An End-to-end Delay Metric for Multi-rate Wireless Mesh Networks with Cooperative Retransmission

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***Abstract*—The IEEE 802.11 MAC protocol performance degrades severely as the number of stations in the collision domain increases in a saturated network. Employing cooperative retransmission at the MAC layer provides a way to work around the performance limitations by exploiting the broadcast nature of wireless communication. This paper presents a new routing metric, termed *Expected Cooperative Forwarding Delay* (ECFD), with the aim of selecting a minimum end-to-end delay path for multi-hop multi-rate wireless mesh networks. Different from previously proposed cooperative-aware routing metrics such as ORETT, the ECFD metric is based not only on expected cooperative transmission time but accounts for queueing and backoff delays in the path selection process. We describe the design and implementation of ECFD, and conduct extensive simulation experiments in random topologies showing that, under various realistic network traffic patterns, the use of ECFD instead of ORETT and ETT significantly improves both end-to-end delay and throughput.**

I. Introduction

In wireless mesh networks (WMN), routing paths are generally determined by a shortest-path calculation based on one of the many link metrics proposed in the literature, such as the well-known Expected Transmission Count (ETX) [1] and Expected Transmission Time (ETT) [2], or their extensions that account for inter-flow and intra-flow interference [3], [4]. One parameter that is missing from these traditional routing metrics is the traffic load of the forwarding node. Indeed, a routing protocol should avoid over-selection of a single path by multiple flows, which would cause traffic on that path to suffer excessive congestion delays; thus, a routing metric should avoid giving attractive scores to congested links. Some metrics that incorporate the traffic load and queueing delays along the path have been studied more recently [5], [6].

In recent years, several studies have aimed to design a cross-layer metric for networks with *cooperative routing*, aiming to reflect the benefit of MAC-layer cooperation in the route choice. Among these, the ones most closely related to our work are the ETTC [7] and CETT [8] metrics, as well as our own recent ORETT metric proposed to account for cooperative MAC-layer retransmission with a particular focus on multi-rate mesh networks [9]. However, none of the cooperative-aware metrics in the literature, to the best of our knowledge, were designed to take into account the queueing and medium access delays so as to avoid routing over congested regions in the network.

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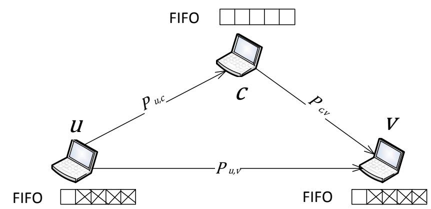


Fig. 1: A link from node u to node v using node c for cooperative retransmission.

In this paper we propose the Expected Cooperative Forwarding Delay (ECFD) metric, designed to capture the combined effect of all IEEE 802.11 MAC-layer delay components, namely the queueing delay in the node and the cooperative relay, the backoff delay (including the time during which backoff is frozen due to neighbor transmissions), and finally the packet transmission time itself. To implement the metric in practice, we also design a low-overhead procedure to estimate the necessary delay parameters in a distributed manner. Through extensive simulation of the DSR routing protocol with the ECFD metric, we explore the effectiveness of ECFD under different priority regimes for cooperative packets, and show that the proposed metric achieves a superior performance compared to other existing metrics in terms of network throughput and end-to-end delay in a variety of network scenarios.

To introduce ECFD we focus on the scenario shown in Figure 1, consisting of a one-hop data transmission from node u to node v with node c as the cooperating relay. Each node maintains a FIFO queue of packets for MAC-layer processing. If the direct transmission from node u to v is unsuccessful, node c takes the opportunity to retransmit the packet to v, provided that it overhears the original transmission from u and the expected packet forwarding delay to node v from c is less than that from u. For further details we refer the reader to the Δ-MAC protocol introduced in our previous work [10], which uses a mechanism similar to RTS/CTS handshaking to alleviate collisions, with a minor modification to include the cooperative relay node as well as the sender and receiver. In this paper, we employ the same Δ-MAC protocol for evaluation of the ECFD metric, extending it only to include the selection of the best rate as well as the best relay as described in section II-B.

II. MAC-LAYER ONE-HOP DELAY ANALYSIS

A. The MAC service delay components

In the following, given a set of three nodes u, v and c, we assume that the links between them and the corresponding transmission failure probabilities p_{urv}, p_{urc} and p_{crv} are statistically independent and known to the nodes. The mechanism by which these probabilities are estimated is orthogonal to the implementation of the ideas presented in this section. For the purpose of evaluation of the ECFD metric by simulation (Section III), we assume the nodes use the same probing mechanism as proposed for the ORETT metric [9], where each node sends one probe per second on average to its neighbors, (cycling among the various available transmission rates), and expires its record of received probes after 60 seconds; this mechanism is suitable for mesh networks with stable topology and channel quality. However, we note that the ECFD metric is compatible with any alternative estimation mechanism of link probabilities, e.g. based on signal-to-noise (SNR) measurements that may be more suitable for mobile ad-hoc networks.

We now proceed to elaborate the delay components affecting the total delay in the link between node u and node v, with and without using cooperative retransmissions by node c.

1) Medium Access Delay: According to the 802.11 DCF, a random backoff procedure is followed when a station wishes to initiate a packet transmission. During the backoff, carrier sensing is performed continuously and the backoff counter is suspended whenever the medium is sensed to be busy, to be resumed as soon as the channel is sensed to be idle for the duration of a DIFS period (or EIFS, as appropriate [11]). The number and duration of such interruptions during the backoff counting depends on the density of the contending nodes in the vicinity and their transmission probabilities. While many existing studies attempt to use analytical models in order to calculate these parameters, they work well only under certain assumptions and tend to break down in real settings (e.g. when hidden terminals are present). Accordingly, we prefer to use a direct estimation method rather than an approximate model to find the medium access delay. Specifically, define D_u to be the time between a packet becoming active (i.e. rising to the top of the MAC-layer queue) and its actual transmission at node u, and define θ as the total number of backoff ticks counted before that packet's transmission. Consequently, we define an effective *average tick duration* τ_u, calculated as

$$\tau_u = \frac{D_u}{\theta}. \tag{1}$$

Every node u calculates a sample value of τ_u whenever it gets to transmit a packet, and feeds it into an exponentially weighted moving average to produce an ongoing estimate of the expected value of this parameter:

$$\tau_u(t) = \alpha \times \tau_u(t) + (1-\alpha) \times \tau_u(t-1), \tag{2}$$

where α is the tuning parameter to smooth the estimated value.

We assume a standard 802.11 DCF protocol is followed with a maximum retransmission limit (equivalently, backoff stage) M. Using τ as the average tick duration as defined above, and with the expected number of backoff ticks at the j-th backoff stage being $E[W_j] = \frac{CW_j - 1}{2}$ where $CW_j = 2^{j-1} CW_{min}$ is the maximum contention window value at that backoff stage, we obtain the expected medium access delay for link $u - v$:

$$\mathrm{MT}_{urv} = \sum_{m=1}^{M} {p_{urv}}^{m-1}(1-p_{urv}) \sum_{j=1}^{m} \left(E[W_j] \times \tau\right). \tag{3}$$

For the Δ-MAC cooperative MAC protocol, the transmission by u is considered successful when it is received by either the destination v or the cooperative node c. Accordingly, we define $p_{urv}^{(c)} (= p_{urv} \times p_{urc})$ as the effective loss probability, when both of the nodes v and c fail to receive the packet. Thus, the MAC access time spent by node u in the presence of cooperation by relay c is

$$\mathrm{MT}_{urv}^{(c)} = \sum_{m=1}^{M} {p_{urv}^{(c)}}^{m-1}(1-p_{urv}^{(c)}) \sum_{j=1}^{m} \left(E[W_j] \times \tau\right). \tag{4}$$

Note that the above expression accounts only for the MAC access time of node u itself, and excludes the time spent in the backoff process by the cooperative relay. In the implementation of the ECFD metric each node is responsible for estimating only its own contribution to the delay (this applies equally to the MAC access time and the other delay components described hereafter). The overall delay metric for a cooperative link, including the delays incurred by the relay node, is computed as part of the cooperative node selection step, which is elaborated further below.

2) Transmission time: The transmission time of a packet for a one-hop sender-receiver pair is a direct function of the transmission rate and packet size. For a one-hop link between node u and node v, the total expected time spent in the transmission of a packet of size L is

$$\begin{aligned}\mathrm{TT}_{urv} &= \sum_{m=1}^{M} {p_{urv}}^{m-1}(1-p_{urv}) \sum_{j=1}^{m} \left(\frac{L}{r}\right) \\ &= \left(\frac{L}{r}\right) \frac{1-(p_{urv})^M}{1-p_{urv}}.\end{aligned} \tag{5}$$

In case the link is assisted by a cooperative node c, node u only needs to keep retransmitting until the packet is received by either v or c (or the retransmission limit is reached). Thus, we similarly obtain the expected transmission time spent by node u in this case to be

$$\mathrm{TT}_{urv}^{(c)} = \left(\frac{L}{r}\right) \frac{1-(p_{urv}^{(c)})^M}{1-p_{urv}^{(c)}}, \tag{6}$$

where $p_{urv}^{(c)}$ is, again, the effective failure probability for the packet to be received by neither node v nor c.

3) MAC-layer Service Time: We define the total MAC service time for a packet to be the time since the packet first becomes active (i.e. reaches the top of the queue at node u) until it is successfully received. Thus, the service time is the sum of the access delay (due to the backoff procedure) and the transmission time:

$$\begin{aligned}&\mathrm{ST}_{urv} = \mathrm{MT}_{urv} + \mathrm{TT}_{urv} = \\ &\sum_{m=1}^{M} {p_{urv}}^{m-1}(1-p_{urv}) \sum_{j=1}^{m} \left(E[W_j] \times \tau\right) + \\ &\qquad \left(\frac{L}{r}\right) \frac{1-(p_{urv})^M}{1-p_{urv}}\end{aligned} \tag{7}$$

for the direct one-hop link without cooperation, or

$$\mathrm{ST}_{urv}^{(c)} = \mathrm{MT}_{urv}^{(c)} + \mathrm{TT}_{urv}^{(c)} = \sum_{m=1}^{M} {p_{urv}^{(c)}}^{m-1}(1-p_{urv}^{(c)}) \sum_{j=1}^{m} (E[W_j]\times\tau) + \left(\frac{L}{r}\right)\frac{1-(p_{urv}^{(c)})^M}{1-p_{urv}^{(c)}} \quad (8)$$

when node c takes part in the cooperative Δ-MAC protocol.

B. Cooperative node and rate selection

In a typical dense network, a choice between multiple cooperative nodes will usually be available for most links. Accordingly, the calculation of the link metric from node u to node v involves a choice of the best cooperative relay node, as well as the optimal transmission rate.

For a given candidate cooperative node c for transmissions on the link $(u-v)$, the optimal transmission rate by the source u is found by exhaustive search among all possible rates so as to minimise the resulting value of the MAC service time:

$$r^* = \arg\min_r \mathrm{ST}_{urv}^{(c)} \quad (9)$$

Similarly, the optimal rate to use for the retransmission between nodes c and v is found by:

$$r^{*(c)} = \arg\min_r \mathrm{ST}_{crv} \quad (10)$$

Finally, the total MAC service time for the link $(u-v)$ with cooperation is found by adding the MAC service time at node u to that of node c when a retransmission is in fact required, i.e. multiplying the service time of node c by the conditional probability that the transmission(s) by node u resulted in a successful reception by node c, rather than directly by node v or exhausting the retransmissions limit:

$$\mathrm{CST}_{ur^*v}^{(c)} = \mathrm{ST}_{ur^*v}^{(c)} + \sum_{m=1}^{M} {p_{ur^*v}^{(c)}}^{m-1}(1-p_{ur^*c})p_{ur^*v}\cdot\mathrm{ST}_{cr^{*(c)}v} \quad (11)$$

If more than one potential cooperative node exists in the vicinity of u and v, the above process is repeated for every individual candidate, and the cooperative node c^* (and corresponding rate r^*) is chosen to be the one that minimises the $\mathrm{CST}_{urv}^{(c)}$ (cooperative service time) value overall.

C. Queuing Delay

The queueing delay is the time a packet waits in the node's FIFO queue until it becomes active and begins to be served by the wireless MAC. A node can estimate the expected queueing delay for any newly arriving packet by summing the expected MAC service times for all the packets ahead of it in the queue:

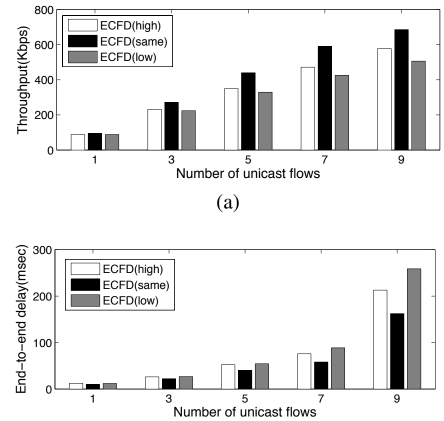
$$\mathrm{QD}_u = \sum_v \mathrm{ST}_{urv}^{(c)} \times \mathrm{N}_{uv} \quad (12)$$

where the summation above is taken over all nodes v that are neighbors of u, and N_{uv} is the number of queued packets waiting to be transmitted on the $u-v$ link.

Finally, we define $\mathrm{ECFD}_{u,v}^{(c)}$ as the expected cooperative packet forwarding delay, including the queueing delay, from node u to node v with node c as the cooperating node:

$$\mathrm{ECFD}_{u,v}^{(c)} = \mathrm{QD}_u + \mathrm{CST}_{ur^*v}^{(c)}, \quad (13)$$

using the optimal rate r^* found by (9).



(a)

(b)

Fig. 2: Throughput and end-to end delay of unicast flows *vs* varying priority schemes.

III. Performance Evaluation

We use QualNet [12] to simulate a WMN of 50 stationary mesh nodes that are uniformly distributed in an area of 1500m×1500m. A number of source-destination pairs (varying between 1 and 9 randomly selected pairs) simultaneously transmit constant bit rate (CBR) traffic at 25 packets per second, with a data payload size of 512 bytes. The channel model is configured with bit error rates corresponding to a transmission power of 15dBm and receiver sensitivity of -89dBm.

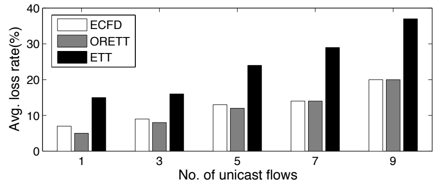
In addition, background multicast flows are randomly generated, in the form of multicast CBR sessions (running ODMRP [13] as the multicast routing protocol) with one source and 10 group members, sending 10 packets per second with a payload of 512 bytes. This allows to explore ECFD-based routing in a more challenging environment where multicast background traffic increases the frequency of packet collisions.

We focus on three important performance measures for the unicast flows: (1) end-to-end packet delay, (2) average MAC-layer packet handling time (including retransmissions), and (3) throughput, i.e. average rate of successful packet deliveries (measured in Kbps).

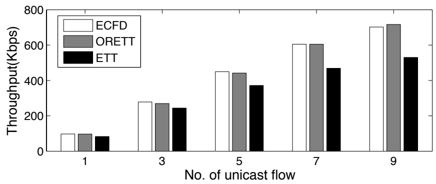
A. Impact of various priority schemes

In the following we call a unicast packet overheard by a relay node for cooperative retransmission a "cooperative packet", as opposed to other, "regular" packets that may be queued in that node as well. There are several ways that cooperative packets can be prioritized in a relay node; for example, (i) high priority — always processed immediately upon being overheard; (ii) low priority — retransmitted only when the relay node's own packet buffer is empty; and finally (iii) same priority as regular packets, joining the same queue and processed in FIFO manner. In this subsection, we examine the impact of these priority schemes on network performance.

Our simulation uses ECFD as the routing metric with the above three priority schemes, represented as ECFD(high), ECFD(low), and ECFD(same) (referring to the priority of the cooperative packets). Figure 2a shows the average throughput with different priority schemes under varying traffic. While

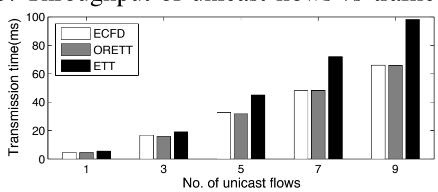


(a)

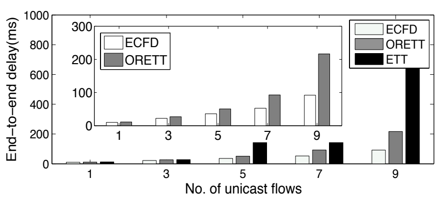


(b)

Fig. 3: Throughput of unicast flows *vs* traffic load.



(a)



(b)

Fig. 4: Delay performance of unicast flows *vs* traffic load.

perhaps counterintuitive at first, it is clearly evident that the network throughput is significantly higher when the cooperative packets are processed with the same priority as regular packets; for example, routing with ECFD(same) achieves 25% and 38% higher throughput than with ECFD(high) and ECFD(low), respectively, for 7 concurrent unicast flows. Figure 2b demonstrates that ECFD(same) has the lowest end-to-end delay compared to other schemes as well.

B. Effectiveness of ECFD vs other metrics in moderate-to-high traffic conditions

We investigate the performance of ECFD-based routing and compare it against ORETT [9] and ETT-based routing [1]. In all experiments, the DSR protocol is implemented for routing, using the standard 802.11 MAC layer for ETT and the cooperative Δ-MAC variation (without priority) for ORETT and ECFD. The DSR implementation maintains a buffer of 50 packets, with packets kept in the buffer for 30 seconds at most or dropped otherwise. The link metrics are updated at regular intervals of 60 seconds.

Figure 3a shows the packet loss rate with increasing traffic demands. Clearly, ETT-based routing exhibits the highest packet loss rate due to the non-cooperative retransmissions. ECFD has a slightly higher loss rate compared to ORETT, due to its focus on minimizing end-to-end delay, which may not always coincide with the most reliable path. Nevertheless, Figure 3b

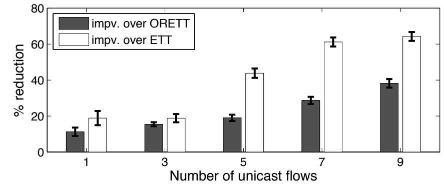


Fig. 5: Delay improvement of ECFD *vs* traffic load.

shows that the improved end-to-end delay performance does not come at the expense of throughput, with ECFD and ORETT attaining similar throughputs irrespective of the network traffic load (and considerably better than for ETT).

The results with respect to delay performance for different traffic conditions are presented in Figure 4. Considering only the time spent in packet transmissions, Figure 4a shows that ECFD and ORETT result in less transmission time compared to ETT (by as much as 33% with 9 simultaneous flows) due to using higher transmission rates in the presence of cooperative nodes. Figure 4b presents the average end-to-end packet delays; clearly, with respect to this parameter, ECFD consistently outperforms ETT and ORETT regardless of network load, due to the fact that ECFD takes into account the queueing delays, and consequently avoids regions with heavy traffic load during path selection. The improvement (in percentage terms) is highlighted in Figure 5, showing that ECFD reduces the end-to-end delay by 11% and 19% when compared with ORETT and ETT respectively in the case of one traffic flow, rising to as much as 38% and 64% respectively with 9 simultaneous flows in the network.

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