A Cross-Layer Load-Independent Link Cost Metric for Wireless Mesh Networks

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ABSTRACT

We present Cross-layer Unicast Transmission Time (X-UTT), a MAC-aware load-independent link cost metric for 802.11-based wireless mesh networks. X-UTT utilizes information acquired from a network-layer unicast probing system and a MAC-layer monitoring system. It is designed to capture the wireless link capacity and be independent of the load induced by self-interference and cross-interference in a mesh network. We present experiments that validate these two properties on our mesh network testbed. These properties can be further exploited in the design of stable path metrics and routing protocols for wireless mesh networks.

1. INTRODUCTION

Wireless mesh networks aim to provide high-speed Internet access at a small fraction of broadband wireline access cost. A crucial factor that determines mesh networks performance is the ability to route efficiently over the multi-hop wireless mesh infrastructure. Existing metrics such as ETX and ETT [1, 3], characterize link quality by incorporating measurements of packet loss [1], enhanced by measurements of available bandwidth [3]. Such link cost metrics have been incorporated to mesh routing protocols as path metrics and have demonstrated performance improvements over hop count. Still, they are based on network-layer measurements –broadcast probes for packet loss estimation and packet-pair probes for link bandwidth estimation– which only provide coarse-grain link quality estimation. Furthermore, they have recently been shown to be extremely load-sensitive [2]. This in turn can lead to highly unstable routing in highly-loaded wireless mesh backbones.

We propose the Cross-Layer Unicast Transmission Time (X-UTT)link cost metric for 802.11-based mesh networks. X-UTT is designed to be load-independent and to characterize wireless link quality only in terms of the link capacity presented to the network layer by the underlying MAC protocol operation. X-UTT combines measurements from both network layer and MAC layer to enhance accuracy of link quality characterization. It is based on unicast network-layer probes and a MAC layer monitoring system implemented at the wireless card driver. The monitoring system extracts from the driver detailed information about each MAC layer (re-)transmission of a network-layer unicast probe packet.

We proceed to describe how MAC layer and network layer quantities are combined to yield X-UTT in Section 2. In Section 3 we present experiments from our mesh network testbed that validate the two basic properties of X-UTT: load-independence and relation to link capacity. Section 4 concludes.

2. METRIC DEFINITION

X-UTT is based on unicast network-layer probes which are subject to MAC-layer (re)transmissions. The packet transmission time of each probe is the sum of the transmission air-time and the backoff time of all its MAC layer (re)transmissions. The transmission air-time is a function of the bit-rate used; the backoff time prior to each (re)transmission is a function of the number of previously failed transmissions. This information is extracted from a MAC layer monitoring system implemented at the wireless card driver.

X-UTT is defined as the ratio between the average packet transmission time (PTT) and the unicast probe delivery ratio as (d_{u3}):

$$XUTT = \frac{PTT}{d_{u3}} \quad (1)$$

X-UTT is defined to capture the effects that the 802.11 MAC layer error control (ACKs and retransmissions) has on link capacity as perceived by the upper layers. 802.11 MAC error control mechanism retransmits unacknowledged frames to hide losses to the higher layers. Thus it increases link capacity by increasing the network layer delivery ratio. On the other hand, the transmission time of a network layer packet is the sum of the time spent for all the MAC layer retransmissions. Thus, the error control mechanism decreases the link capacity by increasing the total time to transmit a net-

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work layer packet. These opposite effects are captured by the PTT and d_{u3} components of X-UTT.

X-UTT is also designed for low sensitivity to network load. This property stems from the definition of PTT which excludes the time spent by a node for carrier sensing the medium when neighbor nodes transmit. The carrier sensing time is the primary load-based effect in an 802.11 wireless network. However, the network load can also increase packet loss due to collisions. Such packet losses impact X-UTT by increasing the re-transmission count and thus the backoff time, both components of PTT. Furthermore, under significant and bursty packet losses, the MAC layer error control cannot recover and this decreases the unicast probe delivery ratio (d_{u3}). This will be reflected by X-UTT through a decrease in estimated link capacity.

3. EXPERIMENTAL EVALUATION

We evaluate the properties of X-UTT on the our mesh network testbed. The experimental validation is based on the injection of a UDP flow, two minutes long, with constant ingress bit-rate on one link at a time. Each run of an experiment consists of a series of these UDP flows, increasing stepwise the ingress bit-rate. On each link this sequence has been repeated 5 times, each about 2 hours apart. The experiments have been performed on 6 randomly selected links of our network (there are 30 links in total). Figure 1 shows the

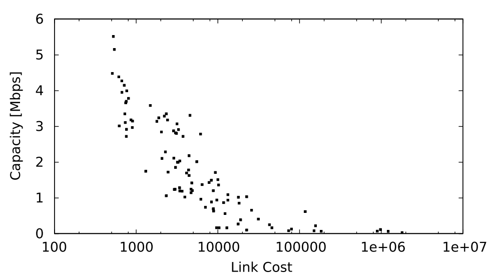

Figure 1: X-UTT (x-axis) relation to link capacity (y-axis).

relation between the link capacity and X-UTT. Each point on the x-axis is the average of X-UTT values over one run of the experiment, while each point on the y-axis is the *critical throughput* (the measured throughput which was 90% of the offered load). As we can see in Figure 1, our results confirm the inversely-proportional relation between X-UTT and the link capacity.

We use the same controlled-load experiments to evaluate the metrics's load independence. For this purpose, we study the self-interference and cross-interference by analyzing the behavior of X-UTT with respect to the increasing load on its own link and on neighbor links, respectively. Figure 2 shows self-interference (left) and cross-interference (right) results for a typical link in our network. The x-axis is the offered load, while the X-UTT and the measured throughput are on the y1-axis (left) and y2-axis (right), respectively. Each data point represents the average and the standard de-

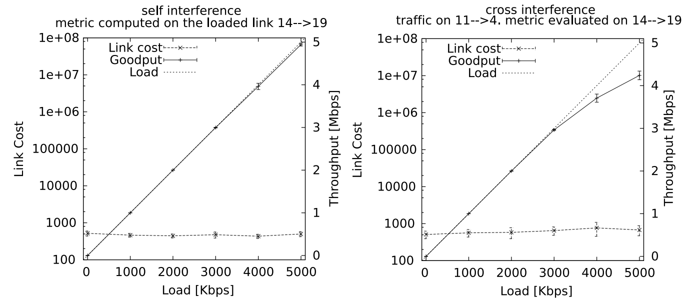

Figure 2: X-UTT load-independence due to self-interference (left) and due to cross-interference (right) on a typical link.

viation over 5 repetitions of the UDP flow at a given ingress rate. As we can see from the graphs, X-UTT remains constant with increasing load, both on its own link and on the neighbor link.

We found that in about 10% of the cross-interferences experiments, the increasing load on a neighbor link had an impact on the X-UTT metric. However, we believe that this is explained by the presence of collisions due to the disabled RTS/CTS in our settings.

In summary, our experimental validation confirms that X-UTT effectively captures the effects of the retransmissions on the link capacity, and that it is independent from traffic load on the measured link, and on neighbor links.

4. CONCLUSIONS

We defined X-UTT, a link cost metric evaluated using a unicast probing system and a MAC layer monitoring system which allow to consider cross-layer information. We experimentally verified the load-independence and the inversely-proportional relation of X-UTT with link capacity.

We plan to use X-UTT as building block of a routing path metric, and to test the obtained performance on the Thomson Mesh Testbed and eventually other testbeds. We would like to compare the resulting path metric with other path metrics, such as ETX and ETT. Moreover, it would be interesting to redefine and implement these other metrics on our system based on unicast probes and a MAC-layer monitoring system.

5. REFERENCES

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