Probabilistically Reliable On-Demand Multicast in Wireless Mesh Networks

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Abstract

This paper studies probabilistically reliable multicast in wireless mesh networks (WMNs), utilizing MAC layer retransmission and wireless broadcast advantage to improve both the multicast throughput and the delivery rate. We first present a new multicast routing metric which we call the expected multicast transmissions (EMT). EMT captures the effect of link packet delivery ratio, MAC layer retransmission and wireless broadcast advantage at the same time. The EMT of a MAC layer multicast transmission is the expected number of data transmissions (including retransmissions) required for a packet to reach all the recipients. The EMT of a multicast tree is the sum over the EMT of each forwarding node. Then, we propose a probabilistically reliable on-demand (PROD) multicast protocol with the objective of minimizing the EMT of the multicast tree. Simulation results show that, in comparison with existing approaches, PROD reduces the end-to-end packet loss ratio by up to 30% and improves the multicast throughput by up to 25%. In addition, it reduces the number of transmissions per packet by up to 40% and thus significantly reduces the network overhead of the multicast session.

1 Introduction

Wireless mesh networks (WMNs) are emerging technologies for providing cheap and high-speed wireless access infrastructure. A WMN is formed through the deployment of wireless mesh routers and creates an extended, multi-hop wireless backbone for transporting user traffic in both urban and semi-urban environments [1]. High-speed WMNs are expected to enable a range of new, exciting multicast-based applications, such as IP-TV and video conference. Accordingly, both MAC layer techniques and routing layer techniques need to be enhanced for WMNs to support such high data-rate multicast applications.

MAC layer multicast in current WMNs is based on the IEEE 802.11 multicast/broadcast protocol [9]. Multicast frames/packets are sent according to the rules of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), but without the acknowledgement mechanism used in unicast transmissions. (This opportunistic use of MAC layer broadcasts, without any retransmission-based frame reliability, is common in 802.11 standards.) Since frame loss at one or more receivers can be quite significant due to the likelihood of interference or collisions, the packet loss ratio of one-hop multicast transmissions can be rather high. Consequently, when such an unreliable MAC layer multicast protocol is used as the basis for network-wide multicast in WMNs, the end-to-end packet delivery ratio decreases exponentially [18]. Thus, a number of reliable MAC layer multicast/broadcast protocols have been proposed to guarantee one-hop reliability [2, 8, 10, 11, 15, 16]. They share the same core idea of having the sender retransmit the MAC frame until all recipients explicitly acknowledge reception of the frame. Experimental results show that such reliable MAC layer multicast mechanisms significantly improve the packet delivery ratio on a multi-hop wireless path.

Relatively little work has, however, been done in adapting the routing layer protocols (for network-wide broadcast or multicast) in a WMN to account for the MAC layer (single-hop) enhancements for reliability. Existing routing metrics, such as ETT, ETX, PP, METX and SPP (see [12] for definitions) are either designed for unicast traffic or based on best-effort wireless transmissions (where each forwarding node broadcast the frame only once). The performance of these routing metrics for multicast traffic was studied in [12] under the assumption of unreliable MAC layer multicast.

The formulation of routing metrics that incorporate the effect of reliable MAC layer broadcasts must not only account for the variable number of transmissions to different neighbors, but should also factor in the *wireless broadcast advantage* (WBA) [19], whereby a single transmission can potentially cover multiple neighboring nodes. In this paper,

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we first formulate a new metric which we call the *expected multicast transmissions* (EMT). The EMT metric accurately captures the transmission overhead resulting from the use of a retransmission-based reliable MAC layer for link-layer multicast transmissions. EMT is not only able to account for the different loss rates on different channels (to individual neighboring nodes), but also able to exploit WBA to reduce the number of independent transmissions that are needed. After formulating the EMT metric, we present a new multicast protocol which we call the *probabilistically reliable on-demand multicast protocol* (PROD). Using EMT as the routing metric and exploiting WBA, PROD can significantly improve both the reliability and throughput of network-layer multi-hop wireless multicast. To our knowledge, there is no prior work on developing a multicast metric at the routing layer that captures the combined effect of MAC layer retransmission-based reliability and WBA.

This paper makes the following key contributions:

- We propose and formulate EMT as a new link-layer metric that captures the effects of both MAC layer retransmissions (under variable link loss rates) and WBA. We discuss the properties of EMT and demonstrate how this metric is significantly different from prior commonly-used metrics, such as METX [12].
- Using EMT as the routing metric, we propose PROD as a new multicast routing protocol for WMNs. PROD enables multi-hop wireless multicast by using a (source,group)-specific forwarding tree. The multicast tree is formed in a distributed fashion, and the formation takes into account the incremental cost of adding a child node to any existing forwarding node. Simulation results show that PROD (with EMT as an underlying metric) can reduce the packet loss ratio by up to 30% in comparison with alternative approaches.

The remainder of this paper is organized as follows. Section 2 presents the design of the EMT metric. Based on the EMT metric, the objective of a reliable multicast protocol is defined as the creation of a packet forwarding tree such that the sum of the EMT over all forwarding nodes is minimized. We present the details of PROD in Section 3, and the results of our simulation-based studies in Section 4. In Section 5, we discuss the related work. Finally, Section 6 draws our concluding remarks.

2 EMT Metric Design

This section describes the design of the EMT metric, which captures the expected number of distinct transmissions needed to support a link-layer multicast to multiple next-hop neighbors. The overall objective of this metric is to help form a multicast tree with the least number of total multicast transmissions, including possible retransmissions to achieve reliability, so that it can save network resource consumption and increase the network throughput.

A link-layer wireless multicast/broadcast transmission must factor in the WBA (first defined in [19]), as each broadcast transmission can effectively reach each one of the downstream one-hop neighbors. The original WBA formulation is, however, based on the notion of a reliable wireless link (100% packet delivery), i.e. a deterministic binary packet reception model. In reality, individual wireless links are prone to time-varying failure (packet loss) due to effects such as fading and interference. Accordingly, the probability of successful reception of a multicast transmission may vary significantly across the receivers. For reliable transmission of multicast frames at the MAC layer, the sender will keep on sending the data packet until all of its intended recipients acknowledge succesful reception of the packet (and the acknowledgement is itself successfully received). For example, in Batch Mode Multicast MAC Protocol (BMMM) [16], when the data is transmitted, the sender sends an RAK to each recipient, and waits for their ACKs. If some of the recipients failed in receiving data or some ACK messages are lost, the sender will resend the packet until the ACK from each recipient is received successfully.

The EMT metric may be viewed as the multi-receiver analogue of the ETX metric proposed in [5] for unicast routing. ETX characterizes the link loss ratio using the expected number of MAC layer transmissions (including retransmissions) needed to successfully deliver a packet from a sender to a single receiver. In a similar manner, EMT is defined as the average number of MAC layer broadcast transmissions (including retransmissions) needed for all MAC layer multicast recipients to receive a packet successfully.

2.1 EMT formulation

Consider the WMN in the form of a graph $G = (V, E)$, where V is the set of mesh nodes and E is the set of wireless links. A wireless link exists between node i and node j if the two nodes are within the transmission range of each other. The forward and reverse delivery ratios of link (i, j) are given by $d^{\mathrm{F}}_{i,j}$ and $d^{\mathrm{R}}_{i,j}$, respectively. Thus, the probability that a one-hop packet transmission from node i is successfully received and acknowledged by node j is $d^{\mathrm{F}}_{i,j} \times d^{\mathrm{R}}_{i,j}$. For a particular sending node $i \in V$, we define N_i as the set of all nodes within the transmission range of node i wishing to receive the packet. The (nominal) link packet delivery ratio $d_{i,j}$ for each receiving node j in the set N_i is given by $d^{\mathrm{F}}_{i,j} \times d^{\mathrm{R}}_{i,j}$, and the link packet loss ratio $f_{i,j}$ is given by $f_{i,j} = 1 - d_{i,j}$. Let $\Upsilon(N_i,\ c)$ define the set of all combinations of choosing c nodes out of the set N_i. Theorem 1 states an explicit formula for computing EMT$_i$ (EMT of

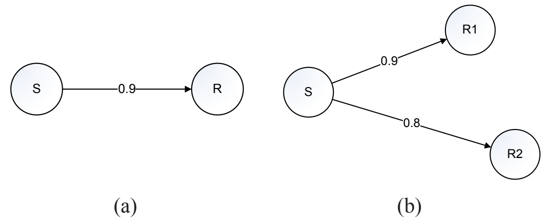


Figure 1. Expected number of transmissions in unicast and multicast. (a) Unicast, ETX $= 1.1$**; (b) Multicast, EMT** $= 1.34$

node i to all recipients in N_i) based on the above setting.

Theorem 1 *For $i \in V$, we have*

$$\mathrm{EMT}_i = \sum_{c=1}^{|N_i|} (-1)^{c-1} \sum_{\mathcal{S} \in \Upsilon(N_i,\, c)} \frac{1}{1 - \prod_{j \in \mathcal{S}} f_{i,j}} \ . \tag{1}$$

The proof of Theorem 1 is provided in the Appendix.

For example, in Figure 1(b), the sender S has two multicast recipients R1 and R2. The link packet delivery ratio is 0.9 for (S,R1) and 0.8 for (S,R2). Thus, the link packet loss ratio is 0.1 and 0.2, respectively. The EMT of node S to $\{$R1, R2$\}$, according to (1), is

$$\begin{aligned} \mathrm{EMT} &= \frac{1}{1-0.1} + \frac{1}{1-0.2} - \frac{1}{1-0.1 \times 0.2} \\ &= 1.34 \ . \end{aligned}$$

EMT has several important features:

- EMT is a function of the individual link packet delivery ratio, which directly affects the throughput. In Figure 1(b), the EMT is larger than the maximum ETX of the two individual unicast links, which is 1.25 transmissions.
- EMT utilizes the WBA. EMT is not a simple sum of the individual ETX values. For example, in Figure 1(b), the ETX of two multicast recipients R1 and R2 is 1.11 and 1.25. However, the EMT of R1 and R2 is 1.34, which is much less than the sum of the ETX of the two individual unicast links which equals to 2.36.

Formally speaking, for a sending node i with a set N_i of multiple recipients, it can be shown that EMT_i has the following lower and upper bounds:

$$\max_{j \in N_i} \mathrm{ETX}_{i,j} \leq \mathrm{EMT}_i < \sum_{j \in N_i} \mathrm{ETX}_{i,j} \ . \tag{2}$$

The equivalence to the lower bound in (2) holds only if the link packet delivery ratio $d_{i,j}$ for each receiving node j in the set N_i is 100%, i.e. $f_{i,j} = 0, \forall j \in N_i$. Intuitively, the EMT of a packet transmission must be lower than the number of transmissions required when the packet is unicast to each receiver, and must be higher than the number of transmissions needed for the receiver with the “worst link quality”.

2.2 Objective of EMT

Let T be the set of forwarding nodes that represent a valid multicast tree solution. The EMT of T is the sum of EMT_i of each forwarding node i in T. Since multicast transmissions consume network bandwidth, it is important to reduce the total number of transmissions so that the throughput of the network can be increased. The objective of an efficient multicast tree in our context is to establish a multicast tree from the source to all destinations aiming to minimize the EMT of T, i.e., $\sum_{i \in T} \mathrm{EMT}_i$. For brevity, we will call the multicast tree with minimal EMT as the minimal EMT tree in the rest of this paper.

Consider the example network topology in Figure 2(a). The solution shown in Figure 2(b) is the minimal EMT tree with EMT = 3.89. If we use ETX as the link metric, both the shortest path tree (shown in Figure Fig.2(c)) and the Steiner tree (shown in Figure 2(d)) give sub-optimal results in terms of EMT.

In [13], it was proved that the problem of finding the *minimal number of transmissions* (MNT) tree with the binary packet reception model is NP-complete [7]. Since the problem of finding the MNT tree is a special case of the problem of finding the minimal EMT tree (by setting the packet delivery rate of each link as 100%), the problem of finding the minimal EMT tree is NP-complete as well. In Section 3, we will provide a receiver-initiated distributed protocol to compute an approximate solution for the minimal EMT tree problem.

The EMT computation is based on several assumptions. First, the MAC layer retransmission mechanism must be used, such as RMAC[15], BMMM[16], etc. Second, EMT assumes that radio has the fixed transmission power. Variable transmission power results in variable reception SINR, which makes the statistical link packet delivery ratio useless. Third, EMT assumes that the reception probability of each receiver is independent of other nodes. Fourth, the EMT metric assumes that a successful transmission occurs only when a single (transmit,ACK) pair is individually successful. Our metric does not capture the possibility of a receiver sending an ACK for a previously successful transmission (for which the ACK may have been lost).

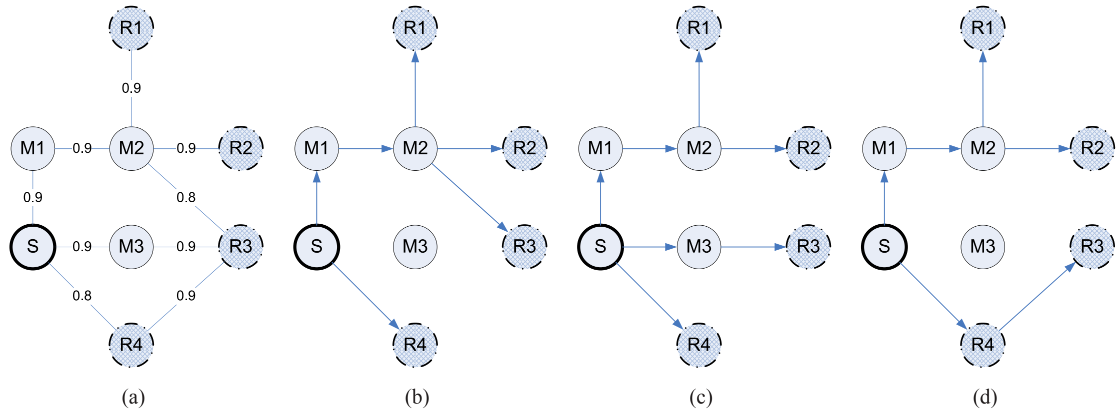


Figure 2. Comparison in total number of transmissions for several multicast trees. (a) Example network topology with link packet delivery ratio; (b) Optimal solution, EMT $= 3.89$**; (c) Shortest path tree, EMT** $= 4.86$**; (d) Steiner tree, EMT** $= 4.75$

3 Probabilistically Reliable On-Demand Multicast Routing Protocol

In this section, we describe the new multicast routing protocol PROD that we propose for establishing an efficient EMT-based multicast tree in a distributed manner. PROD is a receiver-initiated multicast routing protocol. It has three phases, namely, link quality acquisition, tree initialization, and tree maintenance.

3.1 Link Quality Acquisition

In order to acquire the link packet delivery ratio to compute EMT, each node broadcasts a probe message to all of its neighbors every PROBE_INTERVAL time. (To avoid collisions and anomalous synchronization effects, the transmission of each probe is randomized over a small interval around PROBE_INTERVAL). The node also counts the number of probes, denoted as PROBE, that are actually received from each of its neighbors in the last PROBE_STATISTIC_INTERVAL time. For each neighbor, the node knows the maximum number of probes, denoted as $\overline{\text{PROBE}}$, that can be received in the last PROBE_STATISTIC_INTERVAL, which is given by

$$\overline{\text{PROBE}} = \frac{\text{PROBE\_STATISTIC\_INTERVAL}}{\text{PROBE\_ INTERVAL}}\,. \tag{3}$$

Therefore, the link packet delivery ratio in the last PROBE_STATISTIC_INTERVAL period is

$$r = \text{PROBE}/\overline{\text{PROBE}}\,. \tag{4}$$

In order to represent the long term link packet delivery ratio, we define the Cumulative Link Packet Delivery Rate, given by

$$R = (1-\beta) * R' + \beta * r \tag{5}$$

as the link quality, where R is the current cumulative link packet delivery ratio, R' is the cumulative link packet delivery ratio in the last PROBE_STATISTIC_INTERVAL period and r is the current measured link packet delivery ratio. The 'forgetting factor' β helps smooth over short-term transients in the link quality, and yet allows helping the protocol to be sufficiently responsive to significant, persistent changes in the link quality. R is an appropriate metric for most WMN environments, where the mesh nodes themselves are typically static (e.g., mounted on rooftops or lightposts), and link impairments are thus due to long-term physical effects (e.g., building construction) rather than short-term fades typically observed in mobile environments. Each node will keep the cumulative link packet delivery ratio from each neighbor to itself in the LinkQualityTable for the future path calculation.

3.2 Tree Initialization

PROD is a receiver-initiated multicast routing protocol, which means that the node wishing to join the multicast group initiates the path finding procedure to the multicast tree. The key ideas behind the tree construction process are as follows. Assuming that a multicast tree with a number of receivers (i.e. multicast destinations) has already been built. A new receiver will find a path to the existing tree such that the additional number of EMT required is minimized. In particular, the protocol exploits WBA at the point where the path from the new receiver is grafted onto the existing tree. This is achieved by computing the incremental number of EMT needed to transmit to one additional downstream recipient at the grafting point. (This protocol is thus based on the concept of "incremental cost" originally used by the BIP algorithm in [19]). We will now explain the details of the protocol.

If a node wishes to join a multicast group, it broadcasts a JoinReq packet. The JoinReq packet contains the information about the multicast group address, the IP address of the node itself, sequence number, time-to-live (TTL), the neighbor link quality table and the path cost. The neighbor link quality table in the JoinReq message broadcast by a node X contains the link quality of all wireless links pointing to node X. This allows the neighbors of node X to obtain the link quality from them to node X. The path cost field in JoinReq contains the additional number of transmissions of the whole multicast session when the path is established to the multicast tree. In the beginning, the path cost is initiated as zero.

Here we define the source, forwarding nodes and current destination nodes in the multicast tree as the multicast tree members. If a non-tree member receives a JoinReq packet, it will rebroadcast the JoinReq message. Before forwarding the JoinReq, the node records the incoming node as the reverse entry to the destination who initiates the JoinReq. It also increases TTL by 1 and updates the path cost field by adding the EMT of the link from the node to the neighbor which sent the JoinReq, which is $1/(R_f \cdot R_r)$, where $R_f(R_r)$ is the cumulative link packet delivery rate of outgoing(incoming) link to(from) the neighbor which sent the JoinReq, and is computed by (5). Note that a node can obtain the values of R_f and R_r from its own link quality table and the link quality table within the JoinReq message. This update means that if the node is selected as the forwarding node in the multicast tree, the additional cost is the EMT of the downstream link of the node.

Only the current multicast tree members are eligible to reply with the JoinReq packet. Therefore, for the first node which joins the multicast session, the source node is the only node eligible to reply with the JoinReq. The multicast tree member replies a JoinReply message when receiving a JoinReq. The JoinReply message has the additional cost from the destination to the node which sends the JoinReply. The additional cost is the path cost in the JoinReq message (which currently contains the sum of the $\frac{1}{R}$ values on the downstream path to the receiver) plus the additional cost of the last hop (the link from the existing forwarding node to the immediate downstream node that transmitted this JoinReq) incoming neighbor. This additional cost is calculated based on the difference between two EMT costs. One is the calculation of EMT based on the current recipients of this node, and another one is the calculation of EMT including the incoming neighbor. The difference of two EMTs is the additional cost of the last hop. For example, in Figure 3, node F4 received a JoinReq packet from its neighbor M3. Since F4 is currently a forwarder of the multicast tree,

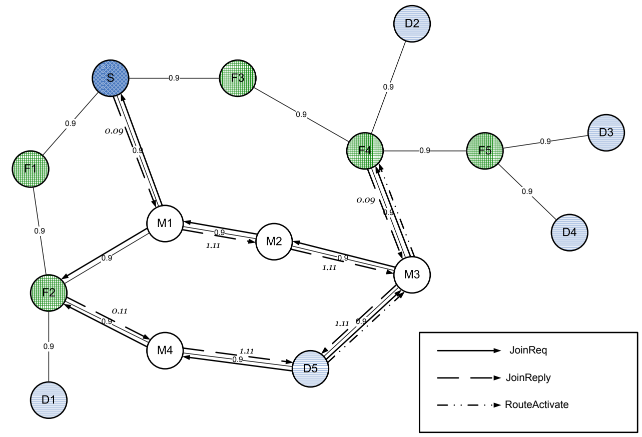


Figure 3. Protocol Example

it produces a JoinReply packet. Firstly, F4 computes the EMT to its current downstream nodes (D2 and F5), which is 1.21 transmissions. The second calculation takes M3 into consideration. Then F4 has 3 recipients with a new EMT of 1.30 transmissions (calculated based on the packet delivery ratios from F4 to D2, F5 and M3). Therefore, the additional cost of the link from F4 to M3 is 0.09 transmissions if F4 is to add M3 as a multicast downstream node. This incremental cost calculation based on EMT allows the PROD to take WBA into consideration. For the node which is only a multicast destination rather than a forwarder, the additional cost of the last hop is the ETX of this link. The JoinReply is unicast backward to the destination node according to the reverse incoming node entries maintained at all intermediate nodes that forwarded the original JoinReq.

The destination may receive multiple JoinReply messages from different nodes. It chooses the one with the minimum cost as the path to the multicast session and sends back a RouteActivate message to activate the route. The RouteActivate message is unicast back to the nominated node which produces JoinReply. Those intermediate nodes are selected as forwarding nodes in the multicast session.

We will now illustrate the operation PROD by using Figure 3. The source node is S. Four multicast destination nodes D1, D2, D3 and D4 have already joined the multicast tree. The nodes F1, F2, F3, F4 and F5 are acting as forwarders in the multicast tree for multicast destinations D1 to D4. The tree members are therefore $\{$S, D1, D2, D3, D4, F1, F2, F3, F4, F5$\}$. All the links are assumed to have a packet delivery probability of 0.9. If node D5 wants to join the multicast session, it broadcasts a JoinReq request. All non-tree members (M1, M2, M3, M4) forward the JoinReq and increase the cost by 1.11. When node F4 receives the JoinReq with cost 1.11, it computes its current EMT with two downstream nodes (D2 and F5), which is 1.21 transmissions. Then it computes the new EMT including the incoming node M3, which is 1.30 transmissions. Therefore, the additional cost of the last hop is 0.09 and the path cost to the destination D5 is 1.20. D5 may receive multiple JoinReply from S (3.42 transmissions), F2 (1.22 transmissions) and F4 (1.20 transmissions). It chooses the path to F4 with the minimum additional cost to send RouteActivate message.

3.3 Tree Maintenance

If a forwarding node fails in the network, its child nodes are responsible for repairing the multicast tree. They will flood out a RouteRepair message and only the forwarding nodes with the Cost to Source which is less than the failed node can reply this RouteRepair message by RREP. This is to prevent loop reply from its downstream nodes.

4 Simulation and Results

4.1 Simulation Setup

We use Qualnet [14] to simulate a network with 50 mesh routers, which are uniformly distributed in a 1500m × 1500m area. Only one interface is installed for each node, which is working in IEEE 802.11b. The channel rate is 2Mbps, used for both broadcast and unicast. Two-ray propagation pathloss model is used in the experiments, with free space path loss (2.0, 0.0) for near sight and plane earth path loss (4.0, 0.0) for far sight. We use PHY802.11b in the physical layer, and modified the MAC layer to use BMMM [16], rather than the default CSMA/CA for multicast. To prevent buffer overflow, we set the maximal number of retransmissions for each node per packet to 5. The unicast flows (cross-traffic for our studies) continue to use the default DCF-based 802.11 MAC.

We form the multicast tree (MMT) using PROD, and compare it with the Shortest Path Tree (SPT) and the Minimum Forwarder Tree (MFT). The SPT is established by finding a shortest path from each destination to the source node separately using METX [12] as the link metric. Therefore, SPT takes the link quality into account but not WBA. The MFT uses the same protocol as PROD except that MFT assumes that the packet delivery probability of all links is 1. Therefore, MFT takes WBA into consideration in forming the multicast tree but is agnostic of the link quality.

In each experiment, the source node sends a multicast constant bit rate (MCBR) traffic to all multicast destinations. Two bit rates are used for different traffic load, 100kbps and 400kbps (512 Byte/packet). Each forwarding node buffers the incoming packets and schedules them for link-layer transmissions in a FIFO fashion (there is thus no channel state-dependent scheduling). To introduce some interference, we randomly choose some background traffic to

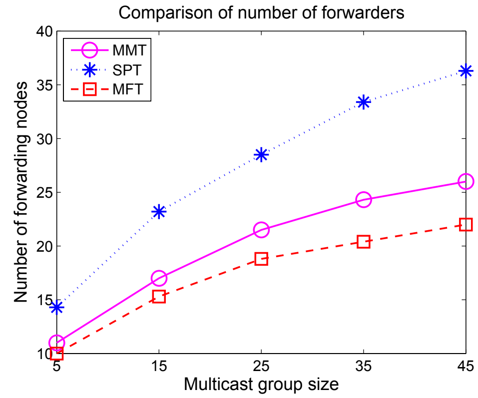


Figure 4. Comparison of number of forwarding nodes

increase the probability of packet collision. We simulate the multicast sessions with multicast group sizes varying from 5 to 45 nodes.

The simulation-based studies focused on the following important metrics:

- *Number of forwarders*, defined as the number of intermediate nodes in any multicast routing tree (a smaller number of forwarders would typically result in a lower tree 'depth').
- *End-to-end packet delivery ratio*, defined as average packets delivery ratio for all destinations, which is the *number of packets received / number of destinations / number of packets sent from the source*.
- *Cumulative throughput*, defined as average throughput of all destinations, which is calculated by *number of packets received / multicast session period*.
- *Cumulative Transmission Overhead*, defined as the average number of distinct MAC layer transmissions over the whole tree, averaged over each individual source packet (a smaller transmission overhead indicates a more efficient combination of routing and MAC).

4.2 Results

Figure 4 shows the number of forwarding nodes required by MMT, SPT and MFT. MMT and MFT both need less number of forwarders to establish the multicast tree since they are able to utilize the WBA.

Figures 5(a) and 5(d) show the end-to-end packet loss ratio of the three multicast trees, for two different source data rates, as the size of the multicast receiver group is varied. The packet loss ratio of MFT is always higher than

SPT and MMT. This is because MFT does not take the link quality into consideration. Thus, it is likely to choose the link with very poor packet delivery ratio so that the end-to-end packet loss ratio is higher. In light traffic load, the performance of MFT and SPT is very similar. Recall that at low loads and small group sizes, losses occur only when the number of MAC layer transmissions reaches the maximum value without success. At low loads, where losses occur only due to the underlying physical link characteristics, the possibility of 5 successive transmission failures is very small. However, when the traffic load is higher (400kbps), the possibility of collision-induced losses increases. As MMT uses a smaller number of forwarding nodes in the network, the possibility of colliding transmissions is smaller; accordingly, MMT results in a significantly lower loss ratio compared to SPT. Figures 5(b) and 5(e) show the corresponding comparison for throughput. We observe that the throughput decreases when group size increases. This is because a larger multicast group implies a larger multicast tree and an increased number of distinct multicast transmissions, effectively increasing the likelihood of packet collisions.

Figures 5(c) and 5(f) reflect the overhead of the three multicast trees. For a packet which is successfully delivered to all of the destinations, the number of transmissions, including retransmissions of MMT is up to 40% less than MFT and 30% less than SPT. This is because MFT only captures WBA and SPT only captures the link-quality, whereas MMT can utilize both WBA and link-quality.

5 Related Work

5.1 Reliable MAC Layer Multicast

In order to increase the one-hop packet delivery ratio, some reliable MAC layer multicast protocols have been proposed. One method is the ARQ-based MAC layer multicast by extending the RTS/CTS/DATA/ACK scheme in IEEE 802.11 Distributed Coordination Function to provide the reliable multicast [11, 16, 17]. In the Leader Based Protocol (LBP) [11], "a leader" elected by the multicast receivers takes the responsibility to reply CTS and ACK to the sender, such that no multiple CTSs or ACKs are generated by the receivers. Although LBP avoids the multiple acknowledgments, selecting and maintaining a "leader" is not an easy task. Tang et al. suggest a round-robin polling strategy in the MAC layer to deliver multicast packets. To tackle the hidden terminal problem, a transmitter polls each of the neighbors before sending the DATA. In [16], Batch Mode Multicast MAC (BMMM) is an extension to the IEEE 802.11 which is similar to [17]. However, to prevent collision among the ACK frames, the transmitter polls each of the neighbors by sending a new packet called RAK (Request to ACK). This protocol adds considerable overhead to transmit a single DATA packet. 802.11MX [8] and RMAC [15] use busy tone to offer reliable MAC layer multicast. Busy tone can prevent data frame collisions and solve the hidden terminal problem. However, it requires a separate channel, which increases the hardware complexity [10].

Although busy tone is a technology different from ARQ, they both share the same core idea, which is the acknowledgment and retransmission mechanism. The simulation results of all reliable MAC multicast protocols above show that they can improve the one-hop packet delivery ratio effectively.

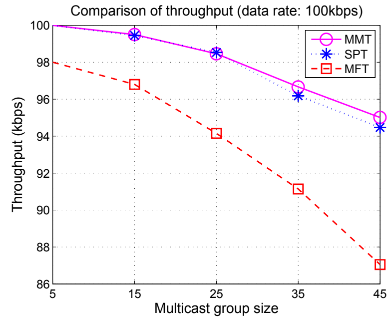
5.2 Metrics

Several metrics have been proposed for high-performance routing of *unicast traffic* in WMNs. Couto et al. proposed ETX in [5]. ETX characterizes the link loss ratio using the expected number of MAC layer transmissions needed to successfully deliver a packet from the sender to the receiver, including retransmissions. The WCETT metric was proposed in [6] to take into account the link bandwidth and loss rates of links in multi-radio multi-channel WMNs. Both metrics take the MAC layer retransmissions into consideration. However, these metrics fail to characterize multicast transmissions. Paper [12] studies different multicast routing metrics in WMNs, namely, ETT, ETX, PP, METX and SPP, where METX and SPP are adapted for multicast. Their simulation results show that the adapted multicast metrics METX and SPP perform much better than the unicast metrics. However, METX and SPP are based on the normal 802.11 multicast, without any retransmission.

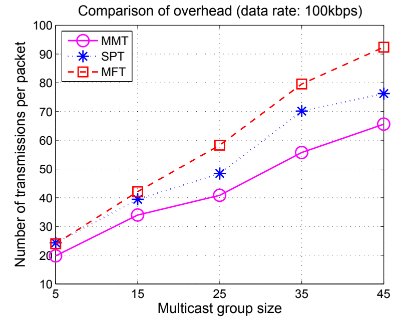
5.3 Multicast Routing Protocols

There is relatively little research on the problem of efficient multicast in WMNs. In [13], the authors formulated the minimal cost multicast tree problem in terms of minimizing the number of broadcast transmissions via WBA under a single transmission rate. Chou et al. [3, 4] studied the problem of multicasting in multi-rate WMNs and proposed several algorithms for achieving low latency multicast in wireless meshes by combining WBA with link-layer rate diversity. In [21], a Resilient Forwarding Mesh (RFM) approach is proposed for protecting multicast sessions from link or node failures. The optimal RFM (ORFM) is a set of forwarding nodes which establishes a pair of node-disjoint paths for each multicast destination with the minimal number of broadcast transmissions by exploiting WBA. Several polynomial time heuristics for getting ORFM are proposed to protect multicast session effectively and efficiently from the single link or node failure in [20]. All of the above papers assume a binary reception model with 100% packet

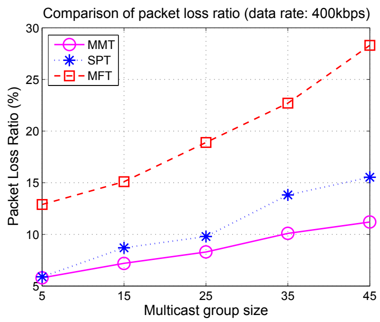
(a) Packet Loss Ratio in light multicast rate (100kbps)



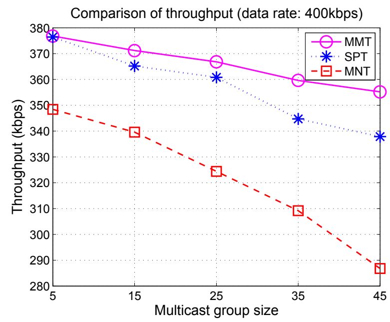
(b) Throughput in light multicast rate (100kbps)



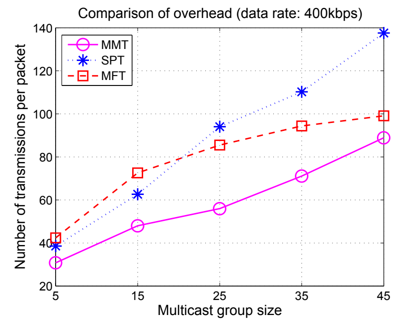
(c) Overhead in light multicast rate (100kbps)



(d) Packet Loss Ratio in heavy multicast rate (400kbps)



(e) Throughput in heavy multicast rate (400kbps)



(f) Overhead in heavy multicast rate (400kbps)

Figure 5. Comparison of Packet Loss Ratio, Throughput and Overhead

delivery ratio that fails to capture the effect of variable loss rates on individual links.

6 Conclusion

Providing reliable multicast (or improving the packet delivery ratio to multiple network-wide receivers) is an important issue in WMNs, where individual packets traverse multiple lossy wireless hops. In this paper, we presented a new link-quality aware metric called EMT for reliable MAC layer multicast in WMN environments. EMT captures the combined effects of MAC layer retransmission-based reliability as well as WBA. We then developed a multicast routing protocol called PROD using EMT as the routing metric to compute a reliable multicast forwarding tree. Our simulation results showed that MMT decreases the packet loss ratio by up to 30% compared with SPT and MFT. MMT also makes significant improvement in network overhead. It reduces the number of transmissions per packet in the multicast session by up to 40%.

From the simulation results, we observe that, when the traffic load of the multicast session is light, the throughput of SPT is very similar to MMT. But MMT still provides significant gains over SPT in network overhead, by reducing the number of distinct transmissions needed. When the multicast traffic load is heavier, MMT outperforms SPT by also offering significantly higher throughput and lower latency for reliable delivery.

For future work, we plan to explore several potential enhancements and issues, including the modification of the EMT metric to account for alternative reliable MAC layer protocols (e.g., those based on opportunistic forwarding) as well as augmenting the EMT metric to account for potential transmission rate diversity on different links.

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Appendix: Proof of Theorem 1

Let $P_i^{(k)}$ denote the probability that it requires k transmissions from the sending node i for a packet to be successfully received and acknowledged by all nodes in the set N_i.

Let $\mathcal{S}$ be the set of nodes in N_i which successfully receive and acknowledge the packet only from the k-th transmission, whereas all nodes in $N_i - \mathcal{S}$ successfully receive and acknowledge the packet during the first $k-1$ transmissions. Given the link packet loss ratio $\{f_{i,j}\}$ between the sending node i and each receiving node j, and assuming $\{f_{i,j}\}$ are statistically independent, $P_i^{(k)}$ is computed by

$$P_i^{(k)} = \sum_{c=1}^{|N_i|} \sum_{\mathcal{S}\in\Upsilon(N_i,\, c)} \prod_{u\in\mathcal{S}} f_{i,u}^{k-1}\Big(1-f_{i,u}\Big) \prod_{v\in N_i-\mathcal{S}} \Big(1-f_{i,v}^{k-1}\Big) \tag{6}$$

where $\Upsilon(N_i,\ c)$ is the set of all combinations of choosing c nodes out of the set N_i.

It can be shown by induction (omitted due to space limitation) that we can rewrite (6) as

$$P_i^{(k)} = \sum_{c=1}^{|N_i|}(-1)^{c-1} \sum_{\mathcal{S}\in\Upsilon(N_i,\, c)} \Big(1-\prod_{j\in\mathcal{S}} f_{i,j}\Big)\Big(\prod_{j\in\mathcal{S}} f_{i,j}\Big)^{k-1}.$$

Thus, by the definition of EMT, we have

$$\begin{aligned}
\text{EMT}_i &= \sum_{k=1}^{\infty} k\cdot P_i^{(k)} \\
&= \sum_{k=1}^{\infty} k \sum_{c=1}^{|N_i|}(-1)^{c-1} \sum_{\mathcal{S}\in\Upsilon(N_i,\, c)} \Big(1-\prod_{j\in\mathcal{S}} f_{i,j}\Big)\Big(\prod_{j\in\mathcal{S}} f_{i,j}\Big)^{k-1} \\
&= \sum_{c=1}^{|N_i|}(-1)^{c-1} \sum_{\mathcal{S}\in\Upsilon(N_i,\, c)} \Big(1-\prod_{j\in\mathcal{S}} f_{i,j}\Big)\sum_{k=1}^{\infty} k\Big(\prod_{j\in\mathcal{S}} f_{i,j}\Big)^{k-1} \\
&= \sum_{c=1}^{|N_i|}(-1)^{c-1} \sum_{\mathcal{S}\in\Upsilon(N_i,\, c)} \frac{1}{1-\prod_{j\in\mathcal{S}} f_{i,j}}
\end{aligned}$$

where the final equivalence follows from the known Maclaurin series of the form

$$\sum_{k=1}^{\infty} k\cdot x^{k-1} = \frac{1}{(1-x)^2}, \quad \text{for } 0 < x < 1.$$

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