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D. Pathirana and M. Kwon, "RODMRP: Resilient On-Demand Multicast Routing Protocol," Advanced Information Networking and Applications Workshops, 2007, AINAW '07. 21st International Conference on, Niagara Falls, Ont., 2007, pp. 85-92. doi: 10.1109/AINAW.2007.315

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Resilient-ODMRP: Resilient On-Demand Multicast Routing Protocol

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Abstract

ODMRP (On-Demand Multicast Routing Protocol) [5] [7] [1] is a popular multicast protocol for wireless ad hoc networks. The strengths of ODMRP are simplicity, high packet delivery ratio, and non-dependency on a specific unicast protocol. ODMRP floods a route request over the entire network to select a set of forwarding nodes for packet delivery. However, a single forwarding path is vulnerable to node failures, which are common due to the dynamic nature of mobile ad hoc networks. Furthermore, a set of misbehaving or malicious nodes can create network partitions and mount Denial-of-Service (DoS) attacks. We propose a ODMRP-based wireless multicast protocol named Resilient-ODMRP that offers more reliable forwarding paths in face of node and network failures. A subset of the nodes that are not on forwarding paths rebroadcast received packets to nodes in their neighborhoods to overcome perceived node failures. This rebroadcasting creates redundant forwarding paths to circumvent failed areas in the network. Each node makes this forwarding decision probabilistically. Our simulation results indicate that Resilient-ODMRP improves packet delivery ratio with minimal overheads, while retaining the original strengths of ODMRP.

1. Introduction

Today more and more consumer devices (i.e., media players and handheld gaming devices) have built in wireless content sharing capabilities. Furthermore, the next generation mobile phones are equipped with wireless networking capabilities in addition to their CDMA and GSM carrier networking functionality. Mobile devices have become an essential ingredient to everyday life (i.e., in 2006, mobile phone sales alone have surpassed 1 billion units [2]). Industry analysts predict a surge of content sharing applications in wireless consumer devices. Such applications can clearly benefit from a simple and lightweight wireless

multicast protocol. A few examples of such applications include sharing of video or audio content in environments where there are no dedicated networking infrastructure (i.e., a subway train), a team of emergency dispatchers sharing information of location of crew members and casualties, and a group of troops in a battle field sharing surveillance information. Compared to individual unicast or broadcast protocols, wireless multicast routing protocols significantly help save resources and adapt to accommodate a large number of group members.

A variety of applications may utilize multicasting to disseminate data from a source to a set of receivers in wireless networks. Streaming video or audio applications, in particular require high-bandwidth and seamless uninterrupted packet delivery. Multicasting is ideal for such applications as it can support packet delivery to a set of participating nodes with a minimal overhead to non-participating nodes. While current wireless multicast protocols (i.e., ODMRP [5, 7, 1, 15, 9, 10, 6]) offer efficient and reliable data delivery services, abrupt network disconnections or node failures cause service interruptions until faulty parts are restored. Such service interruptions are intolerable for live streaming applications since lost frames cannot be recovered. In wireless ad hoc networks, switching to backup network links or nodes take a longer time because alternate paths are not available immediately and need to be reconfigured. Although multiple forwarding paths can overcome this situation to a certain extent, such an alternative will easily introduce a significant amount of extra traffic.

In this paper, we develop Resilient On-Demand Multicast Routing Protocol (Resilient-ODMRP), a wireless multicast protocol that aims at offering seamless and uninterrupted services for live streaming applications. In our protocol, a subset of nodes that are not participating in multicast data forwarding develop soft states by promiscuously listening to forwarding path setup control packets. Based on their observations of control packets, a set of such nodes probabilistically forward multicast data to overcome perceived failure of forwarding nodes. This redundant packet forwarding improves packet delivery ratio, while probabilis-

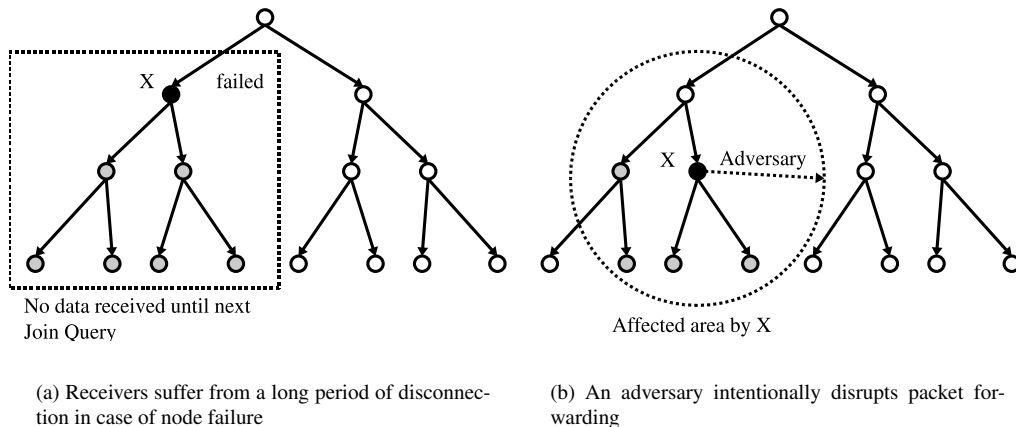


Figure 1. Problems of ODMRP

tic rebroadcasting alleviates the possibility of flooding the network.

Furthermore, our protocol forms the original forwarding paths by selecting the forwarding nodes that are located furthest from the child nodes. The rationale behind this concept is to improve the possibility of having more non-participating nodes between parent and child nodes. Our simulation results indicate that this approach includes more nodes between parent and child nodes, and helps create a short tree. Overall, the combined effect of redundant packet forwarding and path formation increase the data delivery ratio with a reasonable amount of overhead, while retaining the simplicity and elegance of ODMRP.

The remainder of this paper is organized as follows. Section 2 describes the details of the Resilient-ODMRP protocol. In Section 3, we present preliminary results from our experiments. In Section 4, we give an overview of related work. Finally, we summarize our conclusions and future work in Section 5.

2. The Resilient-ODMRP Protocol

2.1. Overview of ODMRP

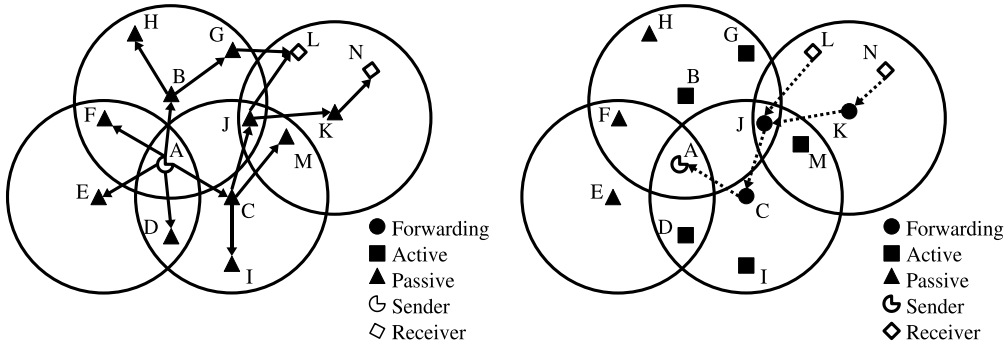
To construct a multicast forwarding tree, an ODMRP source periodically floods a *Join Query* to the entire network. Upon receiving a *Join Query* packet, an intermediate node updates its routing table with the sender as the upstream parent for the particular multicast source and rebroadcasts the packet. Duplicate *Join Query* packets are detected via sequence numbers and suppressed for forwarding. When the *Join Query* reaches a prospective receiver, the receiver selects the best path based on predefined cri-

teria (i.e., least hop path) and sends a *Join Table* packet back to the source. The *Join Table* packets are relayed by intermediate nodes and travel all the way back to the source on the reverse path. A *Join Table* packet reinforces the path established by the *Join Query*. Subsequently, when the multicast source sends data, the intermediate nodes become forwarding nodes in the data delivery tree. ODMRP maintains group membership as a soft-state in which parent-child relationships should be periodically refreshed. This is done by periodic rebroadcasting of *Join Query* packets. Hence, ODMRP does not require explicit procedures to join or leave multicast group.

2.2. Problems of ODMRP

Despite its simplicity and flexibility, ODMRP may cause the receivers to endure long periods of disconnections in case of node failures. In Figure 1(a), node *X* in an ODMRP multicast tree fails, moves away, or runs out of battery power while transmitting video data. In such a case, neither the one-hop children of *X* nor its descendants can receive the video stream. The forwarding tree is not recovered until the next *Join Query/Join Table* packet exchange. As illustrated in the figure, this problem becomes more serious for live streaming data delivery using multicast since missing frames or parts cannot be recovered in real time. In fact, streaming applications can only accommodate periodic packet loss and long periods of network disconnections are intolerable.

Moreover, an adversary or a misbehaving node may intentionally disrupt a group of targeted nodes and deny access to the video stream (Figure 1(b)). The ODMRP recovery mechanism may not be effective against this type of



(a) A sender initiates route discovery by flooding a *Join Query*

(b) A receiver selects the optimal path and reinforces the forwarding path by sending a *Join Table*

Figure 2. ODMRP forwarding node setup

Denial-of-Service (DoS) attacks since forwarding path recovery is based on Join Query/Join Table packets. Furthermore, it would be difficult, if not impossible, for an attacked node or its descendants to be aware of the overall situation and react to it promptly. Worse yet, no single Join Query packet may arrive at a targeted node if the attack is organized to prevent any additional node from existing within the range of the targeted node as a parent. In such a case, the recovery will be delayed for a considerably longer period.

2.3. Description of Resilient-ODMRP

As discussed in Section 2.2, streaming services using ODMRP for data delivery may suffer from intermittent service unavailability due to node/network failures. Moreover, the streaming services are vulnerable to sophisticated attacks, i.e., Denial-of-Service (DoS) attacks. In addition, many duplicate packets are produced and end up useless due to redundant broadcasting.

Resilient-ODMRP exploits these useless packets for more reliable packet delivery in ODMRP. A node forwards a packet probabilistically to a receiver although the packet does not come from the parent in the multicast tree. When the original route is disconnected due to network or node failures, this redundant packet offers the receiver an additional route for the data stream from the source, and ensures uninterrupted delivery of the data stream. To be effective, Resilient-ODMRP has to address two important questions: (1) How does a node probabilistically decide on which packets are redundantly forwarded? (2) Can we ensure that an additional forwarding node exists with high probability?

To design our protocol and answer the previous two questions, we first define several terms. A *forwarding* node denotes a node that is on the forwarding path established by the Join Query/Join Table packets. A *non-forwarding* node refers to a node that is not a forwarding node. Non-forwarding nodes are further categorized into *active* and *passive* non-forwarding nodes. Active non-forwarding nodes are within the range of a forwarding node while passive non-forwarding nodes are not. *Promiscuous listening* refers to the ability of the active non-forwarding nodes to eavesdrop on Join Query and Join Table packets. Overhearing transmitted control packets, active non-forwarding nodes compute the packet forwarding probability, which is referred to as *passive forwarding probability* based on Join Query and Join Table packet observations. *Passive forwarding* refers to actual redundant data forwarding by active non-forwarding nodes to complement possible packet loss.

The packet forwarding tree construction algorithm is similar to the one in ODMRP. A source (node A in Figure 2) initiates a multicast session by broadcasting a Join Query packet. Intermediate nodes relay the Join Query packet, and update their routing tables with the parent toward the multicast source. The receivers reply with a Join Table packet back to the source via reverse forwarding paths.

By promiscuously listening to Join Query packets from source A, an active non-forwarding node initializes the passive forwarding probability P_A as

$$P_A = \frac{1}{n} \quad (1)$$

where n is the number of unique observations of Join Query packets. As more Join Query packets are seen, the active non-forwarding node lowers the probability since other

| Node | n | m | f | P_A |
|----------------------------|-----|-----|-----|-------|
| A (source) | - | - | - | - |
| B (active non-forwarding) | 4 | 1 | 2 | 1/4 |
| C (forwarding) | - | - | - | - |
| D (active non-forwarding) | 4 | 1 | 1 | 1/4 |
| E (passive non-forwarding) | - | - | - | - |
| F (passive non-forwarding) | - | - | - | - |
| G (active non-forwarding) | 4 | 2 | 2 | 1/2 |
| H (passive non-forwarding) | - | - | - | - |
| I (active non-forwarding) | 2 | 1 | 1 | 1/2 |
| J (forwarding) | - | - | - | - |
| K (forwarding) | - | - | - | - |
| L (receiver) | - | - | - | - |
| M (active non-forwarding) | 4 | 4 | 2 | 1 |
| N (receiver) | - | - | - | - |

Table 1. Computing the packet forwarding probability in Resilient-ODMRP

nodes in the neighborhood are likely to send redundant packets. On the other hand, upon observing Join Table packets, the active non-forwarding node increments P_A as

$$P_A = P_A * m \quad (2)$$

where m is the number of unique Join Table packets. The active non-forwarding node increases the passive forwarding probability as more potential receivers are awaiting packets. A node far from the source needs to send more duplicate packets to increase packet arrival rates at receivers. To this end, an active non-forwarding node forwards a packet when the following condition holds:

$$P_A \geq \frac{1}{f} \quad (3)$$

where f is the least number of hops toward the source along a forwarding path.

An example of Resilient-ODMRP is illustrated in Figures 2 and 3. By definition, all nodes are initially passive non-forwarding nodes. Source A initiates the multicast session by broadcasting a Join Query packet, and all the surrounding nodes (B , C , D , E , and F) rebroadcast the received Join Query packet. In the figure, these rebroadcasting forms two potential forwarding paths from the source to receivers L and N . L selects the path from J , while N selects the path from K . Each receiver replies with a Join Table packet to its parent (eventually to the source) to reinforce the selected forwarding path. In the example, B receives a Join Table from J , G receives Join Table packets from L and J , and M receives Join Table packets from J , K , L , and C . Note that B , G , and M are all active

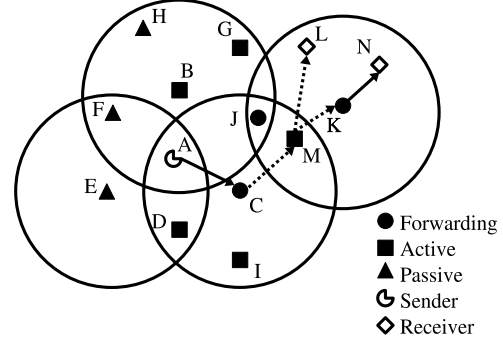


Figure 3. Routing around a failed node

non-forwarding nodes. These node also update their routing tables accordingly to update the passive forwarding probability.

Based on the Join Query/Join Table packet observations, and the current routing paths, these active non-forwarding nodes compute the passive forwarding probability as summarized in Table 1. With these results, M elects to forward redundant packets. Should node J disconnect from the original path, node M can offer a backup forwarding path (as depicted in Figure 3) and ensure uninterrupted packet delivery to the receivers.

As in ODMRP, the source periodically broadcasts Join Query packets to refresh current paths or to discover new or better forwarding paths. This also allows a new member to subscribe to the current multicast session. Receivers also periodically send Join Table packets upstream toward the source to maintain forwarding routes. When a new route is uncovered, the receiver of the new route redirects its Join Table packet to the new parent. To compute the discrepancy more precisely, active non-forwarding nodes reset their passive forwarding probability every time they receive a Join Query from the source.

2.4. Discussion

What happens if no additional node exists within the range to receive and broadcast the same data? No descendants of the failed node can receive data since no data is redundantly relayed by any node in the range of the failed node and its parent. This problem occurs when a node does not include other nodes around the path between itself and the parent as shown in Figure 4(a). The shorter the length of such a path, the higher the possibility of the problem occurrence.

To rectify the problem, Resilient-ODMRP enhances the ODMRP tree construction algorithm such that the furthest node receiving a Join Table from a child node becomes the parent. Figure 4(b) illustrates our approach. When node A

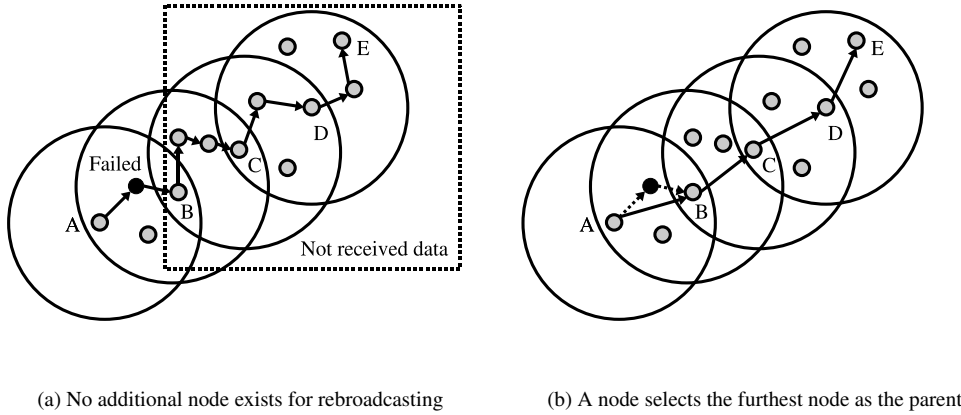


Figure 4. Resilient-ODMRP maximizes the number of active-forwarding nodes

broadcasts a Join Table packet, node *B*, which is located near the range boundary, is chosen as the parent. This process continues until a Join Table packet reaches the source. This algorithm increases the probability that at least one node exists between parent and child nodes in an ODMRP multicast tree.

In ODMRP, each node maintains information for the multicast source, the current parent, the forwarding flag, and the last sequence number in the routing table. This information is updated when a Join Query or a Join Table is received.

Resilient-ODMRP requires three additional attributes in the routing table of an active non-forwarding node: 1) the number of Join Query observations, 2) the number of Join Tables observations, and 3) the passive forwarding probability. A new Join Query from a multicast source resets (or refreshes) all current routing information learned from that source. If an entry in the routing table is not refreshed before its timeout expires, the entry is reset and its current data is removed.

3. Performance Evaluation

3.1. Experimental Setup

The performance evaluation of Resilient-ODMRP was based on network simulator (ns-2.1b6 [12]). The Lucent WaveLAN IEEE 802.11 with a 2Mbps transmission rate and a transmission range of 250 m was used as the radio model. The IEEE 802.11 wireless LAN Distributed Coordination Function (DCF) was used as the link layer model. For the performance evaluation, we considered four test topologies with 25, 50, 75 and 100 mobile nodes in an area of 1200 m x 800 m. In each test scenario, which was run for 10 minutes,

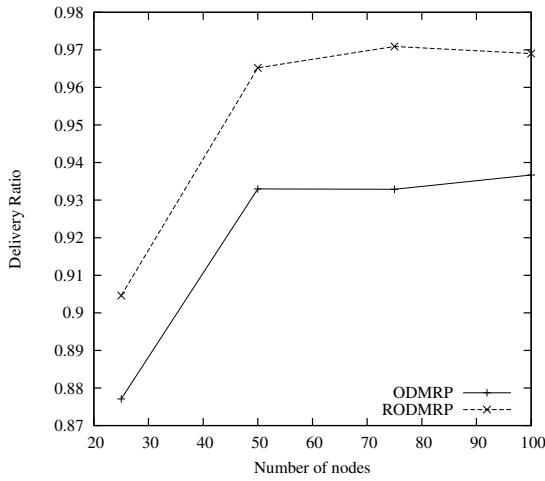
we simulated a single multicast group where a randomly selected multicast source and 25% of nodes participated in a multicast session. Our communication model was based on Carnegie Mellon University Monarch Research Group's multicast communication scenario generator [8]. The node movements were modeled using the random waypoint mobility scenario generator in ns-2. Each test was repeated with movement speeds of 10, 15, 20, 25, 30, 35 and 40 m/s, and an average pause time of 1 second. In addition, each test was repeated five times with different seeds. We believe that these configurations represent real wireless networks with high node mobility.

In addition, Perl scripts were used to gather packet statistics from simulation traces. We consider the following metrics for performance evaluation:

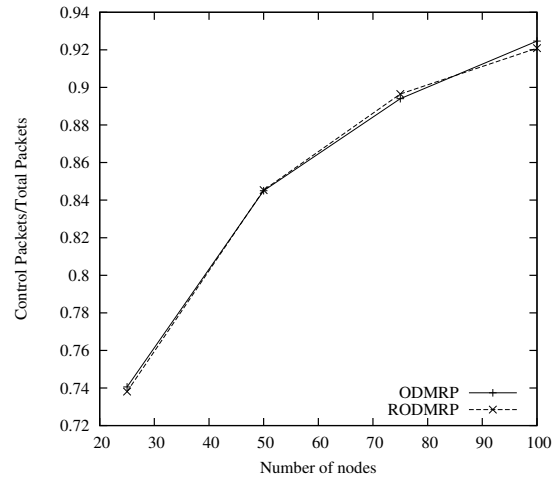
- (1) **Packet delivery ratio:** The ratio of packets received by receivers to the total number of packets sent by senders during the simulation.
- (2) **Control packet overhead:** The ratio of control packets against the total number of packets.
- (3) **Mobility and packet delivery ratio:** The average packet delivery ratio for different mobility scenarios against transmitted data packets.
- (4) **Packet forwarding overhead per node:** The ratio of total data packet forwardings against total data packet initiations.

3.2. Results

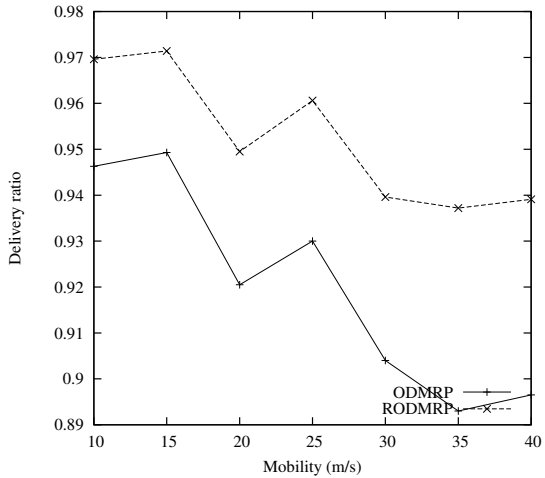
In Figure 5(a), we compare the packet delivery ratio of Resilient-ODMRP and ODMRP when the number of nodes change from 25 to 100. The horizontal axis denotes the



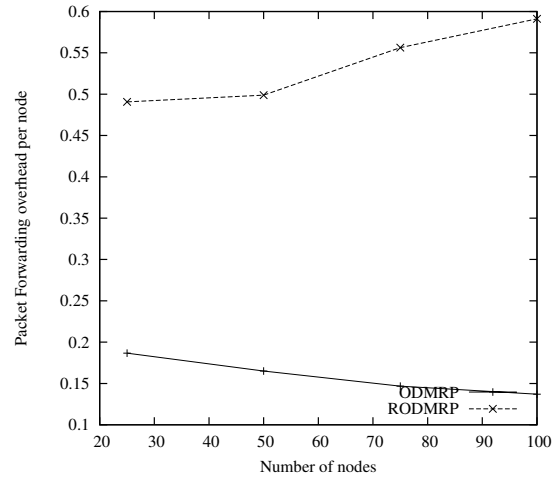
(a) Packet delivery ratio



(b) Control packet overhead



(c) Mobility and packet delivery



(d) Packet forwarding overhead per node

Figure 5. Performance metrics

number of nodes and the vertical axis indicates packet delivery ratio by percentage. In the experiment, Resilient-ODMRP delivered more packets than ODMRP in the range of 2% to 5% in case of failure. The figure also shows that the delivery ratio for both Resilient-ODMRP and ODMRP increases as the number of nodes increases up to 50. The more nodes participate, the more active non-forwarding nodes are available. As the number of nodes exceeds 50, the delivery ratio stabilizes since newly added active non-forwarding nodes provide redundant paths. Overall, these results show that the passive probabilistic rebroadcasting in

Resilient-ODMRP increases the packet delivery, especially when the network fails.

One of the concerns about the Resilient-ODMRP performance is the additional data overheads incurred by rebroadcasting. Figure 5(b) analyzes the control packet overheads (defined above) for different node sizes (from 25 to 100). The figure shows that Resilient-ODMRP introduces virtually the same amount of control packets (or a little additional data overhead). For example, when 80 nodes run the protocols, Resilient-ODMRP incurs less than 1% additional control data overhead to achieve nearly the 97% packet

delivery ratio. For most of the network sizes, Resilient-ODMRP requires control overhead less than 1% to attain packet delivery ratio of over 90%.

Resilient-ODMRP can reliably deliver more packets to destinations even when nodes are highly mobile. Figure 5(c) shows the average packet delivery ratios of Resilient-ODMRP in comparison to the average packet delivery ratios of ODMRP. When the speed of a mobile node is low (10-15 m/s), the delivery ratio of Resilient-ODMRP improves approximately 2.5% against the delivery ratio of ODMRP. As mobility becomes higher, the delivery ratio of Resilient-ODMRP shows more significant increase compared to ODMRP with a maximum of 4.5%. Both schemes show similar curves in the figure because the design of Resilient-ODMRP is based on ODMRP.

Figure 5(d) illustrates the packet forwarding overhead per node. As the number of nodes increases in ODMRP, packet forwarding overhead per node decreases since no additional forwarding nodes are needed. In contrast, the packet forwarding overhead of Resilient-ODMRP increases since Resilient-ODMRP requires additional forwarding nodes. In the worst case, the packet forwarding overhead of Resilient-ODMRP amounts to four times the corresponding ODMRP packet forwarding overhead.

4. Related Work

The flooding of Join Query packets in ODMRP [5] wastes network bandwidth, causes congestion, and drains node resources. To decrease the number of redundant packets, efficient flooding with passive clustering was proposed by Teak *et al.* [4, 14, 13]. In passive clustering, nodes maintain soft states by eavesdropping on packet transmissions that indicate successful rebroadcasting. While we adopt a similar concept of passive clustering, we focus more on fault-resilience, especially for real-time applications. In contrast, passive clustering addresses the flooding of Join Query packets and the formation of the initial forwarding path. Once the forwarding path is established passive clustering is still vulnerable to node failures, which we have addressed.

Enhanced ODMRP with Motion Adaptive Refresh (E-ODMRP) [9] enhances ODMRP with an adaptive route refresh scheme based on reports from receivers. In particular, the enhancement changes the route refreshing period dynamically to reduce the flooding overhead of Join Query packets. Thus, it improves the efficiency of the protocol. In addition, E-ODMRP proposes a local route recovery scheme based on expanded ring search. We believe that this latter enhancement is more relevant to our work. However, this approach adds additional control packets (i.e., Receiver Join) and requires additional processing at nodes, which may not be available in low end mobile devices. Further-

more, malicious or misbehaving nodes can drain resources of multicast receivers and forwarding nodes by initiating frequent expanded ring searches.

ODMRP with Multipoint Relay (ODMRP-MPR) [15] presented a multi-point relaying technique to overcome unidirectional links. The multipoint relaying technique selects a set of nodes as multipoint relays for rebroadcasting of Join Query packets. This is also an alternative approach to reduce the flooding overhead of ODMRP. This protocol adds an additional control packet called Hello packet to identify neighbor nodes. Each node periodically broadcasts a hello packet with a list of its current known neighbors. Upon receiving a Hello packet, a node can identify its two hop neighbors by processing the neighbor list. Although this approach effectively identifies bi-directional links and establishes a reliable forwarding tree, it does not guarantee the delivery of subsequent data transmissions.

Klos and Richard III [3] proposed a reliable group communication protocol based on ODMRP. The rationale behind this proposal was to store a subset of forwarded/received packets to improve the reliability of the protocol. The protocol assumes that even though a given node will be able to store a limited number of packets, the group as a whole will be able to store a substantial amount of packets. In addition, this research proposes a “Reliable Join Query” phase to the protocol, where each node receiving a Join Query packet adds a unique identifier (i.e., its IP address) to create a list of all forwarding nodes. This list enables receivers to identify the whole multicast group members, which can be queried later for missed/delayed packets. Although this technique improves the reliability, we believe it severely limits the scalability of the protocol. Furthermore, this approach may not be effective for real-time data delivery.

In Reliable Multicast Protocol for Wireless Mobile Multihop Ad Hoc Networks (ReMHoc), Sobeih *et al.* [10] have studied the reliability of ODMRP. ReMHoc is a receiver initiated NACK based technique to improve the reliability. In addition, ReMHoc is a distributed protocol, where receivers and forwarding nodes maintain packet caches to facilitate lost packet recovery. Upon detecting a lost packet a receiver or a forwarding node initiates packet recovery by sending a recovery request. Upon receiving a recovery request, nodes identify redundant recovery requests and suppress them. Thus, nodes avoid recovery request explosion.

Reliable Multicast of ODMRP (RODMRP) [11] is another proposal to improve the reliability of ODMRP using a “round robin window”. Each node maintains a send and received packet cache in addition to its neighbor list. Upon receiving a data packet, the receiver identifies any missing packets and indicate the missing packets in its acknowledgment to its parent. The neighboring nodes eavesdrop on these acknowledgments and check their received packet caches for lost packets indicated in the acknowledgment.

On detecting lost packets in its packet cache, neighboring nodes forward those packets to the receiver to improve the reliability of the protocol. Although this approach is similar to our protocol, we altogether avoid caching of received/sent packets at each node. In addition, our protocol neither incurs more processing for monitoring acknowledgments nor does it require additional control packets for acknowledgments.

5. Conclusion and Future Work

We have developed Resilient-ODMRP: a multicast protocol for wireless ad hoc networks. Resilient-ODMRP aims to be resilient to network or node failures and provides uninterrupted multicast service for live streaming data. For a receiver, nodes other than its direct parent redundantly broadcast data so that the receiver can receive data even when its parent node fails. In Resilient-ODMRP, a non-forwarding node determines redundant broadcasting intelligently and efficiently. Our simulation results indicate that our protocol mitigates the interruption of data delivery considerably while building an efficient multicast tree.

However, there is still room for improvement. In addition to observing Join Query and Join Table packets, active non-forwarding nodes can also observe passive forwardings of other active non-forwarding nodes. We believe this could result in a significant reduction in the number of passive packet forwardings without any major impact on the above performance characteristics. We are in the process of integrating the above observation to our routing protocol. In addition, we intend to incorporate enhancements for reliable multicasting.

We hope to conduct large-scale experiments in more realistic environments and to compare performance of Resilient-ODMRP with other multicast protocols. In such experiments, we intend to test Resilient-ODMRP by running an actual video streaming application.

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