Relay-Aided High-Throughput Path Selection in Multi-rate Wireless Mesh Networks

Bipul Sen, Xin Zhao, Lavy Libman, Sanjay Jha
School of Computer Science and Engineering
University of New South Wales
Sydney, NSW 2052, Australia
{bsen,xinzhao,llibman,sjha}@cse.unsw.edu.au

ABSTRACT

This paper proposes an *opportunistic rate-adaptive expected transmission time (ORETT)* metric, which exploits cooperative (relay-aided) retransmissions to achieve high-throughput routing in multi-rate wireless mesh networks. This metric captures the combined effects of MAC-layer cooperative retransmission by neighbor nodes with transmission rate diversity (and rate-dependent link quality). In our approach, a relay node is selected among one-hop neighbors to assist with packet retransmissions and minimize the expected retransmission time. The paper describes the design and implementation of the ORETT routing metric using the DSR routing protocol. Our extensive simulation on the Qualnet platform confirms that multi-rate routing using ORETT significantly reduces the overall transmission time while yielding higher packet delivery ratio compared to single rate unicast or non-cooperative ETT based routing.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and design**]: Wireless Communication; C.2.2 [**Network Protocols**]: Metrics—*Routing Protocols, performance measures*

Keywords

Cooperative routing, routing metric, wireless mesh.

1. INTRODUCTION

The IEEE 802.11 standards support multi-rate capability [8], allowing the physical layer to adapt to varying channel conditions using different modulation techniques and send data at different transmission rates. The method to select rates in multi-rate radio is not specified by the 802.11 standards. As a result, several rate adaptation protocols have been proposed with the aim of selecting the rate that optimizes the throughput for given channel conditions. Most prevailing rate adaptation methods, e.g. [3,10,11], are purely sender-side schemes where the sender selects the best rate based on the number of consecutive successes or losses of MAC-layer acknowledgment (ACK) frames. As an alternative, the Receiver Based Auto Rate (RBAR) scheme [7] allows the receiving node to select the rate using the signal-to-noise ratio (SNR) of the request-to-send (RTS) packet. The Opportunistic Auto Rate (OAR) protocol [15] applies the same receiver-based approach, but sends back-to-back data frames when channel conditions are good. However, all these schemes only consider the data rate of the direct link between the sender and the receiver, without taking into account the possibility of opportunistic overhearing by neighboring relay nodes. In some cases, it may be advantageous to retransmit packets using cooperative relay nodes that have better links to the receiver than the direct one.

Cooperative communication schemes at the MAC layer have been the subject of several studies in recent years, the majority of which are focused on improvements within the IEEE 802.11 MAC context by exploiting the benefit of cooperative communications [4, 13, 20, 22, 23]. In particular, rDCF [22], RAMA [23] and CoopMAC [13] are three similar MAC-layer approaches that take into account the physical-layer transmission rate diversity and volatility, and adaptively respond to variations in the rate that a link can support. Their idea is to temporarily reroute around a slow (low-rate) direct link using a two-hop local "detour" via a neighboring relay. Conversely, COBRA-MAC [1] and coop80211 [14] are MAC schemes based on *opportunistic* cooperation, where relays overhear the transaction on the direct link and only step in to make a retransmission if the direct transmission has failed. From the routing perspective, a few studies have attempted to design a cross-layer metric that reflects the MAC-layer cooperation gain in the route choice; among these, most closely related to our work are the ETTC [21] and CETT [19] metrics, whose designs are based on the CoopMAC [13] and COBRA-MAC [1] cooperative schemes respectively. Despite the extensive research on the benefits of cooperative communications at the physical and MAC layers for single-hop communications, the question of exploiting it for high-throughput routing in multi-hop wireless networks remains largely an open problem; in this context, our proposed ORETT metric extends these prior proposals, combining both the opportunistic overhearing and rate diversity aspects for high-throughput route choice.

The main contributions of this paper are as follows. We propose a new metric, namely the opportunistic rate-adaptive expected transmission time (ORETT), to capture the combined effects of MAC-layer cooperative retransmission and per-link estimates of packet transmission time for achiev-

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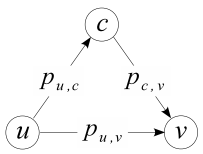

Figure 1: One-hop transmission from node u to node v using node c for cooperative retransmission.

Table 1: PDR at different transmission rates

	$r_1 = 5.5$ Mbps	$r_2 = 11$ Mbps
v	0.7	0.2
c	0.95	0.8

ing high throughput in multi-rate wireless mesh networks (WMN). Using an implementation on the Qualnet platform [16] of a minimal, backward-compatible modification of the 802.11 MAC incorporating a cooperative retransmission mechanism proposed in our earlier work (which we call Δ-MAC [17]), we provide detailed simulation results of the DSR routing protocol with the ORETT metric that demonstrates its effectiveness in multi-rate networks.

The rest of this paper is organized as follows. Section 2 presents a motivating example, followed by our system model in Section 3. Section 4 discusses the ORETT metric and the optimal rate and relay node selection. Section 5 introduces Δ-MAC and our implementation of the DSR protocol. Simulation experiments and results are provided in Section 6. Finally, Section 7 concludes the paper.

2. MOTIVATING EXAMPLE

In wireless networks, link layer protocols employ automatic repeat request (ARQ) mechanisms to combat packet losses. Because of the broadcast nature of wireless transmission, any packet can be opportunistically overheard by neighboring nodes. If a retransmission is necessary, it may often be advantageous to make it from one of the overhearing nodes rather than the original packet source, if this reduces the expected time until the packet is delivered to the receiver; hence, relay-aided cooperative retransmission may reduce the network bandwidth consumption, and thus effectively increase the network throughput.

Consider the scenario in Fig. 1, where node u has a data packet for destination node v and a cooperative relay node c is within the transmission range of both u and v and can overhear the transmission from u to v. Assuming a set of feasible transmission rates $r_k, k = 1, \ldots, K$ in the network, existing cooperative protocols such as rDCF [22] and Coop-MAC [13] aim to replace a slower link with a faster two-hop "detour" so that total transmission time can be reduced. On the other hand, in protocols such as COBRA-MAC [1] and CMAC [18], the relay helps with retransmitting on behalf of the source *opportunistically*, only when the original transmission is unsuccessful. For example, suppose that the successful delivery ratio of a packet of size L from u to the receiver and relay nodes is as shown in Table 1 (assume that the link quality between c to v is 100% perfect at all available rates). Without cooperation, the expected transmission time of a packet (including retransmissions by u) is $\frac{L}{0.7 \cdot 5.5Mbps} \approx 0.26L\mu s$ if the rate $r_1 = 5.5Mbps$ is used, or

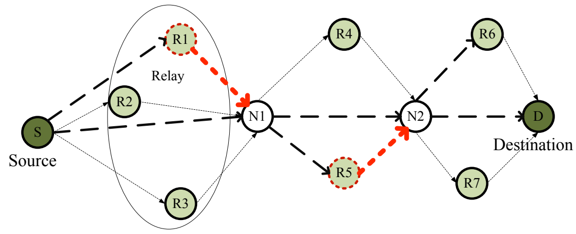

Figure 2: Multi-hop cooperative routing.

$\frac{L}{0.2 \cdot 11Mbps} \approx 0.45L\mu s$ for the rate $r_2 = 11Mbps$. Thus, the lower rate is preferred; in other words, the shorter transmission time does not compensate the significantly lower success rate of the higher rate. On the other hand, with the cooperation of c, node u only needs to keep retransmitting until the packet is received either at v or at c; in the latter case, the final retransmission will then be undertaken by c (at the higher rate of r_2, since the link is assumed to be perfect anyway). Thus, the expected packet transmission times, for rates r_1 and r_2 (used initially by node u) respectively, are

$$\frac{\text{L}}{[1-(1-0.95)(1-0.7)]\cdot 5.5\text{Mbps}} + \frac{0.95(1-0.7)}{1-(1-0.95)(1-0.7)} \cdot \frac{\text{L}}{11\text{Mbps}} \approx 0.21\text{L}\mu\text{s}$$

and

$$\frac{\text{L}}{[1-(1-0.8)(1-0.2)]\cdot 11\text{Mbps}} + \frac{0.8(1-0.2)}{1-(1-0.8)(1-0.2)} \cdot \frac{\text{L}}{11\text{Mbps}} \approx 0.18\text{L}\mu\text{s}.$$

Accordingly, in the presence of the cooperative relay, it is preferable for u to use the higher rate: even though it leads to a very low success probability on the direct link, this is compensated by the overhearing probability of the relay (which decreases only marginally at the higher rate) and the shorter packet transmission time. This example shows that the traditional approach to rate selection, based on the statistics of the direct link alone, is inadequate in the presence of cooperation, and that the questions of rate and relay selection should be addressed *jointly*. To that end, we design a metric (ORETT) that reflects the expected transmission time on a link, accounting both for the MAC-layer cooperative retransmission and the ability to use multiple rates.

3. SYSTEM MODEL

We consider a multi-hop wireless network represented by a directed graph $G = (V, E)$, where V is the set of nodes and E is the set of directed links. A directed link $\langle u, v \rangle$ from node u to node v exists if node v is within the transmission range of node u; more specifically, we require the packet delivery probability of link $\langle u, v \rangle$ to be non-zero for at least one transmission rate in the set of feasible rates $\{r_k\}, k = 1, \ldots, K$. The set of nodes $\{v : \langle u, v \rangle \in E\}$ forms the one-hop neighborhood N_u of node u. Each node is equipped with one radio. All radios are tuned to a common channel with fixed transmission power for all transmission rates.

We now explain the assumed cooperative retransmission scheme using a simple topology depicted in Fig. 2. Suppose that source S has a (network-layer) data packet for destination node D, which is to be forwarded along the route S → N1 → N2 → D. For concreteness, we describe the cooperation protocol assumptions using the first-hop link (from S to N1); cooperation along subsequent links is similar. Assume that a set of neighbor nodes, R = {R1, R2, R3}, are inside the shared transmission area of S and N1 and can overhear and cooperatively retransmit any ongoing transmissions; furthermore, assume that node R1 is identified to be the best relay node in this set (the relay node selection process is described in detail in the next section). In this case, the cooperative scheme works as follows.

If the first transmission attempt from node S to N1 is successful, the transmission is completed. In that case relay node R1 plays no role. Otherwise, if the transmission from S is overheard by relay R1 but fails to be received by N1, then R1 will take over the role of retransmitting the lost packet. Specifically, relay R1 will send an ACK packet to the packet originator S, and thereafter, R1 follows the standard ARQ mechanism to retransmit the packet to node N1. Finally, as long as neither node N1 nor R1 receives the packet, it is retransmitted by node S. For further details on our cooperative retransmission approach, in particular the protocol actions after ACK losses and recovery from possible duplicate packets, please refer to our previous work [17].

We point out that the use of an explicit ACK by node R1, confirming that it takes responsibility for the packet from that point, differs from the approach of COBRA-MAC; this allows the relay to retransmit the packet several times if necessary, whereas in COBRA-MAC the relay is limited to one attempt before the retransmission must revert to the original source. As a result, the ORETT metric (introduced in the next section) can attain a lower value than the similar metric CETT based on COBRA-MAC [19], even when multiple rates are not used.

4. THE ORETT CROSS-LAYER ROUTING METRIC

For a multi-rate wireless mesh network, an optimum rate as well as best relay node needs to be selected so that total transmission time is minimized. This section discusses the rate and best relay node selection procedure in the computation of the ORETT metric. The computation of ORETT for a one-hop sender-receiver pair uses the packet delivery ratio (PDR) in the links among all the nodes involved, which is a function of the transmission rate used. More specifically, for a given set of three nodes u, v and c as in Fig. 1, we define $\mathrm{ORETT}^{(c)}_{u,r,v}$ as expected transmission time (including retransmission time) required for one-hop transmission of a data packet from node u to node v with node c as the cooperating node at rate r. Let $\mathrm{ORETT}^{(c)}_{u,v}$ as minimal ORETT for the one-hop transmission from node u to node v with the help of the node c across all available transmission rates. $\mathrm{ETT}_{u,r,v}$ is defined as expected transmission time (including retransmissions) required for the one-hop transmission from node u to node v at a rate r. If PDR of link $(u - v)$ is defined as $p_{u,r,v}$ at transmission rate r, the ETT of packet L is given by [6]

$$\mathrm{ETT}_{u,r,v} = \frac{\mathrm{L}}{r} \times \frac{1}{p_{u,r,v}}. \tag{1}$$

In computing ORETT, we assume that the sender keeps transmitting the packet until it receives an ACK from either the receiver or the relay. Similarly, we assume that, after the cooperating node receives the packet, it continues to retransmit the packet until it is acknowledged by the receiver. For simplicity, we henceforth assume that an ACK from either the receiver or the cooperating node is received at the sender with probability one. This is due to the fact that the loss rate of ACK packets (14 bytes in the 802.11 MAC) is typically very low in wireless networks, compared to that of data packets [17]; however, we point out that the ORETT metric can be extended to explicitly account for a positive ACK loss probability in a straightforward manner.

Assuming that the links between u, v and c (and the corresponding successful transmission probabilities $p_{u,r,v}$, $p_{u,r,c}$ and $p_{c,r,v}$) are statistically independent, the one-hop transmission of a data packet from node u to node v with node c as the cooperating node has three possible outcomes:

- With probability $(1 - p_{u,r,v})(1 - p_{u,r,c})$, neither node v nor node c receives the packet. In that case, the expected future retransmission time is again $\mathrm{ORETT}^{(c)}_{u,r,v}$.
- With probability $(1 - p_{u,r,v})p_{u,r,c}$, the transmission from node u is overheard by node c, but node v fails to receive the packet. Since node c will take over the role of retransmitting the packet to node v, the expected future retransmission time in this state is $\mathrm{ETT}_{c,v}$.
- With probability $p_{u,r,v}$, node v receives the packet, and hence no additional retransmissions are required.

Let us define the transmission time of data packet between links (u-v), (u-c), and (c-v) are $\mathrm{T}_{u,r,v}$, $\mathrm{T}_{u,r,c}$, and $\mathrm{T}_{c,r,v}$, respectively. Summing over the above outcomes, $\mathrm{ORETT}^{(c)}_{u,r,v}$ can be derived as

$$\begin{aligned}\mathrm{ORETT}^{(c)}_{u,r,v} &= (1 - p_{u,r,v})(1 - p_{u,r,c})(\mathrm{T}_{u,r,v} + \mathrm{ORETT}^{(c)}_{u,r,v}) \\ &\quad + (1 - p_{u,r,v})p_{u,r,c}(\mathrm{T}_{u,r,v} + \mathrm{ETT}_{c,v}) \\ &\quad + p_{u,r,v}\mathrm{T}_{u,r,v}\ .\end{aligned} \tag{2}$$

Rearranging (2), we have

$$\mathrm{ORETT}^{(c)}_{u,r,v} = \frac{\mathrm{T}_{u,r,v} + (1 - p_{u,r,v})p_{u,r,c}\mathrm{ETT}_{c,v}}{p_{u,r,v} + p_{u,r,c} - p_{u,r,v}p_{u,r,c}} \tag{3}$$

where

$$\mathrm{ETT}_{c,v} = \min_{r}\ \mathrm{T}_{c,r,v} \times \frac{1}{p_{c,r,v}}\ . \tag{4}$$

The optimal transmission rate for $(u - v)$ link in presence of relay c is found by exhaustive search among all possible rates so as to minimize the value of ORETT:

$$r^* = \arg\min_{r}\ \mathrm{ORETT}^{(c)}_{u,r,v} \tag{5}$$

Finally, if more than one potential relay node exists in the vicinity of u and v, the above process is repeated for each candidate, and the relay node c^* (and corresponding transmission rate r^*) is chosen to be the one that minimizes the ORETT value overall. Let $\mathrm{ORETT}_{u,v}$ denote the minimally required ORETT for the one-hop transmission from node u to node v with the help of the best cooperating node:

$$\mathrm{ORETT}_{u,v} = \mathrm{ORETT}^{(c^*)}_{u,r^*,v}. \tag{6}$$

Similarly, the optimal rate for the link $(c^* - v)$ can be derived by exhaustive search among all possible rates so as to minimize the value of ETT

$$r_c^* = \arg\min_r \ \mathrm{ETT}_{c^*,r,v} \ . \quad (7)$$

In a situation where no suitable relay exists between node u and node v, the transmission rate

$$r_u^* = \arg\min_r \ \frac{\mathrm{L}}{r} \times \frac{1}{p_{u,r,v}}. \quad (8)$$

and corresponding cost

$$\mathrm{ETT}_{u,v} = \min_r \ \frac{\mathrm{L}}{r} \times \frac{1}{p_{u,r,v}} \quad (9)$$

are used for direct communication between node u and node v instead, and the ORETT metric is defined to be equal to ETT for consistency.

THEOREM 1. $\mathrm{ORETT}_{u,v} < \mathrm{ETT}_{uv}$ if ETT_{cv} is less than ETT_{uv}.

PROOF. To satisfy the above theorem, the difference between Eq. 3 and Eq. 1 must be less than zero. Comparing (1) and (3) and after some algebraic manipulation, we have $\mathrm{ECTT}^{(c)}_{u,r,v} - \mathrm{ETT}_{u,r,v}$ as follows:

$$\frac{(p_{u,r,v}\mathrm{T}_{c,r,v} - p_{c,r,v}\mathrm{T}_{u,r,v})(1-p_{u,r,v})p_{u,r,c}}{p_{u,r,v}(1-p_{u,r,v})p_{u,r,c}p_{c,r,v} + p^2_{u,r,v}p_{c,r,v}} \ .$$

Clearly, $(p_{u,r,v}\mathrm{T}_{c,r,v} - p_{c,r,v}\mathrm{T}_{u,r,v}) < 0$ when $\mathrm{ETT}_{c,v}$ is less than $\mathrm{ETT}_{u,v}$. This means, as long as $p_{u,r,c} > 0$, using c for cooperative retransmission reduces the expected transmission time. □

5. CROSS-LAYER ROUTING WITH ORETT

The objective of cooperative routing based on the ORETT metric in multi-hop WMNs is to find the optimal path for a unicast session that minimizes the sum of ORETT required for delivering data packet from a source to destination. Minimizing the per-packet transmission time generally reduces the radio resources usage, and results in lower interference in the network and eventually higher network throughput. Below we consider the adaptations required at the lower layers to enable ORETT-based routing, specifically, transmission rate adaptation at the physical layer and the changes required to the distributed coordination (DCF) among the nodes at the MAC layer. With regard to the routing protocol at the network layer, we use DSR [9] for evaluation purposes in this work (for a discussion of some minor adaptations in DSR to support cooperative retransmissions, see [17]).

In our cooperative retransmission policy, each node periodically sends a broadcast (probe) packet at all 802.11b bit-rates. Every node keeps track of the fraction of probe packets it receives from each of its neighbors at each bit rate. Based on the predicted link quality values gathered from probing, each node calculates the optimum transmit rate as discussed in section 4 before sending packets to the physical layer. We do not follow cooperative communication schemes such as [13,23] where the transmit bit-rate selection is based on observing the signal-to-noise ratio (SNR) of the preceding RTS at the receiver. The latter approach to rate selection is more suitable when nodes are mobile, so that immediate channel quality is preferable over long-term measurements where the relationship between the SNR and error rate is predictable [2]; on the other hand, ORETT is designed for wireless mesh networks with stationary nodes, thus rate selection based on recent packet loss history is better-suited to this context. In our implementation, one probe packet of size 512 bytes is sent once per second on average. More specifically, we consider three 802.11b rates (2, 5.5 and 11 Mbps) to evaluate the performance of our ORETT based cooperative transmission policy. We have used 802.11b in our simulations for simplicity; however, our scheme is applicable to 802.11a/g/n standards as well. In each three-second interval, our implementation sends a probe at each of the three rates at an independently chosen random point. Finally, each receiving node expired its record of received probes after 60 seconds.

The Δ-MAC protocol introduced in our previous work [17] uses a mechanism similar to that of RTS/CTS handshaking in basic IEEE 802.11 DCF 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 purposes of the ORETT metric, extending it only to include the selection of the best rate as well as the best relay as described in section 4.

6. EVALUATION

6.1 Simulation Configuration

We use QualNet [16] to simulate a WMN of 50 stationary mesh nodes that are randomly distributed in an area of 1600 m × 1600 m. Each node has one interface with fixed transmission power. All experiments use the two-ray propagation path loss model, with free space path loss exponent of 2 for near sight and plane earth path loss exponent of 4 for far sight. The physical layer uses PHY802.11b and restricts transmission rates to 2, 5.5, or 11 Mbps. A number of source-destination pairs (varying between 1 and 9 randomly selected pairs) simultaneously transmit constant bit rate (CBR) traffic at 50 packets per second, with a data payload size of 512 bytes. In addition, background multicast flows in the form of multicast CBR (MCBR) sessions are randomly generated, running ODMRP [12] as the multicast routing protocol. This allows us to check the impact of ORETT-based routing in a more challenging situation where multicast background traffic increases the chance of packet collision. In our simulation setup, we use 3 multicast sources and 5 group members, with each source generating MCBR traffic at a rate of 1 packet per second, with a data payload size of 128 bytes. The total simulation time is 550 seconds, allowing the first 120 seconds for warm-up to acquire link PDR's for initial routing set-up and remove transients. In each of the scenarios below, we perform the experiment for 25 independent runs and show the average as well as the standard deviation bars in the graphs. For the estimation of link PDR's required for the metric calculations, we apply the probing technique of [5].

We focus on three important performance measures: (1) End-to-end packet delivery ratio for the unicast flows, (2) Total ORETT, i.e. the sum of all MAC-layer transmission times (including retransmissions) to deliver a data packet in a unicast flow, and (3) Cooperation ratio, defined as the proportion of cooperative relay retransmissions out of the total number of packets transmitted in the network.

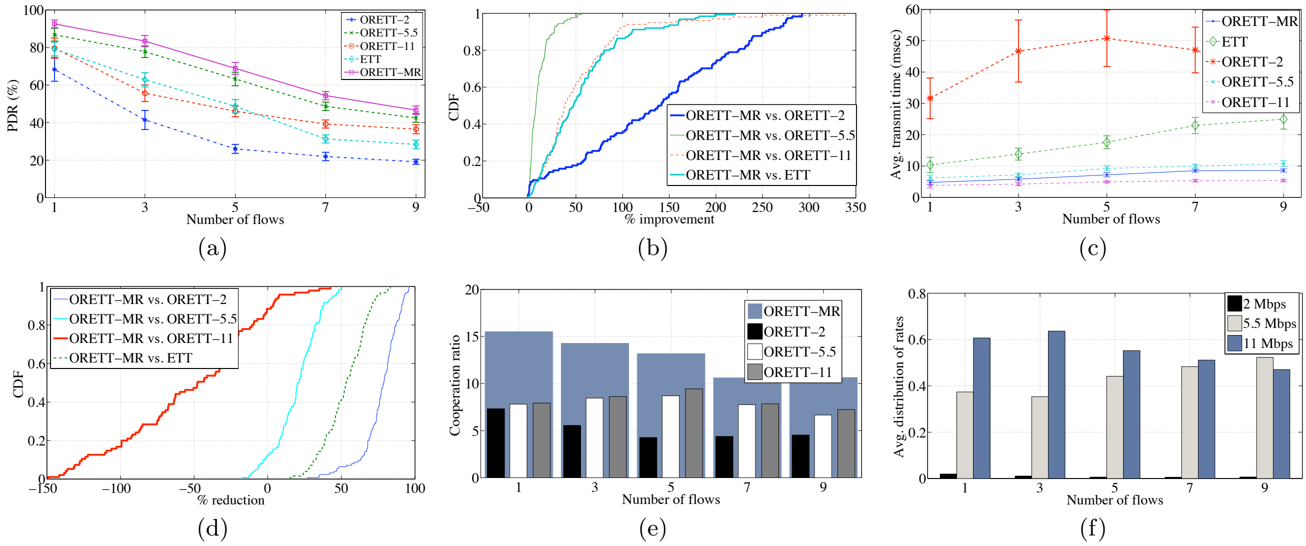

Figure 3: Performance comparison (a) -(b) Line graph display the avg. result of end-to-end PDR. CDF shows the PDR improvement(%) of ORETT-MR over other metrics. (%) of improvement $= (\frac{\mathrm{PDR}_{\mathrm{ORETT-MR}}}{\mathrm{PDR}_{\mathrm{other\ metric}}} - 1) \times 100\%$. (c) - (d) Line plot display total transmit time per packet. CDF shows (%) of reduction in terms of packet transmit time of ORETT-MR over other metrics. Percentage of reduction $= (1 - \frac{\mathrm{TxTIME}_{\mathrm{ORETT-MR}}}{\mathrm{TxTIME}_{\mathrm{other\ metric}}}) \times 100\%$.(e) Percentage of packets transmitted by relay nodes, and (f) Transmit rate distribution in ORETT-MR based routing.

6.2 Simulation Results and Discussion

Our simulations consider the following five scenarios: DSR in conjunction with ETT, DSR in conjunction with ORETT for three single rates (ORETT-2 at 2 Mbps, ORETT-5.5 at 5.5 Mbps, and ORETT-11 at 11 Mbps), and DSR in conjunction with ORETT for a multi-rate network (ORETT-MR). Figure 3(a) shows the average end-to-end PDR for the five different setups. Almost in all simulation runs, ORETT-MR based routing presents higher PDR compared to ETT. For example, ORETT-MR presents 34% higher PDR than ETT when there are three simultaneous flows in the network. Without considering the rate diversity, single-rate cooperative routing shows lower PDR than ORETT-MR. With five simultaneous flows, ORETT-MR achieves 102%, 9%, and 51% higher PDR than routing at ORETT-2, ORETT-5.5, ORETT-11, respectively. In Figure 3(b), the cumulative distribution function (CDF) for the improvement (in percentage terms) of ORETT-MR over ETT and single-rate routing is presented. To calculate the CDF, we have considered 125 different PDR measurements for each routing metric. As the figure shows, the median improvement of PDR is 47% compared to ETT, and the improvement of ORETT-MR over single-rate routing is similarly significant.

Generally, the paths between nodes become longer (in terms of hop count) at higher rates due to possible loss of connectivity on some links. As a result, a larger proportion of packets are lost due to retransmit limits being reached at ORETT-11. Conversely, under clear channel conditions, using a lower rate leads to higher end-to-end PDR. However, under heavy load and channel errors, the longer channel occupancy times lead to increased incidence of collisions and other failures, and the actual PDR can become much lower; indeed ORETT-2 shows the worst performance as expected. For ETT, which does not utilize cooperative retransmission policy, the performance in terms of PDR is clearly different from ORETT-MR. Overall, multi-rate ORETT based routing outperforms single-rate and ETT based routing, because the path selection accounts for the advantages of rate diversity and results in paths with a higher reliability.

The result in Figure 3(c) shows the average end-to-end packet transmit time at different traffic configurations. In comparison to ETT, ORETT-MR consumes 51% less transmission time. It consistently outperforms single rate cooperative routing metrics regardless of network load. For example, ORETT-MR reduces transmission time by 79.15% and 20.30% when compared with ORETT-2 and ORETT-5.5 respectively in the case of three simultaneous flows. Although ORETT-11 requires less packet transmission time, the actual end-to-end PDR is much lower compared to ORETT-MR. In Figure 3(d), a CDF is shown over the 125 different measurements. The median transmission time is reduced by 53% with ORETT-MR compared to ETT. For up to 60% of simulation runs, ORETT-MR reduces transmission time by more than 15% over routing with ORETT-5.5. Interestingly, in some simulation runs, ORETT-5.5 requires less transmission time than ORETT-MR; indeed, because of low link PDR at higher rates, in some instances ORETT-MR prefers 2 Mbps links with a higher transmission delay. However, the overall reduction of transmission time for ORETT-MR compared to ETT clearly shows the effectiveness of cooperative retransmission policy. The results confirm that, by exploiting the rate diversity, ORETT consumes less transmission time than routing at single-rate or ETT.

Figure 3(e) shows how often relay nodes cooperate to forward data packets. ORETT-MR shows higher cooperation ratio irrespective of traffic load in the network; in other words, relay nodes are much more likely to be selected when multiple transmission rates are considered. This effect is clearly evident in Figure 3(e) where a large fraction of packets has been forwarded by relay nodes when ORETT-MR is used. Note that the cooperation ratio for ORETT-MR varies from 11% to 16% even when the number of flows is increased from one to nine. Figure 3(f) shows how optimal rate selection by ORETT-MR makes use of all the available rates, explaining why ORETT-MR always performs better than single rate routing. The rate selection mostly oscillates between 5.5 Mbps and 11 Mbps; however, in absence of alternate high speed links, a few node pairs selected 2 Mbps as an optimal rate. For example, we have 55% of node pairs using 11 Mbps, 44% using 5.5 Mbps, and 1% using 2 Mbps as the optimal rate when five simultaneous flows are present in the network.

7. CONCLUSION

In this paper, we have introduced ORETT as a new high throughput routing metric for multi-hop multi-rate WMNs. ORETT effectively utilizes wireless broadcast advantages for MAC-layer relay aided retransmission mechanism on an opportunistic basis, and includes an adaptive transmission rate control to minimize the expected transmission time in the presence of such cooperative retransmission. Our simulation experiments have confirmed that routing in multi-rate WMNs using the ORETT metric achieves a significant reduction of packet latency and higher end-to-end packet delivery ratio than either traditional ETT or single-rate cooperative routing.

8. ACKNOWLEDGMENTS

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