CDMR: Cooperative Diversity-based Multi-Copy Relaying in Mesh Networks

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Abstract

The standard way to handle frequent transmission errors over wireless links is to use a link-layer automatic retransmission mechanisms. However, multiple retransmissions per link along an n-hop path leads to significant channel usage inefficiency and poor end-to-end performance. We propose a novel cooperative diversity-based multi-copy relaying (CDMR) scheme for wireless mesh networks. CDMR improves system performance by effectively utilizing available network resources, allowing neighboring (helper) nodes along a selected route to cooperatively deliver (as opposed to using retransmissions) packets to the final destination. CDMR operates in two phases: helper establishment and cooperatively delivery. The fundamental challenges are to identify effective helpers and to synchronize helper transmissions in order to avoid collisions. CDMR provides a simple and effective solution with low overhead. Simulation results show that (even with just one helper node), CDMR is able to reduce retransmissions and improve end-to-end delay by 39% to 86% depending on the path length.

I. Introduction

Wireless mesh networks (WMNs) are packet radio networks that combine the dynamically self-organizing and self-configuring principles of the multi-hop ad hoc networking paradigm with the cellular-based structure of traditional wireless LANs. WMNs have two types of wireless nodes: mesh routers and mesh clients. As depicted in Figure 1, the mesh routers form a large-scale (e.g., municipal size) multihop wireless backhaul network, which is used by mesh clients to communicate to each other or to the Internet via gateway-enabled mesh routers. The fundamental goal of wireless mesh networking is to provide the same physical coverage (as a singled high-powered transceiver) by using quickly deployable multihop mesh routers that use a signficantly lower transmission power. This offers the benefit of less interference which may enable higher data rates. Due to their ease of deployment and low cost, the mesh networking architecture has received considerable commercial and research interests [1], as illustrated by the plethora of commercial, municipal, and experimental testbed deployments that have occurred in recent years. A fundamental challenge facing the mesh networking paradigm is overcoming the performance effects of inherently and highly error-prone multihop wireless paths. Because of the broadcast nature of the radio medium, the router-to-router wireless link quality and performance varies frequently and unpredictably due to wireless channel effects and random traffic conditions, leading to relatively high packet error rates. The traditional approach to reducing the effects of frequent transmission errors over wireless links is to use a link-layer retransmission scheme. For example, the IEEE 802.11 MAC protocol will retransmit a data frame a maximum of four times before declaring the frame undeliverable. Research results have show that the cumulative effect of multiple per link retransmissions significantly reduces the total performance.

In this work, we focus on improving end-to-end performance in WMNs using a very interesting concept called cooperative diversity. While much of the previous work in wireless networking ignores the broadcast nature of the wireless channel (e.g., modeling the channel similar to that of a wired point-to-point link), the concept of cooperative diversity attempts to take advantage of the broadcast nature of the wireless channels by allow nodes to cooperatively share their available resources in an effort to improve channel efficiency and overall system performance. Co-
operative diversity was first proposed in [2] as a technique for increasing uplink capacity in single-hop cellular-based communication systems.

The distributed multi-hop nature of WMNs and the relatively static mesh backhaul provides significant opportunity for applying cooperative diversity to improve channel usage efficiency. Specifically, we proposed a MAC-layer cooperative diversity-based multi-copy relay (CDMR) protocol that significantly reduces the need for link-layer retransmissions; thereby improving end-to-end delay, throughput, and delay variance over an n-hop path.

CDMR is based on the underlying observation that although a primary relay node along a path may fail to receive a data frame, one of its neighboring nodes may correctly receive the transmitted packet. In which case, the neighboring node can forward the frame further down the path, alleviating the need for a frame retransmission by the original transmitter and, thereby, improving channel usage efficiency. CDMR is based on a hybrid method such that traditional routing protocol discovers a stable route to the destination and the CDMR-enabled MAC protocol handles packet forwarding, allowing neighboring nodes (helpers) of intermediate nodes to cooperatively forward packets to the destination.

The remainder of this paper is organized as follows. Section II discusses the related work and distinguishes it from the proposed solution. Section III describes the basic idea, operation, and design details of our proposed cooperative-diversity based relaying protocol followed by a discussion of simulation results in Section IV. The paper then concludes with a summary of contributions and a discussion on future research directions.

II. Related Work

CDMR is motivated by the concepts of multi-copy relay [3]–[5] and cooperative diversity-based Extremely Opportunistic Routing (ExOR) mechanisms [6]. Multi-copy relay protocols have been used primarily in intermittently connected mobile ad hoc and sensor networks. To our knowledge multi-copy relay has not been explicitly studied in wireless mesh networks (WMNs). In traditional unrestricted multi-copy relay, a packet is replicated multiple times at each relay each node [3]. Adaptive multi-copy routing (AMR) [4] tries to limit the replication factor by allowing the intermediate nodes to independently decide whether to replicate a packet based on current network condition and the end-to-end target delay. The intermediate nodes also use intermeeting time with the destination as one of the factors in determining the value of the replication factor. As shown by the results in Section IV, current multi-copy relaying schemes cause an excessive number of packets in mesh networks. In CDMR, packets are not replicated by multiple relay nodes. Instead, a single transmitter unicasts a packet to the current next-hop along the source-destination route. Helper nodes (neighbor nodes selected by the current next-hop) listen for any packets intended for the next-hop and will cooperatively deliver a single copy of the packet along the source-destination path. That is, there is no packet replication. CDMR improves efficiency by reducing the number of potential relay nodes to only those nodes inline with a stable route selected by the routing protocol.

Cooperative opportunistic routing [7] attempts to exploit multi-user and transmit diversity to improve throughput. The protocol operates at medium access control and network layer. The protocol modifies RTS/CTS and uses them extensively in its design. The sender includes in its header a list of candidate forwarders. Only are these candidate forwarders able to forward packets. RTSs are used by senders to compete for the channel and ensure that only one sender is chosen. When a sender acquires the channel to send RTS, it waits for the candidates to reply with a CTS before sending the data packet. If the CTS is not received by the sender, the sender again will compete for the channel to transmit RTS. When a data packet arrives, the candidates send ACKs in return. If the ACK is lost, the original sender will send an RTS with a sequence of the previous data packet so that the candidates can resend the ACK instead of having the sender resend the data packet. RTS/CTS/ACK are used extensively in this protocol and they often result in very poor performance in multihop wireless networks as shown in [8], [9]. Thus, by using RTS/CTS multiple times, the channel usage efficiency may be jeopardized. CDMR on the other hand uses very few packets to establish candidate forwarders and the process...
of establishing candidate forwarders does not take place at every packet transmission.

Cooperative Diversity Slotted ALOHA [10] also utilizes the available resource at the vicinity of transmitters to help forwarding packet. A sender transmits a packet at the beginning a slot. Any node that has at least the same or smaller hop-count as the intended next hop can be a relay node. The relay nodes need to communicate with the sender in order to determine the next relay node. This protocol uses many control messages (PRD/ACK1/PRD/RRF/ACK2.1/.../ACK2.\(n\)/CRF) in any single slot, which may result in significant overhead.

ExOR [6] is the first work that attempts to use opportunistic routing, where a set of nodes acts as relay nodes, whose selection is based on their past probability of delivering packets to destination. ExOR is an integration between routing protocol and MAC protocol. Each packet is included in itself a list of forwarders and their corresponding priority. A node transmits packets based on its priority. Lower priority nodes must wait and learn the status of their higher priority nodes from the channel. The lower priority nodes will send next if a predefined period has passed and they do not know the status of the higher priority nodes. If the status is known, they can calculate when to send and what packets are missing to prevent from packet duplications. ExOR has a lot of overheads because nodes in the network need to know ETX value of other nodes and the inclusion of forwarder list in every packet. ExOR chooses the best possible node for the next hop to relay packets and it also removes MAC layer retransmissions. The helpers in CDMR act as a retransmission mechanism, however the retransmissions are done without the involvement of the intermediate nodes. There are other protocols that utilize opportunistic technique for sensor networks such as [11], [12]. These protocols use multiple nodes to transmit the same packets thus they are highly inefficient and have high delay.

Distributed Spatial Diversity [13] uses multiple radios for transmitting and receiving signal. Depending on the signal strength of the received signal transmissions, a node decides to resend its packet or relay packet to be forwarded. This protocol is very similar to ExOR but instead of SNR, ExOR uses ETX value. [13] does not have the relay nodes to communicate to each other so there is a high chance of duplicate transmission. CDMR works with single radio. It does not use nodes closer to the destination to relay packets. Instead, it uses nodes that have the same previous hop and next hop to relay packets. The helper nodes are there to assist best-path routing.

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**III. The Cooperative Diversity-based Relaying Protocol**

**A. Motivation and Basic Idea**

The failure to deliver MAC layer frames over a router-to-router link in mesh networks is typically due to wireless channel effects or interference at the receiving router, resulting in MAC layer retransmissions. If multiple retransmissions occur at each hop along the path, network performance is severely impacted (i.e., high end-to-end delay, throughput). The usefulness of removing MAC retransmissions by utilizing neighboring nodes can be understood in the example of Figure 2 [6]. Suppose the probability of successfully delivering frames between node \(S\) and a primary node \(R_p\) is 0.25 and that the probability of delivering a frame between \(R_p\) and \(D\) is 1. In this case, the expected number of transmissions required to successfully deliver a frame from node \(S\) to node \(D\) is equal to 5 transmissions \((1/0.25 + 1)\). Now suppose that the three (3) neighbors of \(R_p\) could cooperate to help deliver frames forwarded from \(S\) to \(D\) via \(R_p\). In this case, the expected number of transmissions can be reduce to 2.5 transmissions \((1/(1 - (1 - 0.25)^4) + 1)\). This advantage can be profound in multi-hop networks.

In this work, we attempt to alleviate the need for MAC layer retransmissions by utilizing the broadcast nature (and its resulting effects) to allow neighboring nodes to cooperatively relay packets that failed to be delivered to the intended next hop along a source-destination path. Our solution is based on the underlying observation that although the intended next-hop (e.g., \(R_0\) in Figure 2) may fail to correctly receive a packet, one of its neighboring nodes may have overheard the packet and may (depending on its location) be able to forward the packet further along the source-destination path; thereby, avoiding a retransmis-
operate at the MAC-layer and consists of two phases:

**B. CDMR Design Details**

The CDMR protocol is designed and implemented to operate at the MAC-layer and consists of two phases: *helper establishment* and *cooperative delivery*. An existing routing protocol is used in this scheme as a basis for finding a route to the destination. This design decision is based on the idea that when a route is found by a routing protocol, that route is chosen based on the network characteristics (e.g., traffic conditions) at a given time and should be stable over the long term. On the other hand, short term signal variations and interference can be handled more effectively at the MAC layer.

**Phase I: Helper Establishment.** A key factor in the performance of CDMR is the selection of effective helpers (i.e., neighbors with the highest probability of delivering packets to the next-hop). In our current implementation of CDMR, we use the ETX concept defined in [14] as the delivery probability of a link between neighboring nodes. Briefly, ETX is an expected transmission count that quantifies the effect of lossy links. If the loss probability of a lossy link is high, a packet is expected to be transmitted many times before it arrives at the destination, resulting in a high ETX value. The success probability of a given link is computed as the inverse of the ETX value [6]. At start-up and periodically thereafter, a node broadcasts an information packet consisting of its neighbor list and their corresponding ETX values.

Thereafter, each node identifies and establishes its own helper nodes as follows (see Algorithm 1). When an intermediate node receives a unicast packet, the routing protocol provides the next-hop to which the packet should be forwarded. If there is no helper yet established for this route at this intermediate node, the intermediate node will establish helpers by going through its neighbor list. If there are neighbors with the same previous hop and next hop, the intermediate node adds these neighbors to a candidate list based on the neighbors overall ETX value. For each candidate helper, an overall ETX value is calculated by averaging the ETX values for previous-hop and next-hop links. An average is used because the importance of previous-hop and next-hop links is the same. The intermediate node chooses helper nodes by selecting the neighbors with the smallest overall ETX value (i.e., highest successful transmission probability).

Once an intermediate node has compiled its candidate helper list, it will broadcast a helper request message. When a neighbor node receives the helper request packet, it checks to see if its own ID is in the list. If so, the neighbor node sets itself to be the intermediate node’s helper and begins listening for packets transmitted by the previous-hop (pHop) to the intermediate node and destined for the next-hop (nHop). To further limit the overhead of the helper establishment phase, the size of helper request packet is reduced because the node ID is hashed from 32 bits to 8 bits and a helper priority field is 8-bits long. Helper nodes do not need to send a confirmation-reply back to the intermediate node. If a potential helper failed to correctly receive helper request packet, CDMR assumes that the helper is unreliable at the time. The potential helper may receive the helper request message during the next helper request period. Moreover, an intermediate node can confirm whether or not its helpers are cooperating by observing the packet transmissions on the channel. Our experimental results confirm this design choice to avoid helper confirmation messages (i.e., handshaking), as the overhead of coordinating the transmission of confirmations did not yield performance gains. As shown in Section IV, one helper will significantly benefit the intermediate node.

In the special case, where an intermediate node does not have any forwarding helpers, it will notify the previous-hop, which will then operate using the standard IEEE 802.11 retransmission mechanism. This is discussed further under Phase II.

**Phase II: Cooperative Delivery.** A fundamental challenge in realizing the benefits of cooperative diversity is synchronizing helper nodes in order to avoid packet collisions. CDMR achieves node synchronization as follows. After a node compiles its candidate helper list, each candidate is assigned a send-priority based on its overall ETX value. The candidate ID and its corresponding priority are included in the helper request packet. Upon first receiving a data packet intended for the intermediate node, all helper nodes listen for an ACK from the intermediate node to the previous-node. If the helper nodes do not hear an ACK

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**Algorithm 1** finding neighboring helpers

**Require:** pHop, nHop, int

**Ensure:** candidateList

1: \( o\_ETX \)
2: \( \textbf{for all } i \textbf{ in neighborList}[\text{int}] \textbf{ do} \)
3: \( \textbf{if } \text{pHop and nHop in neighborList}[i] \textbf{ then} \)
4: \( o\_ETX = (pHop\_ETX + nHop\_ETX)/2 \)
5: \( \textbf{add } i \textbf{ and } o\_ETX \textbf{ to candidateList} \)
6: \( \textbf{end if} \)
7: \( \textbf{end for} \)

\{\( pHop, nHop, \text{int, } o\_ETX \) for previous-hop, next-hop, intermediate node and overall ETX\}
from the intermediate node for a packet transmitted by
previous-hop, it is assumed the the packet was not correctly
received at the intermediate node. In which case, the helper
nodes will cooperate to relay the packet to the next-hop. The send-priority tells the helper nodes how long
to wait before attempting to relay the received frame to
the next-hop. For example, a helper node with a priority
of two means the helper will wait for two packet times
before attempting to relay the frame to the next-hop. If
the helper node does not hear an acknowledgement from
the next-hop, it concludes that higher priority nodes were
unsuccessful and that it should proceed.

In order for helper nodes to know which packets to send
or discard, a small header (Figure 3(a)) is added to every
packet. This header sits between IP and MAC headers. The
SEQ_NO field is a sequence number and is combined with
the node ID to distinguish packets. When a helper node
receives a data packet it stores the packet along with the
node ID and SEQ_NO. When a helper node overhears an
ACK for a packet with the same SEQ_NO, it knows that
the packet has been received successfully and it removes
the packet from its buffer. HOP_CNT is the hop count of
a current packet. It is increased at each hop. Helpers only
store packets if they are from nodes with a lower hop-
count than itself. When a packet arrives at an intermediate
node, the packet has its header stored, removed from the
packet, and then forwarded to the IP layer. When it exits
the IP layer, the header is added back with the hop count
increased by one. Upon the arrival of a data packet, the
helper nodes check to see if they are indeed the helpers
by matching the hop count and address of the original
source and destination nodes in the IP header against the
information it got from the intermediate node. If there is
a match, it will send according to its priority.

A small header is also added to ACK packets (Figure 3(b). SEQ_NO is used to inform all helper nodes that
a packet has been successfully received. HOP_CNT is also
used to informed a sender whether the receiver has helper
nodes or not. Intended next-hop nodes that do not have
any helper send back ACKs with HOP_CNT set to zero.
Otherwise, the HOP_CNT of the intended next-hop node
is included in the ACK. When an intermediate node or the
source receive ACKs for their packets with HOP_CNT of
zero and they do not have any helper, they will revert back
to the original method of packet retransmission.

IV. CDMR Performance Evaluation

A. Simulation Details and Setup

To evaluate its actual benefit in WMNs and to under-
stand any potential interactions within the protocol stack,
we implemented CDMR directly in Qualnet simulator,
which includes detailed implementations of all layers of
the protocol stack. CDMR is coded at the MAC layer,
which is based on 802.11 standard. The CDMR code reads
the IP header to get source and destination address but does
not in anyway modify the IP header. The physical layer
is 802.11b. The topology consists of 21 nodes distributed
as shown in Figure 4. We choose this topology to prove
that our protocol works when there are helpers. If there
is no helper the protocol works exactly like 802.11 with
an extra header of 8 bytes, which adds approximately
half a percent overhead to a 1500-byte packet. A CBR
traffic generator is used generate twenty 1460-byte packets
per second. The RTS-CTS handshake is not used in the
experimental design. The size of network queue is 50000
bytes. The queue size can impact the end-to-end delay and
drop probability of a packet.

All simulation results are based on the topology shown
in Figure 4, which depicts the mesh backhaul network. The
topology does not change during simulation as the mesh
routers are typically stationary. The source-destination path
length varies 1 to 6 hops, which represents realistic topolo-
gies in current deployments. We compare our protocol
against AODV [15] and DSR [16] operating over standard
IEEE 802.11b physical and MAC protocols. In this case, a
data frame will be retransmitted a maximum of four times
before being discarded. CDMR does not use MAC-layer
retransmission except when source and destination are 1-
hop neighbors, since there is no benefit in establishing
throughputs. Each simulation scenario is replicated five times.

B. Results and Analysis

We do not provide extensive comparisons between CDMR and existing multi-copy relay protocols such as [4] or [5] because these protocols are used in intermittently-connected mobile ad hoc networks, which have low arrival rates and high delay. However, we do implement AMR [4] in Qualnet to show that our assumptions are valid. Table I shows that AMR is no fit for mesh networks. This can be explained as follows. Each node relays messages to every node it meets along its trajectory to the destination. The wireless mesh backhaul network only consists of stationary nodes. Thus a packet is replicated multiple times before it gets to the next hop, resulting in network congestion (high collision/interference) and a high number of packet retransmissions. The consequence is high end-to-end delays, low PDR, and low throughput as shown in Table I.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Throughput (kbps)</th>
<th>Delay (s)</th>
<th>PDR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 hops</td>
<td>6 hops</td>
<td>3 hops</td>
</tr>
<tr>
<td>AODV</td>
<td>539.38</td>
<td>219.83</td>
<td>0.1529</td>
</tr>
<tr>
<td>AMR</td>
<td>73.44</td>
<td>25.51</td>
<td>0.31</td>
</tr>
</tbody>
</table>

1) Packet Delivery Ratio (PDR): Recall that a fundamental goal of CDMR is to improve the overall end-to-end packet delivery delay. However, before examining the end-to-end delay of CDMR, we first study its packet delivery reliability. This is an important point, since CDMR removes the standard retransmission mechanisms and relies on helper nodes that face several obstacles, including failing to receive the original packet and failing to effectively coordinate with other helpers. In improving the per packet end-to-end delay, CDMR must maintain high level of reliability. PDR can be used as an indicator of how well the network can tolerate errors. PDR is calculated by taking the number of packets received divided by the number of packet sent. Figure 7 shows that the PDR of CDMR is comparable to that of AODV and DSR. For one hop, all protocols perform similarly because they used the same method of MAC layer retransmission. As the hop-count increases, CDMR shows a steady performance increase. Starting from 3 hops, CDMR delivers more packets than AODV and DSR at 2% and 28% respectively. At 4 hop, CDMR outperforms AODV and DSR with MAC-layer retransmissions by 23% and 17%, respectively. For AODV and DSR, this result is due to the standard retransmission scheme that causes increased channel contention, causing the half-duplex nature of wireless channel to become worse and increasing queuing delay and packet drops. AODV drops the most packets because AODV keeps refreshing its routes after a predefined period. The route refreshing causes all nodes to temporarily stop sending packets so they can do a route rediscovery. For CDMR, however, it does drop packets but not as much because packets are not queued long at each node since there are no MAC layer retransmissions. When using DSR, packets drops occur to a much lesser extent than AODV because the DSR route discovery only activates when a route error occurs and all backup routes fail. For CDMR, there is no route rediscovery even if there is a route error. Instead, when a node fails to send a packet, its helpers will deliver the packet.

2) Throughput and Delay: While PDR simply indicates the ability of CDMR to tolerate errors, end-to-end delay and throughput indicate how quickly CDMR can overcome errors and deliver packets to the final destination. The throughput is calculated as the number of packets (bits) received divided by the time difference between the first packet sent and the end of the simulation, as each source continues to transmit until the specified simulation time expires. It is important to note that the end-to-end delay (see Figure 6) is computed only for packets that are actually delivered to the final destination. To fully understand the decrease in delay for AODV and DSR at a path length of 4 hops, the reader should examine the throughput and packet deliver ratio. MAC layer retransmission schemes are widely used to increase PDR and throughput in multihop wireless networks that use best-effort routing protocols. Figure 5 and 6 show that the throughput and delay of CDMR is very competitive to that of AODV and DSR at 1 and 2 hops. The benefit of CDMR can be seen as the path-length increases, where CDMR achieves a stable throughput and delay while the performance of DSR and AODV over 802.11b continues to decrease. Based on the path-length, CDMR yields a 5% to 22% throughput increase and 39% to 86% lower delay compared to AODV and DSR. This phenomenon can be explained as follows. With the standard 802.11 MAC, retransmitted packets increase the channel contention in the current collision domain. This has a chain effect on all transmitters within two hops. The faster a packet can be transmitted down the source-destination path, the faster the original source node can begin its next transmission. CDMR achieves this goal. When packets are not delivered to the primary relay node, the helper nodes are able to deliver the packets to the next-hop on behalf of the intended primary relay node. This approach results in less channel contention at the original sender (i.e., the previous-hop to the primary relay node) and reduces queuing delays, while simultaneously forwarding the packet further down the source-destination path.
3) Impact of Number of Helpers on Performance: Based on Figure 2, increasing number of helpers should also increase the packet delivery probability, thereby improving the packet delivery ratio and packet delivery delay. However, our results show that too many helper nodes also increase the chance of having collisions in the wireless channel when nodes fail to synchronize correctly or fail to detect signal transmissions. For example, suppose a primary relay node correctly receives a data packet form a previous-hop and then successfully relays that packet to the next-hop node. If the primary relay’s helper node also receives the data packet (from the previous-hop) but fails to receive the ACK sent back to the primary relay node, the helper will assume that the packet was not correctly received and attempt to transmit a second packet. The result is a duplicate packet in the network, wasted bandwidth, and queueing resources.

Figure 8(a) shows that with no helper and not using standard retransmission scheme, CDMR (as expected) delivers fewer packets. However, throughput and PDR are improved considerably even with 1 helper (as shown Figure 8). The initial results (i.e., the fluctuations in PDR, throughput and delay (see Figure 8(a), 8(b), 8(c)) as the number of helpers is increased) indicate that, in practice, additional helpers do not necessarily yield a performance improvement due to the protocol overhead required to manage such helpers.

V. Conclusion

In this paper, we have presented CDMR, a MAC-layer cooperative diversity-based multi-copy relaying mechanism for wireless mesh networks. CDMR yields a lower end-to-end delay of 36% to 86% (compared to standard retransmission mechanisms), while maintaining a PDR higher than both AODV and DSR operating over standard IEEE 802.11b physical and MAC protocols. The results indicate that as hop-count increases, CDMR is able to maintain a stable performance. CDMR has several advantages when compared to related multi-copy and cooperative diversity schemes. First, it is based on a simple design to use available network resources with low overhead. Unlike previous work, CDMR does not require a forwarder list to be included in every packet, batch maps, or other complicated book-keeping structures. Second, CDMR does not use a large number of control packets to achieve neighbor establishment and helper coordination. Third, in the case of no helpers, CDMR easily reverts to the standard retransmission mechanism. Fourth, CDMR does not require any changes to existing routing strategies.

The current results indicate that CDMR has merit for improving overall performance in WMNs. Our future work will focus on a more comprehensive performance evaluation, including multiple traffic flows and non-uniform network topologies. We must also study the sensitivity of CDMR to errors in the link probability metric. In the current implementation, we use the ETX value as a measure of delivery probability, which is used to determine
helper nodes and their respective delivery probabilities. Is this the best measure? In future work, we will explore this question by studying ETX metric and its the correlation with metrics such as busy-time-ratio, packet drops, and queue size. Finally, we must also investigate the impact of CDMR on TCP flows. It is well-known that out-of-order packets present problems to TCP. These comprehensive evaluations of CDMR will include mathematical analysis, simulation, and empirical results from our 14-node mesh testbed.

References


