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***Abstract*—Recent work in multicast routing for wireless mesh networks has focused on metrics that estimate link quality to maximize throughput. Nodes must collaborate in order to compute the path metric and forward data. The assumption that all nodes are honest and behave correctly during metric computation, propagation, and aggregation, as well as during data forwarding, leads to unexpected consequences in adversarial networks where compromised nodes act maliciously.**

In this work we identify novel attacks against high-throughput multicast protocols in wireless mesh networks. The attacks exploit the local estimation and global aggregation of the metric to allow attackers to attract a large amount of traffic. We show that these attacks are very effective against multicast protocols based on high-throughput metrics. We conclude that aggressive path selection is a double-edged sword: While it maximizes throughput, it also increases attack effectiveness in the absence of defense mechanisms. Our approach to defend against the identified attacks combines measurement-based detection and accusation-based reaction techniques. The solution also accommodates transient network variations and is resilient against attempts to exploit the defense mechanism itself. A detailed security analysis of our defense scheme establishes bounds on the impact of attacks. We demonstrate both the attacks and our defense using ODMRP, a representative multicast protocol for wireless mesh networks, and SPP, an adaptation of the well-known ETX unicast metric to the multicast setting.

I. Introduction

Wireless mesh networks (WMNs) emerged as a promising technology that offers low-cost high-bandwidth community wireless services. A WMN consists of a set of stationary wireless routers that form a multi-hop backbone, and a set of mobile clients that communicate via the wireless backbone. Numerous applications envisioned to be deployed in WMNs, such as webcast, distance learning, online games, video conferencing, and multimedia broadcasting, follow a pattern where one or more sources disseminate data to a group of changing receivers. These applications can benefit from the service provided by multicast routing protocols.

Multicast routing protocols deliver data from a source to multiple destinations organized in a multicast group. In the last few years, several protocols [2]–[8] were proposed to provide multicast services for multi-hop wireless networks. Initially, these protocols were proposed for mobile ad hoc networks (MANETs), focusing primarily on network connectivity and using the number of hops (or *hop count*) between the source and receivers as the route selection metric. However, many of the applications that benefit from multicast services also have high-throughput requirements, and hop count does not maximize throughput [9], [10] as it does not take into account link quality. Given the stationary nature and increased capabilities of nodes in mesh networks, recent protocols [11], [12] focus on maximizing path throughput by selecting paths based on metrics that capture the quality of the wireless links [10], [13]–[16]. We refer to such metrics as *link-quality* metrics or *high-throughput* metrics, and to protocols using such metrics as *high-throughput protocols*.

In a typical high-throughput multicast protocol, nodes periodically send probes to their neighbors to measure the quality of the links from their neighbors. During route discovery, a node estimates the cost of the path by combining its own measured metric of adjacent links with the route cost accumulated on the route discovery packet. The path with the best metric is then selected. High-throughput metrics protocols require the nodes to collaborate in order to derive the path metric, thus relying on the assumption that nodes are collaborative and behave correctly during metric computation and propagation. However, this assumption is difficult to guarantee in wireless networks that are vulnerable to attacks coming from both insiders and outsiders, due to the open and shared nature of the medium and the multi-hop characteristic of the communication. An aggressive path selection introduces new vulnerabilities and provides the attacker with an increased arsenal of attacks leading to unexpected consequences. For example, adversaries may manipulate the metrics in order to be selected on more paths and to draw more traffic, creating opportunities for attacks such as data dropping, mesh partitioning, or traffic analysis.

Previous work showed vulnerabilities of unicast routing protocols that use hop count as a metric. Several unicast routing protocols were proposed to cope with outsider [17]–[20] or insider attacks [19], [21]–[24]. Secure wireless multicast was less studied [25], [26] and focused primarily on tree-based protocols using hop count as a path selection metric.

In this work, we study the security implications of using high-throughput metrics. We focus on multicast in a wireless mesh network environment because it is a representative environment in which high-throughput metrics will be beneficial. Although the attacks we identify can also be conducted in unicast, the multicast setting makes them more effective and, at the same time, more difficult to defend against. We

*A preliminary version of this paper appears in the Proceedings of SECON 2008 [1]. This is the full version of the paper.

focus on mesh-based multicast protocols as they have the potential to be more resilient to attacks. We use ODMRP [6] as a representative protocol for wireless mesh networks and SPP [11], a metric based on the well-known ETX [10] unicast metric, as a high-throughput multicast metric. We selected SPP since it was shown to outperform all the other multicast metrics for ODMRP [11]. To the best of our knowledge, this is the first paper to examine vulnerabilities of high-throughput metrics in general, and in multicast protocols for wireless mesh networks in particular. We summarize our contributions:

• We identify attacks against multicast protocols that exploit the use of high-throughput metrics. The attacks consist of *local metric manipulation* (LMM) and *global metric manipulation* (GMM), and allow an attacker to attract significant traffic. We show that aggressive path selection is a double-edged sword: It leads to throughput maximization, but in the absence of protection mechanisms it also increases attack effectiveness. For example, in our simulations, the GMM attack requires only about a quarter of the number of attackers needed by a simple data dropping attack to create the same disruption in the multicast service. Since a small number of attackers can severely impede the protocol, an effective solution must identify and isolate all malicious nodes.

• We identify a dangerous effect of the attacks, referred to as *metric poisoning*, which causes many honest nodes to have incorrect metrics. Consequently, any response mechanism cannot rely on poisoned metrics for local recovery and must either use a fallback procedure not relying on the metric or refresh the metric before starting recovery.

• We propose a defense scheme that combines measurement -based detection and accusation-based reaction techniques. To accommodate transient network variations, we use temporary accusations that have a duration proportional to the disruption created by the accused node. To prevent attackers from exploiting the defense mechanism itself, we limit the number of accusations that can be generated by a node.

• We perform a detailed security analysis of our defense scheme and establish bounds on the impact of attacks. Extensive simulations with ODMRP and the SPP metric confirm our analysis and show that our strategy is very effective in defending against the attacks, while adding a low overhead.

II. High-Throughput Mesh-Based Multicast Routing

We consider a multi-hop wireless network where nodes participate in the data forwarding process for other nodes. We assume a mesh-based multicast routing protocol, which maintains a mesh connecting multicast sources and receivers. Path selection is performed based on a metric designed to maximize throughput. Below, we provide an overview of high-throughput metrics for multicast, then describe in details how such metrics are integrated with mesh-based multicast protocols.

A. High-Throughput Metrics

Traditionally, routing protocols have used hop count as a path selection metric. In static networks however, this metric was shown to achieve sub-optimal throughput because paths tend to include lossy wireless links [10], [27]. As a result, in recent years the focus has shifted toward high-throughput metrics that seek to maximize throughput by selecting paths based on the quality of wireless links (*e.g.*, ETX [10], PP [15], [27], RTT [14]). In such metrics, the quality of the links to/from a node's neighbors is measured by periodic probing. The metric for an entire path is obtained by aggregating the metrics reported by the nodes on the path.

Several high-throughput metrics for multicast were proposed in [11]. All of these metrics are adaptations of unicast metrics to the multicast setting by taking into account the fundamental differences between unicast and multicast communication. Transmissions in multicast are less reliable than in unicast for several reasons. In unicast, a packet is sent reliably using link-layer unicast transmission, which involves link-layer acknowledgments and possibly packet retransmissions; in multicast, a packet is sent unreliably using link-layer broadcast, which does not involve link layer acknowledgments or data retransmissions. Moreover, unicast transmissions are preceded by a RTS/CTS exchange; in multicast there is no RTS/CTS exchange, which increases collision probability and decreases transmission reliability. Many metrics for unicast routing minimize the medium access time, while metrics for multicast capture in different ways the packet delivery ratio.

All the high-throughput multicast metrics proposed in [11] showed improvement over the original path selection strategy. The SPP metric [11], an adaptation of the well-known ETX [10] unicast metric, was shown to outperform the other multicast metrics [11], [28]. Thus, in the remainder of the paper and in our experimental evaluation, we consider SPP for demonstrative purposes. Below, we first give an overview of ETX, then show how it was extended to SPP.

ETX Metric. The ETX metric [10] was proposed for unicast and estimates the expected number of transmissions needed to successfully deliver a unicast packet over a link, including retransmissions. Each node periodically broadcasts probe packets which include the number of probe packets received from each of its neighbors over a time interval. A pair of neighboring nodes, A and B, estimate the quality of the link $A \leftrightarrow B$ by using the formula $\text{ETX} = \frac{1}{d_f \times d_r}$, where d_f and d_r are the probabilities that a packet is sent successfully from A to B (forward direction) and from B to A (reverse direction), respectively. The value of ETX for a path of k links between a source S and a receiver R is $\text{ETX}_{S\to R} = \sum_{i=1}^{k} \text{ETX}_i$, where ETX_i is the ETX value of the i-th link on the path; $\text{ETX}_{S\to R}$ estimates the total number of transmissions by all nodes on the path to deliver a packet from a source to a receiver.

SPP Metric. ETX was adapted to the multicast setting by Roy *et al.* in the form of the SPP metric [11]. The value of SPP for a path of k links between a source S and a receiver R is $\text{SPP}_{S\to R} = \Pi_{i=1}^{k}\text{SPP}_i$, where the metric for each link i on the path is $\text{SPP}_i = d_f$ and d_f is defined as in ETX. The rationale for defining SPP as above is twofold:

- Unlike in unicast, where a successful transmission over a link depends on the quality of both directions of that link, in multicast only the quality of the forward direction matters because there are no link layer acknowledgments.

The quality of a link $A \rightarrow B$, as perceived by node B, is $\text{SPP}_i = d_f$ and represents the probability that B receives a packet successfully from A over the link $A \rightarrow B$. Node B obtains d_f by counting the probes received from A over a fixed time interval.

- Also unlike unicast, in which the individual link metrics are summed, in multicast they are multiplied. This reflects the fact that for SPP the probability of a packet being delivered over a path from a source to a receiver is the product of the probabilities that the packet is successfully delivered to each of the intermediate nodes on the path. If any of the intermediate nodes fails to receive the packet, this causes the transmission for the entire route to fail, since there are no retransmissions. $\text{SPP}_{S \rightarrow R}$ (in fact $1/\text{SPP}_{S \rightarrow R}$) estimates the expected number of transmissions needed at the source to successfully deliver a packet from a source to a receiver.

SPP takes values in the interval $[0, 1]$, with higher metric values being better. In particular, $\text{SPP} = 1$ denotes perfect reliability, while $\text{SPP} = 0$ denotes complete unreliability.

B. High-Throughput Mesh-Based Multicast Routing

Multicast protocols provide communication from sources to receivers organized in groups by establishing dissemination structures such as trees or meshes, dynamically updated as nodes join or leave the group. Tree-based multicast protocols (*e.g.*, MAODV [7]) build optimized data paths, but require more complex operations to create and maintain the multicast tree, and are less resilient to failures. Mesh-based multicast protocols (*e.g.*, ODMRP [6]) build more resilient data paths, but have higher overhead due to redundant retransmissions.

We focus on ODMRP as a representative mesh-based multicast protocol for wireless networks. Below we first give an overview of ODMRP, then describe how it can be enhanced with any link-quality metric. The protocol extension to use a high-throughput metric was first described by Roy *et al.* [11], [28]. We refer to the ODMRP protocol using a high-throughput metric as ODMRP-HT in order to distinguish it from the original ODMRP [6] protocol.

ODMRP overview. ODMRP is an on-demand multicast routing protocol for multi-hop wireless networks, which uses a mesh of nodes for each multicast group. Nodes are added to the mesh through a route selection and activation protocol. The source periodically recreates the mesh by flooding a JOIN QUERY message in the network in order to refresh the membership information and update the routes. We use the term *round* to denote the interval between two consecutive mesh creation events. JOIN QUERY messages are flooded using a *basic flood suppression* mechanism, in which nodes only process the first received copy of a flooded message.

When a receiver node gets a JOIN QUERY message, it activates the path from itself to the source by constructing and broadcasting a JOIN REPLY message that contains entries for each multicast group it wants to join; each entry has a *next hop* field filled with the corresponding upstream node. When an intermediate node receives a JOIN REPLY message, it knows whether it is on the path to the source or not, by checking if the next hop field of any of the entries in the message matches

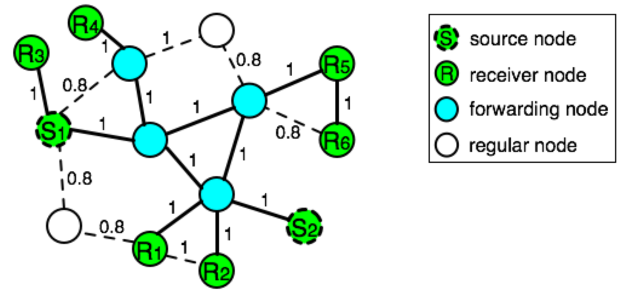


Fig. 1: An example of ODMRP-HT mesh creation for a multicast group with 2 sources (S_1, S_2) and 6 receivers ($R_1, \ldots, R_6$). The label on each link represents the value of the link's SPP metric.

its own identifier. If so, it makes itself a node part of the mesh (the FORWARDING GROUP) and creates and broadcasts a new JOIN REPLY built upon the matched entries.

Once the JOIN REPLY messages reach the source, the multicast receivers become connected to the source through a mesh of nodes (the FORWARDING GROUP) which ensures the delivery of multicast data. While a node is in the FORWARDING GROUP, it rebroadcasts any non-duplicate multicast data packets that it receives.

ODMRP takes a "soft state" approach in that nodes put a minimal effort to maintain the mesh. To leave the multicast group, receiver nodes are not required to explicitly send any message, instead they do not reply to JOIN QUERY messages. Also, a node's participation in the FORWARDING GROUP expires if its forwarding-node status is not updated.

ODMRP-HT. We now describe ODMRP-HT, a protocol that enhances ODMRP with high-throughput metrics. The main differences between ODMRP-HT and ODMRP are: (1) instead of selecting routes based on minimum delay (which results in choosing the fastest routes), ODMRP-HT selects routes based on a link-quality metric, and (2) ODMRP-HT uses a *weighted flood suppression* mechanism to flood JOIN QUERY messages instead of a basic flood suppression.

As required by the link-quality metric, each node measures the quality of the links from its neighbors to itself, based on the periodic probes sent by its neighbors. The JOIN QUERY message is flooded periodically by a source S and contains a *route cost* field which accumulates the metric for the route on which the message travelled. Upon receiving a JOIN QUERY, a node updates the route cost field by accumulating the metric of the last link travelled by the message. Because different paths may have different metrics, JOIN QUERY messages are flooded using a *weighted flood suppression* mechanism, in which a node processes flood duplicates for a fixed interval of time and rebroadcasts flood messages that advertise a better metric (indicated by the route cost field)[1]. Each node also records the node from which it received the JOIN QUERY with the best quality metric as its *upstream* node for the source S.

After waiting for a fixed interval of time, during which it may receive several JOIN QUERY packets that contain different route metrics, a multicast receiver records as its upstream for source S the neighbor that advertised the JOIN QUERY

[1]Several studies [26], [28] show that the overhead caused by rebroadcasting some of the flood packets is reasonable, validating the effectiveness of this weighted flood suppression strategy.

with the best metric. Just like in ODMRP, the receiver then constructs a JOIN REPLY packet, which will be forwarded towards the source on the optimal path as defined by the metric and will activate the nodes on this path as part of the FORWARDING GROUP. In Fig. 1 we give an example of how ODMRP-HT selects the mesh of nodes in the FORWARDING GROUP based on the SPP link-quality metric.

III. ATTACKS AGAINST HIGH-THROUGHPUT MULTICAST

We present several attacks against high-throughput multicast protocols. The attacks exploit vulnerabilities introduced by the use of high-throughput metrics. They require little resource from the attacker, but can cause severe damage to the performance of the multicast protocol. We first present the adversarial model, followed by the targets and the details of the attacks.

A. Adversarial Model

Malicious nodes may exhibit Byzantine behavior, either alone or in collusion with other malicious nodes. We refer to any arbitrary action by authenticated nodes deviating from protocol specification as Byzantine behavior, and to such an adversary as a Byzantine adversary. Examples of Byzantine behavior include: Dropping, injecting, modifying, replaying, or rushing packets, and creating wormholes.

This work considers attacks that target the network level and assumes that adversaries do not have control on lower layers such as the physical or MAC layers. We assume the physical layer uses jamming-resilient techniques such as direct sequence spread spectrum (DSSS) or frequency hopping spread spectrum (FHSS) (as in the case of 802.11). We do not consider the Sybil attack, which can be addressed using techniques such as [29], [30], complementary to our routing protocol. Also, preventing traffic analysis is not the goal of this work.

B. Attack Goals

We focus on attacks that aim to disrupt the multicast data delivery. The two main attack targets that allow the attacker to achieve this goal are the path establishment and data forwarding phases of the protocol.

Path establishment attacks prevent receivers from connecting to multicast sources. In ODMRP-HT, since each receiver only activates a single path to each source, an attacker lying on that path can prevent path establishment by dropping the JOIN REPLY message. *Data forwarding attacks* disrupt the routing service by dropping data packets. In both cases, the attack effectiveness is directly related to the attackers' ability to control route selection and to be selected on routes. Traditionally, such ability can be achieved via wireless-specific attacks such as rushing and wormholes. The use of high-throughput metrics gives attackers additional opportunities to be included in the mesh by manipulating the routing metric. Rushing and wormholes are general attacks against wireless routing protocols that have been studied extensively [31]–[34]. Thus, below we focus on metric manipulation attacks, which require only little effort to execute, yet are extremely detrimental to the protocol performance.

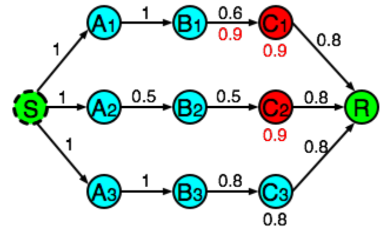


Fig. 2: Metric manipulation attack during the propagation of the flood packet from the source S to receiver R. A label above a link is the link's real SPP metric; a label below a link is the link's metric falsely claimed by a node executing a LMM attack; a label below a node is the accumulated route metric advertised by the node.

C. Metric Manipulation Attacks

As discussed in Section II, multicast protocols using high-throughput metrics prefer paths to the source that are perceived as having high-quality, while trying to avoid low-quality paths. Thus, a good strategy for an attacker to increase its chances of being selected in the FORWARDING GROUP is to advertise artificially good metrics for routes to the source.

The use of high-throughput metrics requires each node to collect *local* information about its adjacent links based on periodic probes from its neighbors. This local information is accumulated in JOIN QUERY packets and propagated in the network, allowing nodes to obtain *global* information about the quality of the routes from the source. Adversaries can execute two types of metric manipulation attacks: *local metric manipulation* (LMM) and *global metric manipulation* (GMM). These attacks are Byzantine in nature, as they are conducted by nodes that have the credentials to participate in the routing protocol, but are under adversarial control.

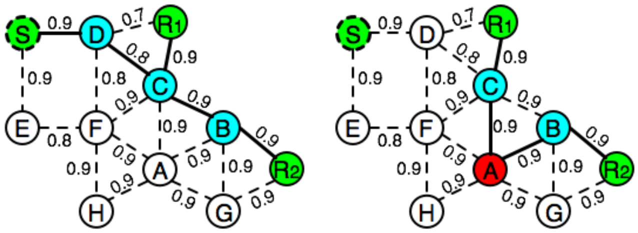
Local Metric Manipulation (LMM) Attacks. An adversarial node artificially increases the quality of its adjacent links, distorting the neighbors' perception about these links. The falsely advertised "high-quality" links will be preferred and malicious nodes have better chances to be included on routes.

A node can claim a false value for the quality of the links towards itself. In Fig. 2 a malicious node C_1 claims that $\text{SPP}_{B_1 \to C_1} = 0.9$ instead of the correct metric of 0.6. Thus, C_1 accumulates a false local metric for the link $B_1 \to C_1$ and advertises to R the metric $\text{SPP}_{S \to C_1} = 0.9$ instead of the correct metric $\text{SPP}_{S \to C_1} = 0.6$. The route S-A_1-B_1-C_1-R will be chosen over the correct route S-A_3-B_3-C_3-R.

Global Metric Manipulation (GMM) Attacks. In a GMM attack, a malicious node arbitrarily changes the value of the route metric accumulated in the flood packet, before rebroadcasting this packet. A GMM attack allows a node to manipulate not only its own contribution to the path metric, but also the contributions of previous nodes that were accumulated in the path metric. For example, in Fig. 2 attacker C_2 should advertise a route metric of 0.25, but instead advertises a route metric of 0.9 to node R. This causes the route S-A_2-B_2-C_2-R to be selected over the correct route S-A_3-B_3-C_3-R.

D. Impact of Metric Manipulation Attacks on Routing

The attacks we described allow attackers to attract and control traffic. In addition, the epidemic nature of metric



(a) benign case (b) attack case

Fig. 3: Metric manipulation attack in a network with one source (S), two receivers (R_1, R_2) and one attacker (A). The label on each link represents the value of the link's SPP metric.

derivation causes an epidemic attack propagation, which "poisons" the metrics of many nodes in the network. We exemplify both of these effects with the scenario in Fig. 3.

When no attackers are present (Fig. 3(a)), nodes B, C and D are activated as part of the FORWARDING GROUP. Consider that node A executes a metric manipulation attack (Fig. 3(b)): Upon receiving the JOIN QUERY, node A changes the metric and advertises a perfect metric with value 1. Consequently, both receivers R_1 and R_2 are "attracted" to it and only nodes B and C will be selected as part of the FORWARDING GROUP. The net effect is that both R_1 and R_2 are denied service since they do not have a path to the source.

The false metric advertisement by node A also poisons the metrics of many nodes in the network. For example, node C derives an incorrect metric of 0.9, and then propagates it to its neighbors, causing them to derive an incorrect metric as well. Besides distorting path establishment for data delivery, a severe side effect of the attack is that it introduces a significant challenge for attack recovery. For example, even if A's neighbors are able to detect A is an attacker, they cannot rely on the metric to find a new route to the source. Indeed, if node C detects that A is malicious, it can try to activate nodes F or B, which advertised the second best metric; however, routes through either F or B lead back to the attacker. The problem stems from the fact that the metric cannot be relied upon and nodes do not know the right direction to "break free" from the attraction of A. Hence, we make the observation that defense mechanisms cannot rely on the existing metric for recovery and have to either resort to a fallback procedure not using the metric or refresh the metric before starting recovery.

IV. SECURE HIGH-THROUGHPUT MULTICAST ROUTING

In this section, we present our secure multicast routing protocol (S-ODMRP) that accommodates high-throughput metrics.

A. *Authentication Framework*

We assume that each user authorized to be part of the mesh network has a pair of public and private keys and a *client certificate* that binds its public key to a unique user identifier. This defends against external attacks from users that are not part of the network. We assume source data is authenticated, so that receivers can distinguish authentic data from spurious data. Efficient source data authentication can be achieved with existing schemes such as TESLA [35]. Finally, we assume the existence of a secure neighbor discovery scheme [36].

B. S-ODMRP *Overview*

Our approach relies on the observation that regardless of the attack strategy, attackers do not affect the multicast protocol unless they cause a drop in the packet delivery ratio (PDR). We adopt a reactive approach in which attacker nodes are detected through a *measurement-based detection* protocol component, and then isolated through an *accusation-based reaction* protocol component. We next describe these two components.

Measurement-based attack detection. Whether by packet dropping alone or by combining it with with metric manipulation to attract routes, the effect of an attack is that data is not delivered at a rate consistent with the advertised path quality. We propose a generic attack detection strategy that relies on the ability of honest nodes to detect the discrepancy between the *expected* PDR (ePDR) and the *perceived* PDR (pPDR). A node can estimate the ePDR of a route from the value of the metric for that route[2]; the node can determine the pPDR for a route by measuring the rate at which it receives data packets from its upstream on that route[3].

Both FORWARDING GROUP nodes and receiver nodes monitor the pPDR of their upstream node. If ePDR − pPDR for a route becomes larger than a detection threshold δ, then nodes suspect that the route is under attack because the route failed to deliver data at a rate consistent with its claimed quality[4].

Accusation-based attack reaction. We use a *controlled-accusation* mechanism in which a node, on detecting malicious behavior, temporarily accuses the suspected node by flooding in the network an ACCUSATION message containing its own identity (the accuser node) and the identity of the accused node, as well as the duration of the accusation. As long as the accusation is valid, metrics advertised by an accused node will be ignored and the node will not be selected as part of the FORWARDING GROUP. This strategy also successfully handles attacks against path establishment. From the downstream node point of view, the dropping of a JOIN REPLY message causes exactly the same effect as the attacker dropping all data packets, thus the downstream nodes will react and accuse the attacker.

To prevent the abuse of the accusation mechanism by attackers, a node is not allowed to issue a new accusation before its previously issued accusation expires. Accused nodes can still act as receivers even though they are excluded from the FORWARDING GROUP. We use a temporary accusation strategy to cope with transient network variations: The accusation duration is calculated proportional to the observed discrepancy between ePDR and pPDR, so that accusations caused by metric inflation and malicious data dropping last longer, while accusations caused by transient network variations last shorter.

Finally, to address the metric poisoning effect caused by metric manipulation attacks, the metric in the entire network is refreshed shortly after attack detection. In S-ODMRP,

[2]For the SPP metric, a route's ePDR is equal to the route's metric.

[3]Source data authentication allows nodes to distinguish authentic packets from spurious ones and only authentic packets are counted towards pPDR.

[4]Note that the rate inconsistency may also be caused by natural link quality variations. We do not differentiate between losses caused by adversarial behavior and natural link variations because lossy links must also be avoided in order to maintain a good performance level.

Sign(m): sign message m using this node's private key
Verify(n_id, sig): verify the signature sig using node n_id's public key and exit the procedure if the verification fails
Start_timer(timer, t): start timer timer with timeout t
Refresh_timer(timer, t): if timer is not active, then call Start_timer(timer, t); otherwise, set timeout of timer to t
Broadcast(m): broadcast message m one hop
Flood(m): flood message m in the entire network
Send_message(m, n_id): reliably send message m to neighbor n_id
Link_metric(n_id): return the measured link metric to neighbor n_id
Get_best_metric(query_set): return the best metric of all queries in the set query_set, regardless of accusation status
Get_neighbor_best_metric(query_set): return the neighbor that has the best metric in the set query_set, regardless of accusation status

Fig. 4: Basic procedures used in the S-ODMRP protocol description

the metric refreshment is achieved automatically through the periodic JOIN QUERY messages.

C. S-ODMRP *Detailed Description*

To describe S-ODMRP in detail, we use the list of procedures described in Fig. 4. For simplicity, we limit the description to one multicast group and one multicast source. However, the scheme can easily be extended to multicast groups with multiple sources.

1) Mesh Creation: S-ODMRP mesh creation follows the same pattern of ODMRP-HT presented in Sec. II-B. As described in Fig. 5, the source node S periodically broadcasts to the entire network a JOIN QUERY message in order to refresh the membership information and to update the routes (lines 1-5). The JOIN QUERY message is signed by S and is propagated using a weighted flood suppression mechanism. Nodes only process JOIN QUERY messages that have valid signatures (line 8) and that are received from nodes not currently accused (indicated by an ACCUSATION LIST maintained by each node) (lines 18-19). Nodes record the upstream node and the metric corresponding to the route with the best metric as best_upstream and best_metric (line 23).

The JOIN REPLY messages are then sent from receivers back to S along optimal paths as defined by the high-throughput metric, leading to the creation of the FORWARDING GROUP (the multicast mesh) (lines 28-33). After sending a JOIN REPLY to its best_upstream, a node starts to monitor the PDR from its best_upstream in order to measure its perceived PDR (pPDR) (line 38).

To address attackers that strategically accuse certain nodes in order to disconnect the network, we make one exception from the rule that only non-accused nodes are included in the FORWARDING GROUP: If the best metric is advertised by an accused neighbor, a node also activates this neighbor (by sending a JOIN REPLY) in addition to the best non-accused neighbor (line 39-41). This ensures that good paths are still utilized, even if honest nodes on these paths are falsely accused. In Sec. VI-E, we show that this strategy only adds a very low overhead.

2) Attack Detection: As described in the protocol overview, we detect attacks using a measurement-based mechanism, where each FORWARDING GROUP and receiver node continuously monitors the discrepancy between ePDR and pPDR and flags an attack if ePDR $-$ pPDR $> \delta$.

```
Executed at the source node to initiate a new JOIN QUERY message:
 1: create a JOIN QUERY message q
 2: q.source = source_id; q.from = source_id
 3: q.metric = 0; q.seq = join_seq
 4: join_seq + +
 5: Sign(q); Broadcast(q)
Executed at a node upon receipt of a JOIN QUERY message q:
 6: if (latest_received_join_seq > q.seq) then
 7:     return // ignore old queries
 8: Verify(q.from, q.sig)
 9: get_new_query = FALSE
10: if (latest_received_join_seq < q.seq) then
11:     // get a new (non-duplicate) query
12:     latest_received_join_seq = q.seq
13:     best_metric = 0
14:     best_upstream = INVALID_NODE
15:     fastest_upstream = q.from // for fallback recovery
16:     get_new_query = TRUE
17: received_queries.insert(q) // store the query
18: if (accusation_list.contains_accused_node(q.from)) then
19:     q.metric = 0
20: else
21:     q.metric = q.metric × Link_metric(q.from)
22: if (get_new_query OR q.metric > best_metric) then
23:     best_upstream = q.from; best_metric = q.metric;
24:     q.from = node_id
25:     Sign(q); Broadcast(q)
26: if (get_new_query AND is_receiver) then
27:     Start_timer(reply_timer, REPLY_TIMEOUT)
Executed at a node upon timeout of reply_timer:
28: Send_reply()
Executed at a node upon receipt of a JOIN REPLY message r:
29: if (latest_received_reply_seq < r.seq) then
30:     latest_received_reply_seq = r.seq
31:     Refresh_timer(FG_timer, FG_TIMEOUT)
32:     if (not is_receiver) then
33:         Send_reply()
Send_reply()
34: create a JOIN REPLY message r
35: r.seq = latest_received_join_seq
36: Send_message(r, best_upstream)
37: if (best_metric > 0) then
38:     start monitoring the PDR of best_upstream
39: if (Get_best_metric(received_queries) > best_metric) then
40:     // Activate the accused neighbor with best metric
41:     Send_message(r, Get_neighbor_best_metric(received_queries))
42: received_queries.clear() // purge stored queries
```

Fig. 5: Mesh creation algorithm

The most straightforward method for estimating pPDR is to use a sliding window method, with pPDR calculated as pPDR $= r/w$, where r is the number of packets received in the window and w is the number of packets sent by the source (derived from packet sequence numbers) in the window. Albeit being simple, this method is sensitive to bursty packet loss. In addition, this approach requires a node to wait until at least w packets are sent in a round before being able to make any decision. Therefore, setting w too large causes delay in making decisions, whereas setting w too small results in inaccurate pPDR estimation and hence more frequent false positives. In general, it is difficult to determine the optimal value for w, as it depends on the network conditions and the specific position of a node. To avoid these shortcomings, we propose an efficient statistical-based estimation method for pPDR that naturally adapts to the network environment of each node.

The main idea is to use the Wilson estimate [37] to determine a confidence interval for pPDR, instead of trying to obtain a single estimated value. Let m be the number of packets received by a node and n be the number of packets sent by the source in the same time period, which can be derived from packet sequence numbers. The Wilson estimate requires that $n \geq 5$ [37], so whenever $n \geq 5$, we can obtain a confidence interval for pPDR as $(\hat{p} - e, \hat{p} + e)$, where

$$\hat{p} = \frac{m+2}{n+4} \text{ and } e = z\sqrt{\frac{\hat{p}(1-\hat{p})}{n+4}}.$$

We assign $z = 1.96$ to obtain the commonly used confidence level of 95%. An attack is detected if the upper bound of the confidence interval for pPDR is less than the estimated PDR even after accounting for normal network variations, *i.e.*, if:

$$\hat{p} + e < \text{ePDR} - \delta,$$

where δ is the estimated PDR discrepancy under normal network conditions. In this method, the exact number of packets required for attack detection naturally adapts to the path quality and the severity of the attack. In addition, there is a precise level of confidence on the accuracy of our estimation. This method has the advantage that it applies for both constant rate and variable rate data sources.

Addressing Silent Periods. If a node fails to receive any data packets in a round, the above method will be not able to compute the confidence interval of pPDR for its upstream node, since the value of n is derived from sequence numbers contained in received packets. We address this issue by including the current data sequence number in JOIN QUERY packets, which are periodically flooded in the network. Thus, unless a node does not have any adversarial-free path to the source, it can always obtain the current data sequence number and compute the pPDR confidence interval to detect attacks.

3) Attack Reaction: To isolate attackers, our protocol uses a controlled-accusation mechanism which consists of three components, staggered reaction timeout, accusation message propagation and handling, and recovery message propagation and handling.

As described in Fig. 6, when a node detects attack behavior, it starts a React_Timer with timeout value $\beta(1-\text{ePDR})$, where β is a system parameter that determines the maximum timeout for reaction timer (line 1). Since ePDR decreases monotonically along a multicast data path, nodes farther away from the source will have a larger timeout value for the React_Timer. This staggered timeout technique ensures nodes immediately below the attacker will take action first, before any of their downstream nodes mistakenly accuse their upstream node. When the React_Timer of a node N expires, N accuses its best_upstream node and cancels the React_Timer at its downstream nodes with the following actions:

- create, sign, and flood an ACCUSATION message in the network, which contains N's identity (the accuser node) and the identity of N's best_upstream node (the accused node). The message also contains a value accusation_time $= \alpha(\text{ePDR}-\text{pPDR})$, indicating the amount of time the accusation lasts (lines 8-13). α is a tunable system parameter that determines the severity of attack punishment.
- create, sign, and send to its downstream nodes a RECOVERY message, which contains the ACCUSATION message (lines 15-19). This message serves the role of canceling the React_Timer of nodes in N's subtree and activating the fallback procedure at the receivers in N's subtree (see Sec. IV-C4).

```
On detecting a discrepancy between ePDR and pPDR:
 1: Start_timer(React_Timer, β(1 − ePDR)
Executed at node on timeout of React_Timer:
 2: if (is_receiver) then
 3:     create salvage message ss // fallback
 4:     Send_message(ss, fastest_upstream)
 5: if (accusation_list.contains_accuser_node(node_id)) then
 6:     return // each node can only accuse once
 7: // create and flood accusation message
 8: create accusation message acc
 9: acc.accused = best_upstream
10: acc.accuser = node_id
11: acc.accusation_time = α(ePDR − pPDR)
12: accusation_list.add(acc)
13: Sign(acc); Broadcast(acc)
14: // send recovery message to the subtree
15: create recovery message rr
16: rr.accusation = acc
17: Sign(rr)
18: for each downstream node d do
19:     Send_message(rr, d)
Executed at a node on receipt of an accusation message acc:
20: if (accusation_list.contains_accuser_node(acc.accuser)) then
21:     return // only allow one accusation from a node at a time
22: Verify(acc.accuser, acc.sig)
23: accusation_list.add(acc)
24: Broadcast(acc)
Executed at a node on receipt of a recovery message rr:
25: if (handled_recovery_messages.contains(rr)) then
26:     return // ignore duplicate recovery
27: if (accusation_list.contains_accuser_node(rr.acc.accuser)
    OR rr.acc.accusation_time < α(ePDR − pPDR)) then
28:     return // ignore recovery mesage if the accuser has an unexpired
        accusation or if the accused time is inconsistent
29: Verify(rr)
30: handled_recovery_messages.insert(rr)
31: if (React_Timer is active) then
32:     cancel React_Timer
33: for each downstream node d do
34:     Send_message(rr, d)
35: if (is_receiver) then
36:     create salvage message ss // fallback
37:     Send_message(ss, fastest_upstream)
Executed at a node on receipt of a salvage message ss:
38: Refresh_timer(FG_timer, FG_TIMEOUT)
39: Send_message(ss, fastest_upstream)
```

Fig. 6: Attack reaction algorithm

Upon receipt of an ACCUSATION message, a node checks if it does not have an unexpired accusation from the same accuser node and verifies the signature on the message. This enforces our limited accusation mechanism, which allows nodes to only have one active accusation at a time. If both checks pass, the node adds a corresponding entry to its ACCUSATION LIST (lines 20-23). Accusations are removed from the ACCUSATION LIST after the accusation_time has elapsed.

Upon receipt of a RECOVERY message rr from its best_upstream node, a FORWARDING GROUP node N checks if it does not have an unexpired accusation from the same accuser node and verifies the signature on the message. In addition, the node also checks that the accusation_time in the message is at least as much as its own observed discrepancy (the ePDR$-$pPDR value) (lines 27-28). This prevents attackers who cause a large PDR drop from bypassing our defense by accusing its upstream node only for a short amount of time. If all checks pass, it cancels its pending React_Timer, forwards rr to its downstream nodes (lines 31-34), and if it is a receiver, activates the recovery procedure (lines 35-37) (see below).

4) Fallback Recovery: The accusation mechanism ensures that when the metric is refreshed in the round after the attack detection, the accused nodes are isolated. However, during the round when an attack is detected, the receiver nodes in the subtree of the attacker need to find alternative routes to "salvage" data for the rest of the round. As shown in Sec. III-C, a side effect of metric manipulation attacks is *metric poisoning*, which prevents recovery by relying on the metrics in the current round. We address this inability by falling back to the fastest route for routing during the remainder of the round[5]. Specifically, during the JOIN QUERY flooding, besides recording the best_upstream node, each node also records the upstream for the fastest route as fastest_upstream (Fig. 5, line 15). To recover from an attack, a receiver sends a special JOIN REPLY message (a salvage message) to its fastest_upstream node (Fig. 6, lines 2-4 and 35-37). Each node on the fastest route forwards the special JOIN REPLY message to their fastest_upstream node and becomes part of the FORWARDING GROUP (Fig. 6, lines 38-39).

D. Impact of False Positives

Even though our defense scheme takes into account normal network variations with the parameter δ, it is still possible that some honest nodes are mistakenly accused. We argue that such false positive accusations have little impact on the performance of the system for two main reasons. First, under most cases honest nodes cause only a small discrepancy on the PDR, thus even if mistakenly accused, their accusation duration is relatively short. Second, for most receivers there are redundant paths to the source. Thus, even if some honest nodes are wrongly accused, affected receiver nodes can obtain a similar performance by using nearby alternate routes.

E. Practical Implementation Issues

1) Parameter Selection: S-ODMRP has three tunable parameters, the attack detection threshold δ, the coefficient for accusation duration α, and the coefficient for React_Timer β.

The selection of δ trades off tolerance to normal network variations with sensitivity of the scheme to attacks. A larger value for δ reduces false positives of accusing honest nodes, however, it also allows attackers to inflict more impact without being detected. An optimal value for δ is the estimated normal network variation, *i.e.* the sum of the PDR discrepancy under normal network conditions and the error in estimating ePDR from the advertised metric. Our experiments show that a typical value for δ is 20%.

The value for α trades off the effectiveness of the scheme in isolating attacker nodes and the severity of isolating honest nodes due to false positives. In a stable network where the number of false positives is small, or in a dense network where the impact of false positives is small due to path redundancy, it is advisable to have a large value for α in order to reduce the impact of attacks. In Sec. V-A, we give lower bounds for α in order for the scheme to bound the impact of attacks effectively.

The value for β trades off the attack reaction delay and the effectiveness of the staggered reaction timeout technique for preventing honest nodes from mistakenly accusing each other. A smaller β results in quicker attack reaction, however, it also results in a smaller difference in the reaction timeout value for consecutive nodes on a path, increasing the chance of honest nodes being mistakenly accused. In our experiments, we find $\beta = 20ms$ achieves a good balance between these two effects.

2) Ensuring Staggered Timeouts for Reaction Timers: To avoid honest nodes mistakenly accusing each other, it is critical that we ensure the React_Timer at a downstream node does not expire before the node receives a recovery message from its upstream node. Denote the link latency as t, and the estimated PDR of two consecutive nodes on a path as ePDR_1 and ePDR_2. The React_Timer timeout value for the two nodes is $TO_1 = \beta(1-\text{ePDR}_1)$ and $TO_2 = \beta(1-\text{ePDR}_2)$. We need to ensure $TO_2 - TO_1 > t$, that is,

$$\beta(1 - \text{ePDR}_2) - \beta(1 - \text{ePDR}_1) > t,$$

hence $\text{ePDR}_2 < \text{ePDR}_1 - t/\beta$. Therefore, to ensure staggered reaction timeout, we require a node artificially decreases its advertised metric if necessary so that its ePDR is at least t/β smaller than the ePDR of its upstream node.

F. Generalization of S-ODMRP

Although we have described our defense scheme for high throughput multicast protocols using the SPP metric, our defense scheme can be generalized to other high throughput metrics and other high performance multicast protocols.

1) Application to Other High Throughput Metrics: S-ODMRP relies on the ability to derive an estimated PDR (ePDR) from the metric. For the SPP metric, the derivation is straightforward: The estimated PDR equals the SPP metric value. What about other high throughput metrics?

We first observe that the goal of a high throughput multicast protocol is to achieve a high PDR, hence a good metric should reflect the PDR to some extent. For metrics that have a clear connection with PDR, one approach is to define a mapping function that translates metrics to PDR. For example, if the ETX metric is used, one may define an estimation function Φ that maps an ETX value to an estimated PDR, with $\Phi(1) = 1, \Phi(1.5) = 0.6$, etc. The mapping function does not have to be accurate, since inaccuracies in the PDR estimation can be masked as normal network variations, which is accounted for in the protocol with parameter δ.

For metrics that do not easily admit such a mapping function, an alternative approach is to append the PDR value to the metric itself, so the metric is a tuple $\langle metric, PDR\rangle$. The data delivery path is determined based on the value of $metric$, whereas the PDR value determines the lower bound of PDR a node is willing to accept and is used by our technique

[5]The strategy is not attack-proof, as the fastest route may include malicious nodes. However, since the route is only used for the remainder of the round, we prefer to use an efficient procedure than to find attacker-free paths, which is itself a challenging task and requires expensive protocols [24]. We further discuss in Sec. V-B the impact of attacks against the recovery phase.

to prevent attacks. The data delivery path selection algorithm should be enhanced to also consider the consistency between PDR and $metric$ in the received metric tuple, such that nodes advertising low PDR but high $metric$ are avoided.

2) Application to Other Multicast Protocols: Our defense strategy to rely on measurement-based detection and accusation-based reaction generalizes to a class of high performance multicast protocols that exhibit the following characteristics:

- Path selection is based on the greedy approach of selecting path with best metric (*e.g.*, highest SPP, lowest latency).
- An estimation of the target performance metric (*e.g.*, PDR, latency) can be derived from the path metric.
- There exists an efficient metric refreshment protocol that allows nodes to obtain correct metrics for attack recovery. Such metric refreshment can be easily achieved by flooding of a new metric establishment message.

As an example, consider a multicast protocol that aims to achieve low latency communication. Then, a good path metric is the latency of a node to the source, which can be derived and propagated in the same fashion as the SPP metric. Each node greedily selects the neighbor with the minimum latency metric to be on the path. In such a protocol, an attacker can disrupt the protocol by advertising a low latency metric to attract many nodes, but intentionally delays packets. We can apply our defense techniques in a straightforward way to address these attacks: Each node monitors the discrepancy between advertised and actual packet latency, and accuses and isolates nodes with abnormally large discrepancies.

V. S-ODMRP Security Analysis

In this section, we analyze the security of the S-ODMRP protocol and establish bounds on the attack impact and on protocol resilience to various types of attacks.

A. Attack Impact

We upper bound the attack impact on the throughput of S-ODMRP. We first give a precise definition of the attack impact. We then present two theorems that upper bound the attack impact and discuss their practical implications.

Let N denote the network of interest with k attacker nodes. We define N' as the exact same network as N, except that all the attacker nodes are removed. For a given non-attacker receiver node R, let $r_R(t)$ and $r'_R(t)$ be the perceived PDR of R at time t in network N and N', respectively. We define I_R, the *attack impact* on a node R, as

$$I_R = \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} (r'_R(t) - r_R(t))dt,$$

where t_0 and t_1 are the start and end times for the interval of interest. Intuitively, the attack impact is the average PDR degradation caused by the presence of attackers over time compared to a network with no attackers. Alternatively, the attack impact captures the discrepancy between a given defense scheme and a hypothetical perfect defense scheme where all the attackers nodes are perfectly isolated.

Recall that δ denotes the attack detection threshold and α denotes the accusation duration coefficient. Also, recall that a *round* is an interval between two consecutive mesh creation events. We use λ to denote the time duration of a round. The following two theorems bound the attack impact of metric manipulation attacks on any non-attacker receiver node in the presence of our defense mechanisms.

Theorem 1. *In a network with k metric manipulation attackers, for any $\alpha \geq \frac{k\lambda}{\delta^2}$, the attack impact on any non-attacker receiver node in* S-ODMRP *is upper bounded by δ during any time interval of duration $T \gg \alpha$.*

Theorem 2. *In a network with k metric manipulation attackers, if* S-ODMRP *uses a fallback procedure that restores the PDR to the same level as in a benign network, then for any $\alpha \geq \frac{k\lambda}{\delta}$, the attack impact on any non-attacker receiver node is upper bounded by δ during any time interval of duration $T \gg \alpha$.*

Implications of Theorems 1 and 2. According to Theorems 1 and 2, for large enough α, the impact of metric manipulation attacks is bounded by the attack detection threshold δ. For example, with $\delta = 20\%$, round duration of $\lambda = 3$ seconds, and a total of 10 attackers, according to Theorem 1, we can set $\alpha \geq 750$ seconds to ensure the attack impact on any non-attacker receiver node is bounded by δ. In practice, it is rare that attacker nodes can coordinate perfectly to achieve the maximum impact on all receiver nodes. Thus, even if we set α smaller than the required minimum value, the attack impact is likely to be bounded by δ for most receiver nodes.

Assuming the fallback procedure is able to restore the PDR to a normal level, then Theorem 2 tells us that we only need to set $\alpha \geq 150$ seconds. Our experiments reveal that, under most cases, the fallback procedure is indeed able to restore the PDR to a level close to the PDR in a benign network. Therefore, it is sufficient to set α slightly larger than the value derived from Theorem 2 (150 in the example above) to bound the attack impact below the estimated normal network variations.

Theorems 1 and 2 also reveal that one of the most effective attack strategies is to decrease the PDR by a fraction just below δ. Using this strategy, the attack remains undetected and achieves the upper bound for the attack impact. We note that the impact caused by such attackers is unavoidable for any observation-based detection scheme that also takes into account normal network variations.

Proofs. To prove these two theorems, we first introduce some additional notation and two lemmas. We label the start of the time duration of interest of T as t_0. Without loss of generality, let time t_i and t_{i+1} be the start and end times of round i, for $i \geq 0$. Since a node only estimates its metric at the beginning of a round, let $m_B(i)$ and $m'_B(i)$ be the estimated PDR from metric for node B in round i in network N and in N', respectively. We use $\bar{r}_B(i)$ and $\Delta_B(i)$ to denote the average perceived PDR and average PDR discrepancy of node B in round i in network N, respectively, that is $\bar{r}_B(i) = \frac{1}{\lambda} \int_{t_i}^{t_{i+1}} r_B(t)dt$ and $\Delta_B(i) = m_B(i) - \bar{r}_B(i)$. Similarly, we define $\bar{r}'_B(i)$ and $\Delta'_B(i)$ for network N'. With a slight abuse of notation, we denote the attack impact on node B in round

i as $I_B(i)$, that is, $I_B(i) = I_B(t_i, t_{i+1})$. It is easy to see that $I_B(i) = \bar{r}'_B(i) - \bar{r}_B(i)$.

For simplicity, we assume that the network is stable and the PDR estimation from the metric is accurate. Hence, for benign network N', we have $m'_B(i)$ and $\bar{r}'_B(i)$ are constant and $m'_B(i) = \bar{r}'_B(i)$ for all i. Thus, without ambiguity, we use $\bar{r}'_B$ to denote both the estimated and perceived PDR at node B in network N'. Thus, we have $I_B(i) = \bar{r}'_B - \bar{r}_B(i)$.

We also discount any physical layer effects (*e.g.*, interference), which means that $m_U(i) \geq r'_U$ for any node U, since additional attacker nodes cannot decrease the metric derived by honest nodes.

Lemma 1. *For any round i and any non-attacker node B, we have $I_B(i) \leq \Delta_B(i)$.*

Proof: In order for an attack to have any impact on R, it must be the case that $m_B(i) \geq r'_B$, since otherwise attacker nodes will not be selected on the path. Therefore,

$$I_B(i) = r'_B - \bar{r}_B(i) \leq m_B(i) - \bar{r}_B(i) = \Delta_B(i).$$

■

Intuitively, Lemma 1 says that the attack impact of any node is always upper bounded by its observed PDR discrepancy.

Lemma 2. *For any consecutive sequence of time intervals $(t_0, t_1), (t_1, t_2), \cdots, (t_{k-1}, t_k)$ and a non-attacker node B, if $I_B(t_i, t_{i+1}) \leq d$ for all $0 \leq i \leq k-1$, then $I_B(t_0, t_k) \leq d$.*

Proof: This is immediate from the definition of attack impact. ■

Proof of Theorem 1: For ease of exposition, we first analyze the single attacker case, followed by the multiple attackers case.

For the single attacker case, let A be the attacker node in network N and let R be a non-attacker receiver node that is downstream from A. Let node B be the immediate downstream of node A on the path from A to R. Let p_{BR} denote the path PDR between B and R. Since there is no attacker between B and R, we have $r_R = r_B \cdot p_{BR}$ and $r'_R = r'_B \cdot p_{BR}$. Thus,

$$\begin{aligned} I_R &= \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} (r'_R(t) - r_R(t))dt \\ &= \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} (r'_B(t) \cdot p_{BR} - r_B(t) \cdot p_{BR})dt \\ &= \frac{p_{BR}}{t_1 - t_0} \int_{t_0}^{t_1} (r'_B(t) - r_B(t))dt \\ &= I_B \cdot p_{BR} \leq I_B \end{aligned}$$

Therefore, we only need to show $I_B \leq \delta$.

We classify rounds into two categories, Category A for rounds in which the attacker is not detected, and Category B for rounds in which the attacker is detected or isolated.

An attack in a Category A round i implies, by definition, that the attacker is not detected, *i.e.*, it drops data below the δ threshold: $\Delta_B(i) < \delta$. By Lemma 1, we have $I_B(i) \leq \Delta_B(i) \leq \delta$.

Let round a be the round in which the attack is detected and let w be the discrepancy observed at node B when the attack is detected. Then our protocol ensures that $w \geq \delta$ and that node B accuses and isolates node A for time $\alpha w \geq \alpha\delta$. If we denote the time when the attacker recovers from the accusation as t_r, then $t_r - t_a \geq \alpha w$. Therefore, the attack impact on node B from time t_a to time t_r is:

$$I_B(t_a, t_r) = \frac{\int_{t_a}^{t_{a+1}} (r'_B - r_B(t))dt}{t_r - t_a} \leq \frac{\lambda}{\alpha w} \leq \frac{\lambda}{\alpha\delta}$$

Hence, if $\alpha \geq \frac{\lambda}{\delta^2}$, we have $I_B(t_a, t_r) \leq \delta$. Therefore, by Lemma 2, we have $I_B(t_0, t_r) \leq \delta$. Since the maximum accusation time is α, for any time interval with duration $T \gg \alpha$, we have $I_R \leq I_B \leq \delta$.

For the case of multiple attackers, for rounds in Category A, where no attackers are detected, we also have $I_B(i) \leq \delta$. For rounds in Category B, node B may switch to another attacker node in the round after detecting an attacker node, hence for a total of k attacker nodes, we have

$$I_R(t_a, t_r) \leq I_B(t_a, t_r) \leq \frac{k\lambda}{t_r - t_a} \leq \frac{k\lambda}{\alpha\delta}$$

Hence, if $\alpha \geq \frac{k\lambda}{\delta^2}$, we have $I_R(t_a, t_r) \leq \delta$. □

Proof of Theorem 2: In the proof of Theorem 1, we assume a node has perfect path quality in the benign network, whereas the node has zero PDR in the round when the attacker is detected. If the fallback procedure can restore the PDR to the level of the benign network, then the attack impact during that round is bounded by δ (because, once the discrepancy on the average PDR exceeds δ, the attack is detected and the node invokes the fallback procedure). Therefore, we can derive an upper bound for I_R for rounds in Category B as follows:

$$I_R(t_a, t_r) \leq \frac{k\delta\lambda}{t_r - t_a} \leq \frac{k\delta\lambda}{\alpha\delta} = \frac{k\lambda}{\alpha}$$

Hence, if $\alpha \geq \frac{k\lambda}{\delta}$, then $I_R(t_a, t_r) \leq \delta$. Following a similar analysis as in Theorem 1, we obtain that $I_R \leq \delta$ for any time interval of duration $T \gg \alpha$. □

B. Attack Resiliency

We decompose our defense scheme into an attack detection and an attack reaction component, and analyse the resilience of the two components to various types of attacks. We show that relying directly on the monitored throughput for attack detection enables our defense to be oblivious to the underlying attack mechanisms used by the attacker.

Claim 1. *The attack detection mechanism in* S-ODMRP *detects metric manipulation attacks that have an attack impact greater than δ, regardless of the underlying attack mechanisms.*

Proof sketch: Discounting physical layer impact, such as jamming from attacker nodes, by Lemma 1 we see that the attack impact on a node is bounded by its observed discrepancy between expected PDR and perceived PDR. Therefore, by monitoring the discrepancy directly at each node, our mechanism detects all attacks that cause throughput degradation larger than the threshold δ compared to the benign network. The specific types of underlying mechanisms that enable the metric manipulation attack, such as wormholes or flood rushing, do not affect the effectiveness of our detection mechanism. □

Claim 2. *Assuming a stable network and no false accusation attacks, at least one attacker is accused with each attack reaction, regardless of the underlying attack mechanisms.*

Proof sketch: In each attack reaction, there is at least one node accusing another node. In the absence of false accusation attacks, the accuser node must be a honest node. Thus, we need to show that the accused node is an attacker node. In a stable network, an attack reaction can only be triggered by an active metric manipulation attacker. By our staggered reaction timeout, the first downstream honest node on the attacker controlled path will react first by accusing its upstream attacker node. The recovery message from the accuser node also cancels the reaction timer of its downstream nodes, preventing honest nodes accusing other affected honest nodes. Although an attacker node on the path can drop the recovery message, such action will only cause the attacker node itself to be accused by its downstream honest node, since the reaction timer of the downstream node is not cancelled without receiving a recovery message. Therefore, assuming no false accusation attacks, at least one attacker node is accused each time the attack reaction procedure is trigerred. □

Claim 3. *Assuming a stable network with k metric manipulation attackers and no Sybil attacks,* S-ODMRP *bounds the attack impact, regardless of the underlying attack mechanisms.*

Proof sketch: We consider separately the case of no false accusation attacks and false accusation attacks.

By Claim 1, the detection scheme is oblivious to the underlying attack types. By Claim 2, with no false accusation attacks, at least one attacker node is accused per attack reaction. With no Sybil attacks, after at most k attack reaction occurrences, all the attacker nodes will be identified and isolated. Therefore, regardless of the underlying attack mechanisms, choosing a large enough value for α will isolate attackers for a large period of time, bounding the attack impact as shown in Theorems 1 and 2.

We now consider the case when false accusation attacks occur. Our limited accusation mechanism restricts attackers to only have one active false accusation at any time. In addition, our technique of activating the neighbor advertising the best metric regardless of its accused status ensures that falsely accused nodes are also used in routing. This prevents attacker nodes from partitioning the network by strategically accusing certain honest nodes. Therefore, false accusation attacks only cause falsely accused nodes to be ignored in the metric propagation process. However, in a dense enough network, the impact on the metric derived at each node is limited, as each node typically has multiple disjoint paths with similar metric to the source. Therefore, the overall impact of the false accusation attack is limited. □

Finally, we consider attacks against the fallback procedure. Since we do not protect the fallback recovery phase, attackers that are selected as forwarders during the recovery phase may drop packets without being punished. However, since the fallback recovery is only used to salvage data for the remaining of the current round, the impact of the attack is limited. As shown in Theorem 1, even if the attacker is able to completely block all packets to a node during the fallback recovery procedure, the average attack impact is still bounded by δ for sufficiently large values of α.

VI. Experimental Evaluation

In this section, we demonstrate through experiments the vulnerability of metric enhanced multicast protocol by examining the impact of different attacks, and investigate the effectiveness of our defense mechanisms and its associated overhead.

A. Experimental Methodology

Simulation Setup. We implemented ODMRP-HT and S-ODMRP using the ODMRP version available in the Glomosim [38] simulator. Nodes were set to use 802.11 radios with 2 Mbps bandwidth and 250m nominal range. We simulate environments representative of mesh networks deployments by using the two-ray radio propagation model with the Rayleigh loss model, which models environments with large reflectors, *e.g.*, trees and buildings, where the receiver is not in the line-of-sight of the sender.

The network consists of 100 nodes randomly placed in a 1500m×1500m area. We randomly select 20 nodes as multicast group members and among the 20 members one node is randomly selected as the data source. Group members join the group at the beginning of the experiment. At second 100, the source starts to multicast data packets for 400 seconds at a rate of 20 packets per second, each packet of 512 bytes. When attackers are present, they are randomly selected among nodes that are not group members. For S-ODMRP, we use RSA signatures with 1024-bit keys, simulating delays to approximate the performance of a 1.3 GHz Intel Centrino processor. We empirically tune the threshold $\delta = 20\%$ to accommodate random network variations in the simulated scenarios. The timeout for React_Timer is set as $20(1 - \text{ePDR})$ millisecond, and the accusation_time is set as $250(\text{ePDR} - \text{pPDR})$ second. Nodes use the statistical-based method described in Sec. IV-C2 to determine their pPDR.

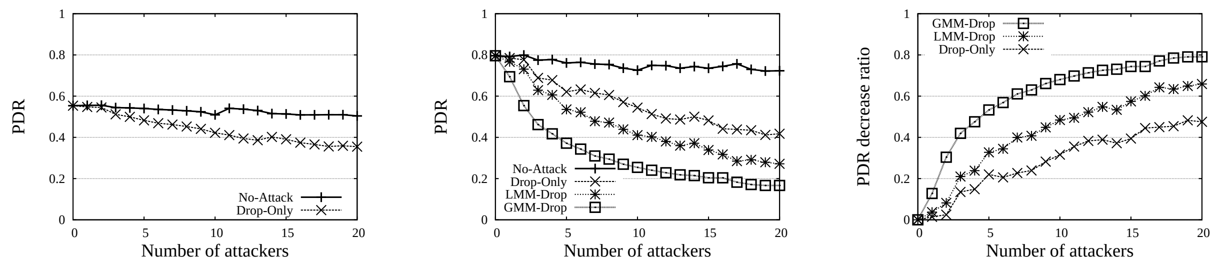
We used the SPP high-throughput metric, configured with optimal parameters as recommended in [11]. Data points are averaged over 10 different random environments and over all group members.

Attack Scenarios. We consider the following scenarios:

• *No-Attack*: The attackers do not perform any action in the network. This represents the ideal case where the attackers are identified and completely isolated in the network, and serves as the baseline for evaluating the impact of the attack and the performance of our defense.

• *Drop-Only*: The attackers drop data packets, but participate in the protocol correctly otherwise. The attack has effect only when attackers are selected in the Forwarding Group. We use this scenario to demonstrate that metric manipulation amplifies data dropping attacks.

• *LMM-Drop*: The attackers combine local metric manipulation (LMM) with the data dropping attack. The attackers



(a) Attacks on ODMRP (b) Attacks on ODMRP-HT (c) Attack strength against ODMRP-HT

Fig. 7: The effectiveness of metric attacks on ODMRP-HT. For comparison we also depict attacks against ODMRP which does not use high-throughput metrics.

conduct the LMM attack by re-advertising the same metric they received in JOIN QUERY, which is equivalent to making their link metric of the previous hop equal to 1 (best).

• *GMM-Drop*: The attackers combine global metric manipulation (GMM) with the data dropping attack. The attackers conduct the GMM attack by re-advertising a metric of 1 (best) after receiving a JOIN QUERY.

• *False-Accusation*: The attackers exploit our accusation mechanism by falsely accusing random a honest node at startup for the whole experiment period in order to reduce the PDR. Due to space constraint, we do not present results for attacks that aim to cause large bandwidth overhead through frequent flooding of accusation messages using false accusations. We can upper bound the frequency of the accusation message flooding from any attacker node to only once a few seconds by imposing a lower bound on the accusation timeout, thus the inflation of overhead is limited.

Metrics. We measure the performance of data delivery using the packet delivery ratio (PDR), defined as PDR $= n_r/n_s$, where n_r is the average number of packets received by all receivers and n_s is the number of packets sent by the source.

We also measure the strength of the attacks using as metric the PDR Decrease Ratio (PDR-DR), defined as

$$\text{PDR-DR} = \frac{\text{PDR}_{\text{noattack}} - \text{PDR}_{\text{attack}}}{\text{PDR}_{\text{noattack}}},$$

where $\text{PDR}_{\text{attack}}$ and $\text{PDR}_{\text{noattack}}$ represent the PDR when the network is under attack and not under attack, respectively.

The overhead of our defense consists of three components, the control bandwidth overhead due to additional messages and larger message size (*e.g.*, accusation messages, signatures on query messages), the computational overhead due to cryptographic operations, and the additional data packet transmissions caused by our protocol. We measure the control bandwidth overhead per node, defined as the total control overhead divided by the number of nodes. The computational overhead is measured as the number of signatures performed by each node per second. To measure redundant data packet transmissions, we define *data packet transmission efficiency* as the total number of data packets transmitted by all nodes in the network divided by the total number of data packets received by all receivers. Thus, data packet transmission efficiency captures the cost (number of data packet transmissions) per data packet received.

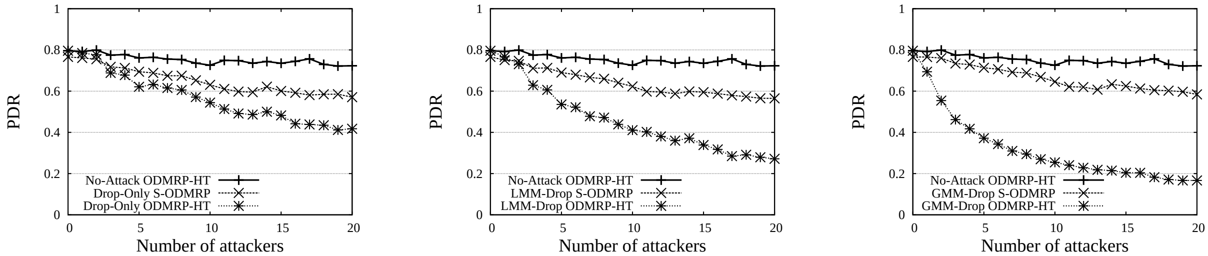
B. Effectiveness of Metric Manipulation Attacks

Fig. 7(a) shows the impact of *Drop-Only* attack on the original ODMRP (not using high-throughput metric). The protocol is quite resilient to attacks, *i.e.*, PDR decreases by only 15% for 20 attackers. This reflects the inherent resiliency of mesh based multicast protocols against packet dropping, as typically a node has multiple paths to receive the same packet.

Fig. 7(b) shows the PDR of the protocol when using high-throughput metric (ODMRP-HT) under different types of attacks. We observe that with the *Drop-Only* attack, the PDR drops quickly to a level below the case when no high throughput metric is used. Thus, simple packet dropping completely nullifies the benefits of high throughput metrics. By manipulating the metrics as in *LMM-Drop* and *GMM-Drop*, the attacker can inflict a much larger decrease in PDR. For example, the PDR decreases from 72% to only 25% for 10 attackers using *GMM-Drop*, in contrast to 55% for *Drop-Only*. Fig.7(c) compares the impact of the attack in terms of the PDR Decrease Ratio. We see that metric manipulation significantly increases the attack strength. For example, with 10 attackers, the PDR-DR of *GMM-Drop* (68%) is more than double the PDR-DR of *Drop-Only* (32%). Thus, we conclude that metric manipulation attacks pose a severe threat to high-throughput protocols.

C. Effectiveness of the Defense

In Fig. 8 we show the effectiveness of our defense (S-ODMRP) against different types of attacks, compared to the insecure ODMRP-HT protocol. S-ODMRP suffers only a small PDR decrease relative to the baseline *No-Attack* case. For example, a total of 20 attackers causes a PDR drop of only 12%, considerably smaller than the case without defense, which shows a PDR decrease by as much as 55% in the *GMM-Drop* attack. To rule out random factors, we performed a paired t-test [37] on the results showing that S-ODMRP improves the PDR for all attack types, with P-value less than 2.2×10^{-16}. For 10 attackers, S-ODMRP improves the PDR of ODMRP-HT for *Drop-Only*, *LMM-Drop* and *GMM-Drop* by at least 4.5%, 16.7%, 33%, with 95% confidence level. Thus, our defense is very effective against all the attacks. The small PDR decrease for S-ODMRP can be attributed to two main factors. First, common to all reactive schemes, attackers can cause some initial damage, before action is taken against them. Second, as the number of attackers increases, some receivers become completely isolated and are not able to receive data.



(a) *Drop-Only* attack (b) *LMM-Drop* attack (c) *GMM-Drop* attack

Fig. 8: The effectiveness of S-ODMRP for different attacks

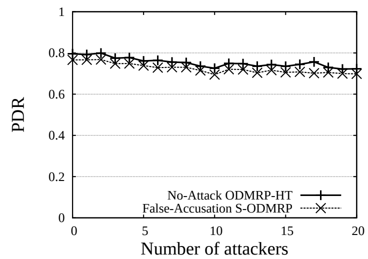


Fig. 9: Impact of the *False-Accusation* attack on S-ODMRP

Fig. 8 also shows an interesting phenomenon: The PDR decrease for S-ODMRP is similar for all attacks, despite the varying strength of the attacks. This outcome reflects the design of our defense mechanism in which accusations last proportional to the discrepancy between ePDR and pPDR: Attacks that cause a small discrepancy (*e.g.*, *Drop-Only*) are forgiven sooner and can be executed again, while attacks that cause a large discrepancy (*e.g.*, *GMM-Drop*) result in a more severe punishment and can be executed less frequently.

Finally, we note that the attack impact with S-ODMRP is less than $\delta = 20\%$, which is consistent with the bound in our analysis in Sec. V-A.

D. Defense Resiliency to Attacks

Attackers may attempt to exploit the accusation mechanism in S-ODMRP. Fig. 9 shows that S-ODMRP is very resilient against the *False-Accusation* attack, in which attackers falsely accuse one of their neighbors. This comes from the controlled nature of accusations, which only allows an attacker to accuse one honest node at a time. Also, as described in Sec. IV-B, falsely accused nodes that advertise a good metric may continue to forward data.

E. Overhead of S-ODMRP

Fig. 10(a) and 10(b) show the control bandwidth and computational overhead for S-ODMRP. We observe that for all attack configurations, the bandwidth and computational overhead are maintained at a stable low level of around 0.95 kbps and 0.9 signatures per node per second. To understand the source of the overhead better, we analyzed different components of the overhead. The result shows that the overhead due to reacting to attackers (such as dissemination of ACCUSATION and RECOVERY messages) is negligible, since the attackers, once detected, are accused for a relatively long period of time The bulk of the overhead comes from the periodic network-wide flooding of authenticated JOIN QUERY packets. Since query flooding is common in all scenarios, we obtain a similar level of overhead across different scenarios. The reason for the slight overhead decrease for an increasing number of attackers for the *False-Accusation* attack is that JOIN QUERY from the falsely accused honest nodes are ignored by their neighbors, resulting a smaller number of transmissions of JOIN QUERY packets.

In Fig. 10(c), we notice that S-ODMRP under various attacks even improves slightly the *data transmission efficiency* of ODMRP-HT with no attacks. This apparent anomaly can be explained because in S-ODMRP nodes that are further away from the source are more likely to be affected by attacks and these are the nodes that require more transmissions to receive data packets.

VII. RELATED WORK

Work studying multicast routing specific security problems in wireless networks is scarce with the notable exception of the authentication framework by Roy *et al.* [25] and BSMR [26] which focus on outsider and insider attacks for the well-known tree-based MAODV multicast protocol.

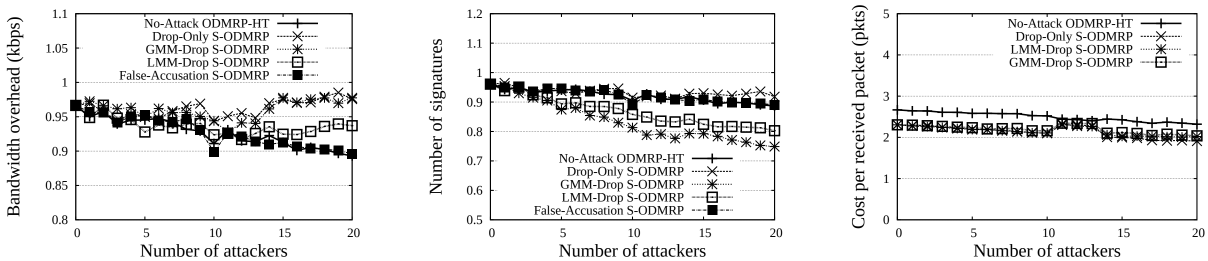
Significant work focused on the security of unicast wireless routing protocols. Several secure routing protocols resilient to outside attacks were proposed in the last few years such as Ariadne [19], SEAD [18], ARAN [20], and the work in [17].

Wireless specific attacks such as flood rushing and wormhole were identified and studied. RAP [31] prevents the rushing attack by waiting for several flood requests and then randomly selecting one to forward, rather than always forwarding only the first one. Techniques to defend against wormhole attacks include *Packet Leashes* [32] which restricts the maximum transmission distance by using time or location information, Truelink [33] which uses MAC level acknowledgments to infer if a link exists or not between two nodes, and the work in [34], which relies on directional antennas.

The problem of insider threats in unicast was studied in [19], [21]–[24]. Watchdog [21] detects adversarial nodes by having each node monitors if its neighbors forward packets to other destinations. SDT [22] and Ariadne [19] use multi-path routing to prevent a malicious node from selectively dropping data. ODSBR [23], [24] provides resilience to colluding Byzantine attacks by detecting malicious links based on an acknowledgment-based feedback technique.

VIII. CONCLUSION

We considered the security implication of using high throughput metrics in multicast protocols in wireless mesh networks. In particular, we identified metric manipulation attacks



(a) Bandwidth overhead per node (b) Computational overhead per node (c) Data transmission efficiency

Fig. 10: The overhead of S-ODMRP

that can inflict significant damage on the network. The attacks not only have a direct impact on the multicast service, but also raise additional challenges in defending against them due to their metric poisoning effect. We overcome the challenges with our novel defense scheme that combines measurement-based attack detection and accusation-based reaction. Our defense also copes with transient network variations and malicious attempts to attack the network indirectly by exploiting the defense itself. We demonstrate through experiments that our defense is effective against the identified attacks, resilient to malicious exploitations, and imposes a small overhead.

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