k)}, \tag{2}$$

where Γ is the nominal bit rate of the link. In the above equation, $ETX(k)$ is used to account for throughput reduction due to packet losses, while $I(k)$ is used to account for throughput reduction due to time-sharing with the contending links. In essence, the above model assumes that all the contending links get the equal time-share, and hence the factor $I(k)$ appears in the denominator. The EDR of a path is then defined as the minimum of the EDRs of all the links of the path. The assumption that all the $I(k)$ links get an equal time-share of the channel holds true when all the links have the same nominal bit rate. However, as Eq. (1) shows, when links have different nominal bit rates, they receive the same average throughput, but different time-share of the channel. Thus, the above model of time-sharing through $I(k)$ fails to capture the bandwidth-sharing mechanism of 802.11 DCF.

In the following section, we propose an improved routing metric that incorporates the MAC-layer interaction between contending wireless links.

III. A MAC-AWARE ROUTING METRIC: EXPECTED THROUGHPUT, ETP

Consider the problem of determining the best route between two nodes in a mesh network. Let P be a candidate path. Let link k belong to path P. Define the contention domain of this link, i.e., S_k as the set of all the links in the network that preclude a transmission on link k. Then, $S_k \cap P$ is the set of links on path P that contend with link k. Let r_k be the nominal bit rate of link k. When all the links of path P are saturated, then as per 802.11 DCF, all the links get equal number of transmission opportunities. Hence, as in Eq. (1), the expected bandwidth received by link k (denoted by b_k) is given by:

$$b_k = \frac{1}{\left(\sum_{j \in S_k \cap P} \frac{1}{r_j}\right)} \tag{3}$$

Note that when a routing path is busy forwarding traffic, *all* the links of the path have packets to send. Since we are only interested in evaluating the quality of a path when the path is actually in use, the assumption that all the links of the path are saturated, is justified. Also note that in (3), we have not taken into account the contention from those links that do not belong to path P. As we discuss later in Section IV, taking into account inter-path MAC interactions increases the complexity of the problem, and hence we use the above approximataion in which we only account for intra-path contention.

Although the link receives this bandwidth, the actual throughput of the link is lowered by packet losses. If $p_k^{(f)}$ and $p_k^{(r)}$ be the packet *success* probabilities of link k in the forward and reverse directions respectively, then the *Expected*

Throughput, ETP of link k is given by:

$$ETP(k) = \frac{p_k^{(f)} \cdot p_k^{(r)}}{\left(\sum_{j \in S_k \cap P} \frac{1}{r_j} \right)} \tag{4}$$

Thus, ETP directly computes the primary quantity of interest which is the expected throughput of a link. As compared to ETX, ETT and EDR, ETP has a more accurate model for the impact of contention in 802.11 MAC. The routing metric of the path, $f(P)$, is then defined as the throughput of the bottleneck link of the path, i.e.,

$$f(P) = \min_{k \in P} ETP(k), \tag{5}$$

and the routing policy is to choose the path with the highest routing metric $f(.)$.

Note that in deriving Eq. (4), we do not make any assumption about the operating channel of the links. We only require that each link be aware of the nominal bit rates of the co-channel links on the routing path under consideration. Even if some of the links of the path operate over different channels, the analytical model for computing the expected throughput in Eq. (4) is still applicable. We can therefore determine the link quality (expected throughput) using Eq. (4), and the route quality (expected throughput of the bottleneck link) using Eq. (5). ETP can thus be used as a routing metric in multi-radio multi-channel mesh networks.

A. Implementation of ETP

We propose to use the following strategy for implementing ETP. The mesh nodes operate in the IBSS mode, so that beacon messages are enabled[1]. Beacon messages are particularly attractive for schemes such as ETP which require the knowledge of the contention domain of a link. To evaluate the ETP metric in Eq. (4), the associated nodes of a link require information about the nominal bit rates of the contending links. For this, each node can encode the nominal bit rates of all its associated links in its beacon message, so that its neighbors can recover this information. It is possible that a link is in the contention domain of a given link, but the beacon messages of the former may not be decodable at the nodes of the latter. This typically happens because the interference range is larger than the transmission range. A simple workaround for this problem is for the nodes to include the link quality information of their one hop neighbors in their own beacons. Furthermore, to estimate the packet loss probabilities in Eq. (4), periodic probe packets can be used as in [2], [3].

B. ETP: Summary

The proposed routing metric ETP, has the following salient features:

1) ETP is a measure of the expected throughput of a link.
2) The analytical model used in ETP captures the bandwidth sharing mechanism of 802.11 DCF. This model is more accurate than the models used in EDR, ETT, and ETX, since the latter do not take into account the throughput reduction of fast links due to contention from slow links. ETP is therefore expected to predict better routes in mesh networks with heterogeneous link rates.
3) Furthermore, ETP is expected to predict better routes than ETX and ETT in mesh networks with long paths, since the latter do not account for spatial reuse, and therefore unfairly penalize long paths.
4) ETP is suitable for multi-rate multi-radio mesh networks.
5) ETP can be easily implemented in the IBSS mode with minor additions to the beacon message contents.

Comparing the performance of ETP with other routing metrics is part of our future work. However, it should be clear that for mesh networks with heterogeneous link rates and long paths, ETP should perform well, since it uses a more accurate model of the 802.11 DCF bandwidth sharing.

IV. INTERDEPENDENCE OF ROUTING AND MAC IN MESH NETWORKS

In Section III, we discussed various routing metrics for mesh networks, and proposed a new routing scheme. While it is well-understood that the MAC layer has a strong impact on routing, we emphasize that routing too, affects the performance of a link at MAC layer. Hence, in this section, we motivate a need for a more holistic approach to routing.

One design choice common to all the routing metrics discussed in Section III, is to study a routing path in isolation. In other words, the MAC interaction between the links of a given path is accounted for. However, the contention from other links in the network is ignored. In the context of wired networks, the capacity of a given link does not depend on the traffic on its neighboring links. In the case of wireless networks however, all the links in a given neighborhood are closely coupled. Ideally, the routing metric for a link should therefore take into account the MAC contention from *all the active links* in the neighborhood of a the link, not just the links on the chosen routing path.

One approach to account for the total contention in our ETP metric for example, is to extend the definition in Eq. (4) by including all the active interfering links, i.e., summing up over S_k instead of $S_k \cap P$. However, the set of links that belong to S_k is determined by the routing choices of other nodes. This is because the routing policy determines the set of active links in the network. At the same time, the MAC layer interaction between these links determines the expected throughput of the links, which in turn determines the optimum routing structure. We thus have a chicken-and-egg problem. The current proposals, such as ETT, ETX, EDR and ETP, address this problem by only looking at the contention between the links of a given path. However, it is clear that such an approach is sub-optimal. We are currently working on refining the definition of ETP, and coming up with a broader

---

[1] To avoid the BSS partitioning problem, the pseudo-IBSS mode used in [2], disables beacon messages. Hence, to use pseudo-IBSS mode, a customized beacon mechanism has to be implemented for our proposed scheme.

routing framework, so as to account for the above cross-layer interdependence.

V. CONCLUSION AND FUTURE WORK

We proposed a new MAC-aware routing metric called Expected Throughput, ETP for wireless mesh networks. ETP incorporates the bandwidth sharing mechanism of 802.11 DCF to determine the expected throughput of a wireless link. ETP is expected to outperform previously proposed routing metrics such as ETX, ETT, and EDR in mesh networks which have links with diverse nominal bit rates, and long paths.

In the future, we plan to compare the performance of ETP with other routing metrics through extensive simulations. We are currently developing a mesh network testbed over which we will prototype ETP, and compare its performance with other routing metrics. We believe that the interdependence between routing and MAC layer interactions, is a fundamental problem in wireless mesh networks. Current approach to routing in mesh networks takes a simplistic view of the above interdependence. Hence, we will be working on proposing a broader framework within which this problem can be addressed.

REFERENCES

[1] D. Aguayo, J. Bicket, S. Biswas, G. Judd, R. Morris, “Link-level Measurements from an 802.11b Mesh Network,” in proc. of *ACM SIGCOMM 2004*, Portland, Oregon, USA, Aug 2004.

[2] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris, “A High-Throughput Path Metric for Multi-Hop Wireless Routing,” in proc. of *ACM MobiCom 2003*, San Diego, California, USA, Sep 2003.

[3] J. Padhye, R. Draves, and B. Zill, “Routing in Multi-radio, Multi-hop Wireless Mesh Networks,” in proc. of *ACM MobiCom 2004*, Philadelphia, Pennsylvania, USA, Sep 2004.

[4] J. C. Park and S. Kasera,“Expected Data Rate: An Accurate High-Throughput Path Metric For Multi-Hop Wireless Routing,” in proc. of IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, *SECON 2005*, Santa Clara, California, USA, Sep 2005.

[5] B. Kauffmann, F. Baccelli, A. Chaintreau, C. Diot and D. Papagiannaki, “Self organization of interfering 802.11 wireless access networks,” INRIA Research Report 5649, Aug. 2005.

[6] S. Choi, K. Park and C. Kim, “On the performance characteristics of WLANs: revisited”, in proc. of *ACM Sigmetrics*, Banff, Canada, 2005.

[7] M. Heusse, F. Rousseau, G. Berger-Sabbatel, A. Duda, “Performance Anomaly of 802.11b,” in proc. of *IEEE Infocom 2003*, San Francisco, California, USA, March 2003.