Enhancing Routing Security in IoT: Performance Evaluation of RPL’s Secure Mode under Attacks

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Abstract—As the Routing Protocol for Low Power and Lossy Networks (RPL) became the standard for routing in the Internet of Things (IoT) networks, many researchers had investigated the security aspects of this protocol. However, no work (to the best of our knowledge) has investigated the use of the security mechanisms included in RPL’s standard, mainly because there was no implementation for these features in any IoT operating systems yet. A partial implementation of RPL’s security mechanisms was presented recently for the Contiki operating system (by Perazzo et al.), which provided us with an opportunity to examine RPL’s security mechanisms. In this paper, we investigate the effects and challenges of using RPL’s security mechanisms under common routing attacks. First, a comparison of RPL’s performance, with and without its security mechanisms, under four routing attacks (Blackhole, Selective-Forward, Neighbor, and Wormhole attacks) is conducted using several metrics (e.g., average data packet delivery rate, average data packet delay, average power consumption, etc.). This comparison is performed using two commonly used Radio Duty-Cycle protocols. Secondly, and based on the observations from this comparison, we propose two techniques that could reduce the effects of such attacks, without having added security mechanisms for RPL. An evaluation of these techniques shows improved performance of RPL under the investigated attacks, except for the Wormhole attack.

Index Terms—Security and Privacy, Resource-Constrained Networks, Secure Communication, Secure RPL, Routing Attacks.

I. INTRODUCTION

Routing is one of the most researched fields in the world of Internet of Things (IoT), due to the constraint nature of these devices. Introduced by Internet Engineering Task Force (IETF), the Routing Protocol for Low Power and Lossy Networks (RPL) had become the standard for routing in many IoT networks as it was designed to efficiently use the constrained resources of IoT devices, while providing effective routing services. Routing security was an integral part of RPL’s design with several, but optional, security mechanisms available.

Since it became a standard in 2012, RPL gained a great deal of research interest, with many of the literature focusing on the security aspects of routing using the protocol, such as types of routing attacks, new mitigation methods and Intrusion Detection Systems (IDSs), and security-minded Objective Functions (OFs). Interestingly, there has been no research discussing the effects of using RPL’s security mechanisms, specifically under routing attacks. This is most probably due to the lack of implementation of RPL’s security mechanisms in any of the available IoT Operating Systems (OSs), such as Contiki OS and TinyOS.

However, recently Perazzo et al. in provided a partial implementation of RPL’s security mechanisms for Contiki OS, which added the Preinstalled secure mode and the optional replay protection mechanism. This implementation provided us with the basis upon which the work in this paper is built on. In this paper, we have experimentally investigated RPL’s performance under four common routing attacks using several metrics to analyze and compare the performance between having RPL’s security mechanisms enabled or disabled.

The work in this paper provides a significant extension to our previous conference paper. Specifically, we introduced a new scenario for an RPL Wormhole attack to the evaluation. Then, we extended the evaluation of RPL’s performance from using one Radio Duty-Cycle (RDC) protocol (the ContikiMAC protocol) to include the effect of using another commonly used RDC protocol, namely the NullRDC protocol - see §IV-D. Finally, for the two techniques we proposed in to improve RPL’s performance under the investigated attacks, we conducted an extensive evaluation of these two techniques and their effects on RPL’s performance under the investigated attacks and using the two underlying RDC protocols.

Our contributions can be summarized as following:

• Through more than a thousand experiments, we provided a performance comparison for RPL between the unsecured mode and the Preinstalled secure mode (PSM); the latter is examined with and without the optional replay protection. We demonstrated that running RPL in PSM (without replay protection) does not use more resources than the unsecured mode, even under attack.

• We verified that RPL in PSM is able to stop external adversaries from joining the IoT network for the investigated attacks, except for the Wormhole attack. Furthermore, we showed that the optional replay protection also provides an excellent mitigation against the Neighbor attack; however, it needs further optimization to reduce its effect on energy consumption.

• We observed and analyzed the effect of the investigated attacks on the routing topology and proposed two simple techniques that could help reduce the effects of the investigated attacks, without using external security measures such as IDSs or added security mechanisms.

• Another performance comparison of the implementation of the proposed techniques was conducted. The results...
showed improved performance of RPL under the Blackhole and Selective-Forward attacks, in terms of packet delivery rate (PDR) and End to End (E2E) latency.

The rest of this paper goes as follows: Section II looks into the related works. In section III an overview of RPL and its security mechanisms is presented. Section IV discusses our evaluation methodology, setup, assumptions, adversary model, and attack scenarios. Evaluation results are analyzed in section V. Section VI discusses our observations from the results and proposes two suggestions to be used when designing RPL-based IoT networks. In addition, an implementation of the proposed suggestions is evaluated and the results are discussed. Finally, our work is concluded in VII.

II. RELATED WORKS

This section highlights some influencing literature that discussed RPL’s performance under common routing attacks. As stated earlier, none of them had investigated RPL’s security mechanisms, except for the conference version of this paper.

Le et al. in [11] evaluated RPL’s performance under four RPL-based attacks: the Decreased Rank, Local Repair, Neighbor, and DODAG Information Solicitation (DIS) attacks. Their work showed that the Decreased Rank and the Local Repair attacks affects the PDR the most, while DIS attack introduced the most E2E latency. Neighbor attack showed the least impact on the network. Compared to our work, the authors only tackled with the unsecured mode of RPL while they ignored the effect of their attacks on power consumption.

Kumar et al. in [12] investigated the effects of the Blackhole attack, on RPL-based network through simulations. As expected, the attack was successful in reducing the PDR and increased both the E2E latency and control messages overhead. However, the authors did not evaluate the power consumption and neglected the existence of RPL’s security mechanisms.

Perazzo et al. in [9], [13] provided the first, standard-compliant as per their claim, partial implementation of RPL security mechanisms. One secure mode, the Preinstalled secure mode, and the optional replay protection, named the Consistency Check (CC) mechanism, were introduced to ContikiRPL (Contiki OS version of RPL). The authors provided an evaluation for their implementation, and compared RPL’s performance between using and not using the PSM. However, it is worth noting that the authors did not evaluate their implementation against actual attacks.

Our previous work in [14] presented the first glimpse of the effect that RPL’s security mechanisms could have on RPL-based IoT networks when there is an actual attack. RPL’s performance (with and without PSM) was investigated under three attacks: the Blackhole, Selective-Forward, and Neighbor attacks using simulations. The preliminary results showed that RPL’s secure modes can mitigate the external adversaries of the investigated attacks, but not the internal adversaries. However, it did not provide a deeper analysis on the results, nor inspected the optional replay protection mechanism.

III. BACKGROUND REVIEW

A. RPL Overview

RPL was developed as a distance-vector routing protocol [1]. It arranges the network devices into a Destination Oriented Directed Acyclic Graphs (DODAGs) [15]: a network of nodes connected without loops and where the traffic is directed toward one root or sink node [1], [16].

The creation of the DODAG depends on the used OF, which defines essential configurations such as the used routing metrics, how to calculate the rank, and how to select parents in the DODAG. To accommodate the different applications and environments where RPL can be deployed, RPL has several OFs [2], [17], [18] available for use [19]. Also, deployments of RPL can have their own OFs.

Three types of traffic are supported by RPL: Multi-Point to Point communication (MP2P) traffic (nodes to sink) through normal DODAG, Point to Multi-Point communication (P2MP) traffic (sink to nodes) through source routing, and Point to Point communication (P2P) traffic (non-root node to non-root node) through RPL’s Modes of Operation (MOP) [1], which dictate how the downward routes are created.

RPL has five types of control messages; four of them have two versions (base and secure versions), and the last one has only a secure version. The secure version of RPL’s control messages adds new unencrypted header fields and either a Message Authentication Code (MAC) or a digital signature field to the end of the base version, then encrypts the base part and the MAC [1].

DODAG Information Object (DIO) and DODAG Information Solicitation (DIS) messages are used for the creation and maintenance of the DODAG [1]. The root node starts the DODAG creation by multicasting a DIO message that contains the essential DODAG configurations and the root node’s rank (the root node has the lowest rank in the DODAG). Upon receiving a DIO message, each node will select its preferred parent, calculate its own rank, and multicast a new DIO with its calculated rank [1], [19]. DIS messages are used to solicit DIO messages from node’s neighbors when it is needed, e.g., a new node wants to join the networks or no DIO messages had arrived for a long time [1].

Destination Advertisement Object (DAO) and DAO Acknowledgements (DAO-ACKs) messages are the backbones of the downward routes creation [1]. The DAO contains path information about reachable nodes by its sender, and depending on RPL’s mode of operation it will be used to create the downward routing table. Based to the DODAG’s configurations, a flag in DAO message will mandate an acknowledgment (DAO-ACK message) from the receiver.

B. RPL’s Security Mechanisms

To secure the routing service, RPL either relies on the security measures at the Link layer (i.e. IEEE 802.15.4 [20]), or uses its own security mechanisms, resembled in three modes of security and an optional replay protection mechanism [1].

\[\text{DODAG} = \text{Destination-Oriented Directed Acyclic Graph}\]
The default mode for RPL is the **Unsecured** mode (UM), where only the link-layer security is applied, if available. The second mode, the **Preinstalled** secure mode (PSM), which uses the preinstalled symmetrical encryption keys to secure RPL control messages. Finally, the **Authenticated** security mode (ASM) uses the preinstalled keys for the nodes to join the network; after which all routing-capable nodes have to acquire new keys from an authentication authority. To protect the routing service from replay attacks, RPL uses Consistency Checks as an optional mechanism that can be used with either the preinstalled (PSMrp) or authenticated mode (ASMrp). In these checks, a special secure control message (CC message) with non-repetitive nonce value is exchanged and used to assure no replay had occurred [1].

### IV. Evaluation of RPL’s Security Mechanisms under Attacks

In this paper, RPL performance is evaluated against four attacks [19], [21]: the Blackhole, the Selective-Forward, the Neighbor, and the Wormhole attacks. Experiments were conducted with RPL in both UM (vanilla ContikiRPL) and PSM (as in Perazzo et al. [9] implementation). For the latter, we evaluated RPL with and without the optional replay protection mechanism.

#### A. Evaluation Setup

Cooja, the simulator for Contiki OS [7], was used for all the simulations (with simulated motes). Fig. 1 shows the topology used in our evaluation for the Blackhole, Selective-Forward, and Neighbor attacks, while Fig. 2 shows the one used to evaluate the Wormhole attack (as two adversaries are needed). A list of simulation parameters is provided in Table I.

Both topologies represent a single DODAG network that has one root or sink node (the green node). To reduce the complexity of the observed metrics, the minimum number of adversaries required for each attack was used. For the Blackhole, Selective-Forward, and Neighbor attacks, node (27) was used as an adversary and it is positioned near the sink node, as that would introduce the biggest effect of the three attacks [21]–[23]. For the Wormhole attack, two adversaries (nodes 27 and 29) were used and positioned to create a wormhole between the node cluster (1, 7, 20, and 26) and the targeted nodes. The targeted nodes for all the attacks are (2, 5, 6, 8, 12, 15, 18, 21, and 28), with node (28) providing an alternative path for the targeted nodes to send their packets toward the sink. Having an alternative path is crucial to our experiments to examine how the self-healing mechanisms of RPL will respond to the attacks.

Note that we tried to implement the simulations using Zolertia Z1 motes [24] (each has 8KB RAM and 92KB Flash memory) to compare our results to that of [14]. However, enabling the replay protection mechanism of RPL in our simulation caused the mote to always run out of RAM, rendering the simulation impractical. Hence, we moved to the more powerful Wismote motes (each has 16KB RAM and a 256KB Flash memory [25]).
B. Assumptions

The following assumptions were used in our evaluation: only the legitimate nodes send data packets toward the sink, while the adversaries only participate in the DODAG formation without sending any data packets. RPL is using the default OF, namely the Minimum Rank with Hysteresis Objective Function (MRHOF) [13]. To keep the focus on RPL at the Network layer, we assumed neither security measures nor encryption was enabled at the Link layer. All the attacks were also implemented at the Network layer.

The results obtained from the simulations were averaged over ten rounds for each scenario with a 95% confidence level.

C. Adversary Model and Attack Scenarios

For each RDC protocol (see §IV-D), we conducted a set of four experiments: the first three experiments (RPL in UM, RPL in PSM, and RPL in PSmrp) have an internal adversary, who participates in the creation of the topology from the beginning (and has the preinstalled encryption keys in the 2nd and 3rd experiments). The fourth experiment (RPL in PSM) uses an external adversary who runs RPL in UM and does not have the knowledge of the secure versions of RPL’s control messages, while the legitimate nodes run RPL in PSM. Table II lists the settings for these experiments.

For the attacks themselves, we have five scenarios:
1) No Attack: the adversary works as a fully legitimate node.
2) Blackhole Attack (BH): the adversary drops all the traffic coming through (RPL control messages and Data Packets) [19].
3) Selective-Forward Attack (SF): the adversary drops data packets only (RPL control messages only will pass) [22].
4) Neighbor Attack (NA): the adversary would pass any DIO message it receives from its neighbors without any processing or modification [11].
5) Out-of-Band Wormhole Attack (WH): two adversaries use an out-of-band link to forward RPL control messages from legitimate nodes between the two locations where the adversaries reside [19], [26]. This scenario is available only in the NullRDC set of experiments, see §IV-D.

The adversary for the Blackhole, Selective-Forward, and Neighbor attacks always starts as a legitimate node, tries to join the network and actively participates in the creation and maintenance of the DODAG, works as a legitimate node for two minutes (to assure full integration with the network), then it launches the attack afterward. For the Wormhole attack, the two adversaries are always in promiscuous mode and they do not participate in the DODAG by any way.

The choice of these attacks was based on the fact that they have a minimum cost for the adversary to launch them, as they require little or no processing of RPL’s messages. At the same time the effect of these attacks can be significant on the network.

It is worth mentioning that our implementation of the Wormhole attack is based upon the work in [27]. The authors implemented an out-of-band wormhole on a real testbed, with a wired link between the adversaries. Each adversary operates in the promiscuous mode, sniffs all types of frames, sends the sniffed frames through the wired link, and replays the frames it received from the wired link. However, our implementation differs from theirs in a few points:
1) Our implementation is simulation-based and is conducted in Cooja. We use the host computer to emulate a fast link between the adversaries.
2) The wormhole is implemented at the Network layer level in order to detect and replay RPL’s control messages only. In addition, the adversaries can identify the secure versions of RPL’s control messages.
3) The adversaries use a multi-buffer approach for the packets received from the radio and for the packets awaiting the replay. This approach accelerates the operation of the adversaries when there are many neighbors, and makes sure that all forwarded packets are replayed without dropping any of them.

D. Implementation Challenges

Contiki OS [7] divides the Link layer into three sub-layers: the Medium Access Control (MAC) sub-layer which is responsible for addressing, sequencing and retransmissions, the FRAMER sub-layer that is responsible of creating and parsing of frames, and the RDC sub-layer that controls the radio component. Now, Contiki OS comes with several RDC protocols, with the mostly used ones are the ContikiMAC [28] and NullRDC.

ContikiMAC is the default setting for RDC protocol in Contiki OS. Here, the radio is kept off most of the time, with the protocol waking up the radio periodically to check for transmissions. If a transmission is detected, the radio is kept on long enough to receive the frame and an ACK is sent to the sender if it was accepted [28], [29], after which the radio is turned off. Similarly, the sender will turn on the radio, probe the channel, then perform several attempts to transmit a frame, waiting for either an ACK which dictates a successful transmission, or reaching a threshold that means a failed transmission [28]. Either way, the radio is turned off afterward. This protocol is proved to be very efficient with power consumption, at the expense of having longer E2E latency [29].

On the other hand, NullRDC protocol keeps the radio always on and does not perform a lot of channel probing. This means lower E2E latency and smaller number of retransmissions, but at the expense of higher power consumption [29].

During our implementation of the Wormhole attack using the ContikiMAC protocol, we found that the messages forwarded through the wormhole were replayed very late by

| Experiment | Secure Mode | Replay Protection | Adversary Type |
|------------|-------------|------------------|----------------|
| UM-I       | ×           | ×                | Internal (I)   |
| PSM-I      | ✓           | ×                | Internal (I)   |
| PSMrp-I    | ✓           | ✓                | Internal (I)   |
| PSM-E      | ✓           | ×                | External (E)   |
the adversaries; hence, they got ignored by the legitimate nodes. A further investigation showed that a mix of simulation environment latency and the long sending procedure of ContikiMAC are the culprits for such late replay. Several trials were made to reduce simulation latency (e.g. reducing output text, using faster host, etc.) and accelerate ContikiMAC sending procedure, all have failed.

However, implementing the Wormhole attack using NullRDC protocol proved to be working perfectly. Since the sending procedure is much simpler than that of ContikiMAC, the Wormhole performed exactly as expected, without any added latency and resulting in full disruption to the routing topology (as explained later). Due to the fact that the power consumption in this case is dominated by the high usage of the always-on radio (almost fixed at 122 milliwatts), we are not able to evaluate the effect of the investigated attacks on power consumption using the NullRDC protocol.

For that reason, only the NullRDC experiment set evaluates the Wormhole attack, omitting the power consumption metric.

V. RESULTS AND ANALYSIS

The results for ContikiMAC and NullRDC sets of experiments are expressed in Fig.3 and Fig.6, respectively. These results are expressed as the average PDR, average E2E latency, the number of exchanged RPL control messages (per legitimate node), and average network power consumption (per received packet). Fig.9 and Fig.10 show the routing DODAG for each node), and average network power consumption (per legitimate node), and average network power consumption (per received packet). Fig.9 and Fig.10 show the routing DODAG for each node, and average network power consumption (per received packet). Fig.9 and Fig.10 show the routing DODAG for each node, and average network power consumption (per received packet). Fig.9 and Fig.10 show the routing DODAG for each node, and average network power consumption (per received packet). Fig.9 and Fig.10 show the routing DODAG for each node.

A. ContikiMAC Set Results

Effects on packet delivery rate (PDR): Looking at Fig.3a it is clear that the RPL in PSM successfully mitigated the BH, SF, and Neighbor attacks when the adversary is external with the PDR hovering around 98%.

On the other hand, when the adversary is internal, the SF attack has the most effect (in all experiments) on the PDR, decreasing it to a low of 70%. The main reason behind the success is that the adversary, due to being an active participant in the DODAG maintenance, is always chosen as the preferred parent for its sub-DODAG but none of their data packets are passed to the sink node. Fig.9a shows the routing DODAG during the SF attack.

For the BH attack, the self-healing mechanisms of RPL were always able to detect the unresponsive adversary after approximately ten minutes from the attack launch time (which is the default setting for "dead parent" timeouts in the Contiki OS) and initiated a local repair for the affected sub-DODAG to switch to an alternative path. Hence, not all data packets got dropped, which explains why PDR is in the range of 80%. Fig.9b shows the routing DODAG after ten minutes from the BH attack launch time and the isolated adversary.

Finally, for the Neighbor attack, the adversary was able to reduce the PDR for the UM-I and PSM-I experiments, as node 18 always chose either node 7 or 13 as its preferred parent (Fig.9c shows that node 18 selected node 7 as its preferred parent), due to receiving their DIO messages through the adversary. Since nodes 7 and 13 are actually out of node 18’s range, all packets sent toward them from node 18 and its sub-DODAG are lost. Hence, the PDR is in the same range as in the BH attack scenario. However, activating the replay protection mechanism results in much better PDR as the mechanism verifies the original sender of each DIO message before processing its contents. Fig.9d demonstrate how the network (in PSMrp-I experiment) opted for the alternative path after a few minutes from launching the Neighbor attack.

Effects on the E2E latency: Confirming our findings mentioned above, Fig.3b shows that the RPL in PSM mitigated the BH, SF, and Neighbor attacks when they were launched by an external adversary, keeping the E2E latency at a minimum. Due to the large number of undelivered data packets for the affected nodes, the SF attack had the largest E2E latency among all the internal attacks. This effect is, again, due to the adversary’s active participation in the DODAG maintenance.

For the same reason, the BH attack introduced some latency to the network. However, since the affected nodes were able to find an alternative path and were successful in delivering the rest of their data packets, the latency was much lower than in the case of the SF attack scenario.

The situation is more complicated for the Neighbor attack scenario, as self-healing mechanisms were triggered several times to recover the affected nodes from the attack, which led to even higher E2E latency than the BH attack scenario. In general, whenever node 18 switches its preferred parent to node 7 or 13, the sub-DODAG suffers from Blackhole-like conditions resulting in losing several data packets. In addition, node 18 will either switch its preferred parent back to the adversary when it does not receive DIO messages from the "ghost parent" (node 7 or node 13), or initiate a local repair procedure (if DODAG inconsistencies were detected) that results in the whole sub-DODAG choosing the alternative path to deliver their packets. Either way it will add more latency to the network. Using the replay protection will significantly reduce the latency from the Neighbor attack, as node 18 will not switch its preferred parent as long as it does not receive the correct CC response from nodes 7 and 13.

Effects on the exchanged number of RPL’s control messages: As seen in Fig.3c the number of control messages exchanged in the network is almost the same for all experiments and all the scenarios, with the replay protection mechanisms adding a bit more control messages. The exception of this conclusion is the Neighbor attack scenario with RPL in PSMrp. In this special case, the replay protection mechanism introduced a much higher number of control messages, due to the exchange of the CC messages whenever a "ghost" DIO message is received by nodes 7, 13, or 18.

It is worth noting that the number of received control messages is always higher than the sent one, because many of the sent control messages are multicast messages which will be received by all neighboring nodes of the sender.

Effects on power consumption: Fig.3d shows the average network power consumption per received packet, as it gives a more accurate look into the effect of the attacks on the power consumption than just using the regular average power consumption readings.
Looking at the results of the external adversary experiment in the No Attack scenario, we can see that the power consumption is a bit higher than the same scenario in the other experiments. The reason is that the data packets from the affected nodes are taking the alternative and longer path, i.e., more power is used by the nodes on that path. However, the power consumption pattern is identical in all the scenarios of the external adversary experiment, which indicates no effect from the attacks; hence, successful mitigation of the attacks.

For all internal-adversary experiments, the power consumption patterns (per each scenario) are very similar between RPL in UM and PSM for the No Attack, BH, and SF attacks scenarios, with the replay protection mechanism having a bit more power consumption than the rest. This is because many data packets were not delivered, and the power consumed for their unsuccessful deliveries is entirely wasted.

Now, it is clear from Fig. 3d that using the replay protection significantly increases the average power consumption when the Neighbor attack is launched, even if almost all of the sent data packets were delivered successfully. This time, the reason behind this behavior is the increased number of control messages exchanged to mitigate the attack, as seen in Fig. 3d.
B. NullRDC Set Results

Comparing Fig[6] to Fig[3], it is clear that we have similar results for the first four scenarios (No Attack, BH, SF, and Neighbor attacks) in both RDC protocols, i.e., NullRDC and ContikiMAC. Hence, the focus of this analysis will be on the Wormhole (WH) attack scenario. The effects of the WH attack on the routing DODAG can be seen in Fig[10].

**Effects on packet delivery rate (PDR):** The WH attack successfully lowered the PDR to the low 80th percentile in all scenarios, regardless of the used RPL's secure mode or the adversary types. Our observation shows that the reason behind such behavior resides in the fact that the adversaries are transparent to the network and that all control messages (from both sides of the wormhole) are forwarded and received within their time-windows, deceiving the legitimate nodes to think they are in close proximity.

**Effects on the E2E latency:** Since most of the affected nodes were not able to deliver their data packets successfully, the average E2E latency of the network rose up to 200 seconds - see Fig[66]. RPL's replay protection mechanism slightly reduced the effect of the WH attack. However, this is due to having slight delays with the the CC message exchanges.
Effects on the exchanged number of RPL’s control messages: At a first look, it is obvious that using RPL over NullRDC protocol reduces the number of exchanged control packets compared to using ContikiMAC protocol, which has been documented in [29]. Besides that, the WH attack exchanged a similar number of control messages as in the other attacks, with the replay protection mechanism in PSMrp slightly increasing that number over the other experiments.

VI. DISCUSSIONS

Based on the analysis of the obtained results, we can put the following observations and, in result, some suggestions to improve RPL’s response to the investigated attacks.

A. Observations

• Using RPL in PSM (and by extension, the ASM) can mitigate the external adversaries of the Blackhole, Selective-Forward, and Neighbor attacks, as long as the adversary does not run RPL in any secure mode.

• RPL’s performance using PSM (without the replay protection mechanism) is similar to that when using UM, but with the added benefit of mitigating the external adversaries of the BH, SF, and Neighbor attacks as investigated in this paper.

• RPL’s secure modes cannot mitigate out-of-band Wormhole attacks (with NullRDC protocol at the Link layer) as their adversaries can operate external to the network.

• It is worth mentioning that we ran another experiment (using ContikiMAC) which had the external adversary running RPL in PSM while not knowing the encryption key used by the legitimate nodes. The results from that experiment were identical to the PSM-E experiment except for the Neighbor attack scenario, which was successfully launched. Since each type of RPL control messages has its unique Internet Control Message Protocol (ICMPv6) “Code” value, with the secure versions having different values than the unsecure ones, only a node that runs RPL in PSM/ASM could identify the secure versions of RPL control messages. Hence, the adversary was able to identify RPL’s secure DIO messages and replay them.

• Enabling RPL’s replay protection mechanism will significantly reduce the effect of Neighbor attacks on PDR and E2E latency. However, in its current implementation, it will increase the power consumption as well, which can lead to energy depletion of the devices. In theory, an adversary can replay DIO messages regularly to keep the affected nodes always busy with the consistency checks, leading to depletion of their energy and to shutdown.

• RPL’s secure modes require more memory and storage spaces than the unsecured mode, which means not all IoT devices can use them – see §IV-A.

B. Suggestions to Reduce the Effects of Routing Attacks on RPL’s Performance

Based on the observations mentioned above, we propose the following suggestions to help reduce the effects of routing attacks on RPL’s performance, without introducing any extra security mechanisms or systems.

1) Designing the network topology in a way where there are more alternative paths toward the root node and more neighbors per node. This would decrease the recovery time required for nodes to overcome a Blackhole attack and reduce the effects from the other investigated attacks on PDR and E2E latency.

2) Reducing the timeout duration after which an RPL router should declare a preferred parent as "dead". Cur-
rently, ContikiRPL uses fixed timeout values for the upward (UIP_CONF_ND6_REACHABLE_TIME) and downward routes (RPL_CONF_DEFAULT_LIFETIME), both set to 10 minutes. Reducing these values could decrease the E2E latency and increase the PDR of the network under some attack situations. However, static decrements may also increase the power consumption when there is no attacks. Our recommendation is to use a dynamic approach for adapting these timeout values to the network’s changing conditions. For example randomizing the timeout values after each expiration, or using the IPv6 over Low-powered Wireless Personal Area Network-Neighbor Discovery (6LoWPAN-ND) protocol [30]–[32], which aids RPL to detect node’s neighbors and checks their status in a resource-friendly way.

C. Evaluation of the Proposed Suggestions

For the first suggestion, having more routes toward the root node means adding more routing nodes. Hence, we added three routing nodes (29, 30, and 31) to the topology - see Fig.11 in the case of the Wormhole attack scenario, the added routing nodes (30, 31, and 32) are located in the same positions as in Fig.7 but with the topology in Fig.2.

To evaluate the effect of the second suggestion on RPL’s performance under the investigated attacks, both "dead parent" timeouts (see §VI-B) were set to five minutes. The use of a fixed value instead of dynamic approach was used to examine the effect of the reduced "dead parent" timeouts only. The topology for the evaluation is the same topology used in Fig.1.

The whole evaluation was conducted using the same metrics and methodology as in §IV.

Effects on packet delivery rate (PDR): Comparing Fig.4a to Fig.3a (ContikiMAC) and Fig.7a to Fig.6a (NullRDC), we can see that the first suggestion slightly enhanced the network’s PDR for the BH, SF, and NA scenarios, adding about 6% more delivered packets. From our observation, the reason behind this improvement is that some of the affected nodes chose the alternative routes, minimizing the effect of the investigated attacks.

On the other hand, the second suggestion affected only the BH scenario, increasing the PDR to a respected 88% - this clear from comparing Fig.5a to Fig.3a (ContikiMAC) and Fig.8a to Fig.6a (NullRDC). The reduced timeouts caused the affected nodes to detect the adversary parent faster and switch to a different parent. However, this suggestion does not have any effect in the case of the other attacks, since their adversary reacts to received messages, unlike the Blackhole’s adversary.

However, neither suggestion had any affect on RPL’s performance in the Wormhole attack scenario.

Effects on the E2E latency: Fig.4b and 7b show that the first suggestion decreased the E2E in the case of the SF scenario, especially for the ContikiMAC protocol (~220 seconds, down from ~320 seconds) compared to NullRDC (~270 seconds, down from ~330 seconds). This is, again, because some of the affected nodes chose the alternative routes away from the adversary and more data packets are delivered.

As for the second suggestion (Fig.5b and 8b), the main enhancement occurred in the case of the BH scenario (10 seconds down from 30 seconds). As the affected nodes were able to detect the dead adversary parent much faster, the total E2E was reduced by more than 50%.

Effects on the exchanged number of RPL’s control messages: As seen in Fig.5c the first suggestion increased the number of exchanged control messages for the ContikiMAC set. However, the reason this time is the added routing nodes themselves and not due to the attacks. On the other hand, the second suggestion (see Fig.5d) slightly reduced the number of exchanged RPL control messages, especially in the case of Neighbor attack scenario.

From Fig.7c and 8c we can see that both suggestions do not have any effect on the exchanged control messages when NullRDC is used. This is due to the always-on radio and the simpler sending mechanism.

Effects on power consumption: Figures 4c and 5c shows that the average network power consumption (per received packet) has been reduced for the first suggestion while increased for the second one. The reason behind the reduction for the first suggestion is due to having much more data packets delivered successfully. However, the increase in power consumption for the second suggestion is because having more probing for parent’s freshness (due to the shorter timeouts). It is worth mentioning that this analysis is only valid for ContikiMAC set and not NullRDC, as we were not able to collect usable power readings for the latter - see §IV-D.

From the discussion above, we can conclude that each of our two suggestions has mostly a positive effect on the network when under an attack. Hence, a combination of both suggestions with a dynamic timeout setup would further enhance RPL’s performance without taxing the scarce resources of the nodes. This, however, should be investigated.

VII. Conclusion

In this paper, we evaluated the performance of RPL and its security mechanisms under the presence of four common
routing attacks (the Blackhole, Selective-Forward, Neighbor, and Wormhole attacks). This evaluation was carried using two widely used RDC protocols, the ContikiMAC and NullRDC. Our analysis showed that using RPL in PSM can mitigate external adversaries of the investigated attacks (except for the Wormhole attack) as long as the adversaries do not run RPL in PSM/ASM. It also showed that using RPL in PSM/ASM without the replay protection does not consume more energy than RPL in UM. It has been confirmed that enabling the replay protection mechanism of RPL reduces the effect of the Neighbor attack at the expense of consuming more energy. We proposed two suggestions to be considered when designing RPL-based IoT networks: having more routes toward the root node and reducing the "dead parent" timeouts. Evaluating these suggestions individually showed improved performance of RPL under investigated attacks. We argue that further investigation should be conducted on implementing both of the suggestions at the same time, while having a dynamic approach for the "dead parent" timeouts optimization.

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