

Introducing Network Coding to RPL: The Chained Secure Mode (CSM)

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Abstract—As the *de facto* routing protocol for many Internet of Things (IoT) networks nowadays, and to assure the confidentiality and integrity of its control messages, the Routing Protocol for Low Power and Lossy Networks (RPL) incorporates three modes of security: the Unsecured Mode (UM), Preinstalled Secure Mode (PSM), and the Authenticated Secure Mode (ASM). While the PSM and ASM are intended to protect against external routing attacks and some replay attacks (through an optional replay protection mechanism), recent research showed that RPL in PSM is still vulnerable to many routing attacks, both internal and external. In this paper, we propose a novel secure mode for RPL, the Chained Secure Mode (CSM), based on the concept of intra-flow Network Coding. The main goal of CSM is to enhance RPL's resilience against replay attacks, with the ability to mitigate some of them. The security and performance of a proof-of-concept prototype of CSM were evaluated and compared against RPL in UM and PSM (with and without the optional replay protection) in the presence of Neighbor attack as an example. It showed that CSM has better performance and more enhanced security compared to both the UM and PSM with the replay protection. On the other hand, it showed a need for a proper recovery mechanism for the case of losing a control message.

I. INTRODUCTION

Made into a standard in 2012, RPL [1] has attracted a great deal of research interest. In particular, routing security in RPL was of special interest, including different routing attacks the protocol is susceptible to [2]–[4], mitigation methods and Intrusion Detection Systems (IDSs) [5]–[8], and performance evaluation of some of RPL's security mechanisms [9]–[12].

Raouf *et al.* in [9], [10] showed that RPL's secure modes, while providing reasonable mitigation of some external attacks, are still vulnerable to many routing attacks (both internal and external) - see §IV-A. In this paper, we propose a novel secure mode for RPL - the Chained Secure Mode (CSM) - which is designed using the principle of intra-flow Network Coding (NC) [13], [14] to introduce an extra layer of security for RPL control communications and to provide RPL with mitigation capabilities against several routing attacks, while keeping the same working principles of RPL - see §IV-B.

Our contributions can be summarized as follows:

- We designed a novel secure mode for RPL, the CSM. This new secure mode uses the principle of intra-flow NC

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to create a linked chain of coded RPL control messages between every two neighboring nodes. The chaining effect can limit adversaries' ability to launch routing attacks, e.g., Wormhole, identity-cloning, or RPL-specific attacks such as replay or Neighbor attacks [2].

- A proof-of-concept prototype of the proposed CSM was implemented in Contiki Operating System (OS) [15].
- To demonstrate the capabilities of the CSM prototype, a security and performance comparison between RPL in CSM and PSM (against the Neighbor attack (NA) as a representative of replay attacks) was conducted using several metrics. The results showed that CSM is capable of mitigating the attack with less overhead and power consumption than PSM with replay protection. In addition, CSM showed enhanced security against other types of attacks.

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. The new secure mode, CSM, is explained in section IV. Section V discusses our evaluation setup and assumptions. Evaluation results are discussed in section VI. Finally, the paper is concluded in VII.

II. RELATED WORKS

Perazzo *et al.* in [16] provided an implementation of PSM for RPL, along with the optional replay protection, named the Consistency Check (CC) mechanism. Their work was based on ContikiRPL (Contiki OS version of RPL). The authors provided an evaluation for their implementation, and compared RPL's performance between PSM and UM. However, It was noted that the replay protection mechanism introduced higher network formation time and increased power consumption. An optimized version of the replay protection mechanism was introduced in [11] that uses RPL options [1] to include another unique nonce value within the exchanged CC messages. The evaluation of the optimized mechanism showed a 36% shorter network formation time and 45% decrease in the CC messages exchanged while maintaining the same level of protection.

Airehrour *et al.* in [17] proposed a modified version of RPL, named *SecTrust-RPL*. The authors used their devised SecTrust framework [18], where the optimum route is chosen based on the trust evaluation of the nodes, resulting in isolating suspected adversaries. Trust is calculated based on the successful

packet exchange between the nodes, and it is dependent on time. SecTrust-RPL was evaluated under the Decreased Rank and Sybil attacks using Contiki OS in both simulation and a real testbed. Compared to RPL in UM under the same attacks, their implementation showed a significant decrease in lost packets ($\approx 60\%$) and lower rank changes among the nodes. However, the authors did not evaluate the effect of their implementation on power consumption and the End-to-End (E2E) latency.

III. RPL OVERVIEW

As a distance-vector routing protocol, RPL arranges the network devices into a Destination Oriented Directed Acyclic Graph (DODAG) [19]: a network of nodes connected without loops with the traffic directed toward one *root* node [1], [20].

An important aspect of creating a DODAG is the *Objective Function (OF)*, which defines the used routing metrics, how to calculate the *rank*¹, and how to select parents in the DODAG, among other essential configurations. To accommodate the different applications and environments where RPL can be deployed, RPL has several OFs [21]–[23] available for use [2]. Also, deployments of RPL can have their own OFs.

Control messages in RPL have five types; four of them have two versions (base and secure versions), and the last one has only a secure version. When enabling any of the secure modes of RPL (explained later in this section), the control messages are switched to their secure versions, which add 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/signature field [1]. All RPL messages are sent as Internet Control Message Protocol (ICMPv6) messages, with the "*Type*" field in its header equal to 155 – as set by Internet Assigned Numbers Authority (IANA) – and the "*Code*" field identifying the type of the RPL control message [1].

For the creation and maintenance of the DODAG, RPL employs the use of DODAG Information Object (DIO) and DODAG Information Solicitation (DIS) messages [1]. The process starts with the root node multicasting a DIO message that contains the essential DODAG configuration and the root node's rank (the root node has the lowest rank in the DODAG). Each node that receives a DIO message will perform the following: select its *preferred parent*, calculate its own rank, then multicast a new DIO with its calculated rank [1], [2]. 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 have arrived for a long time [1].

Destination Advertisement Object (DAO) messages contain path information about reachable nodes by its sender, and depending on RPL's mode of operation [1], it will be used to create the downward routing table. Based on the DODAG's configurations, a flag in the DAO message will mandate a DAO Acknowledgement (DAO-ACK) message from the receiver.

¹The rank of a node represents its distance to the root node based on the routing metrics defined by the OF

RPL standard offers a few security mechanisms to ensure control messages' confidentiality and integrity. Currently, RPL has three modes of security [1], [16]: *UM*, where only the link-layer security is applied, if available (default mode); *PSM*, which uses preinstalled symmetrical encryption keys to secure RPL control messages; and *ASM* uses the preinstalled keys to let the nodes join the network, after that all routing-capable nodes have to acquire new keys from an authentication authority.

As an optional security mechanism that is only available in the preinstalled (PSMrp) or authenticated mode (ASMrp), RPL offers a replay protection mechanism called the Consistency Check. In these checks, special secure control messages (CC messages) with non-repetitive nonce value are exchanged and used to assure no message replay had occurred [1], [17].

It is worth mentioning that all of the popular Internet of Things (IoT) operating systems (e.g., Contiki OS [15] and TinyOS [24]) have implemented RPL in UM only. It was not until recently the PSM was implemented by Perazzo *et al.* [16], albeit in an experimental form.

IV. THE PROPOSED CHAINED SECURE MODE (CSM)

A. Motivations

The authors in [9], [10] examined RPL secure modes' performance under several routing attacks, and have shown that PSM (and by extension, ASM) is able to mitigate most of the external attacks², while it does not enhance RPL's security against the internal attacks³. Furthermore, their work showed that external adversaries still can launch replay attacks, even when PSMrp is used (e.g., in the case of the Wormhole attack.)

A further investigation of RPL standard [1] shows that it only provides confidentiality and integrity of its control messages, without any verification of their authenticity. This opens the door wide open for attacks such as the Rank, Version, Sinkhole, Sybil, identity cloning, eavesdropping, and replay attacks [2] to be launched regardless of the secure mode RPL is running in. For example, an external adversary can launch a *Neighbor attack* (an attack where the adversary replays any DIO messages it hears without modification, deceiving the victim nodes into thinking that the original sender is within their range) by merely monitoring the "*Type*" and "*Code*" header fields in any ICMPv6 message to identify RPL's DIO messages⁴, without the need to decrypt the actual message [9].

The lack of message authenticity in RPL motivated us to devise an innovative method to overcome this problem, and NC came into the light as a possible solution. Incorporating the intra-flow NC into RPL would provide any receiving node with a proof of message authenticity, assuming that the first

²An external attack refers to an attack that is launched by an adversary who is not part of the network, e.g., it does not have the encryption keys used by the legitimate nodes for RPL in PSM, or runs RPL in UM.

³An internal attack is launched by an adversary who is part of the network, e.g., it has the encryption keys used by the legitimate nodes for RPL in PSM.

⁴(Type = 155) means this is an RPL message. (Code = 1 or 129) means it is a regular or secure DIO message, respectively.

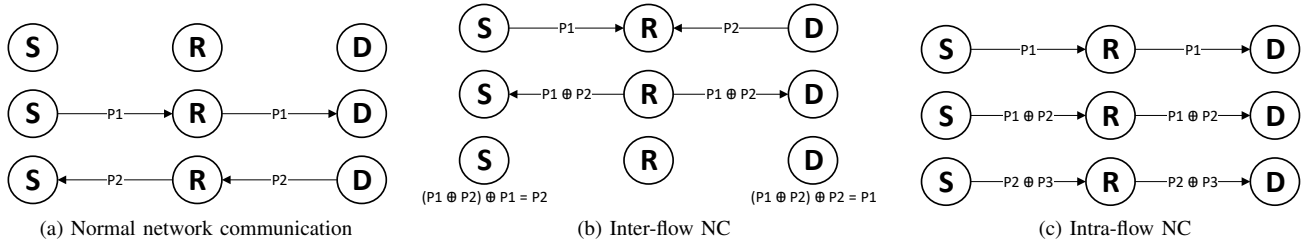


Fig. 1. Examples of NC communication. The \oplus sign represents XOR as a simple NC operation.

message came from the original sender. This case stands true for most attacks as the adversaries normally join the network after it has been initiated and stabilized.

B. Brief Review on Network Coding

NC has received a great deal of attention since it was first proposed by Ahlswede *et al.* [25]. Many researchers have investigated NC schemes, e.g., *XOR*, *Random Linear NC*, etc., for improving network efficiency, e.g., throughput, reliability, delay, using different communication technologies, e.g., wired, wireless, or ad hoc networks [26].

The basic idea of NC is that a source combines multiple pieces of information or packets using a coding scheme and forwards the coded information to the next network device. The receiver then, upon receiving enough information, decodes the combined information to recover the original data. The simplest NC scheme is XOR. For instance, a device can perform bit-by-bit XOR operations of two packets in sequence and forward the XOR-ed packet to the next hop to reduce the number of transmissions.

NC can be applied to either *inter-flow* or *intra-flow* packets. Inter-flow NC applies coding to packets from different flows (see Fig.1b), whereas intra-flow NC uses coding for packets of the same flow [27], [28] (see Fig.1c). Inter-flow NC requires more complex operations, such as buffering and synchronization of packets from multiple flows or different sources. Intra-flow NC, on the other hand, is much easier as it only considers the sequence of packets within the same flow, which makes it suitable to the resource-constrained IoT networks.

This paper proposes an innovative secure mode for RPL, the CSM, using intra-flow NC, where RPL control messages are encoded using a random secret value that is sent within the previous control message. The *chaining* effect from this method adds message authenticity to RPL and increases its resilience against eavesdropping, manipulation, forging, and replay attacks. For concept demonstration, we make use of the simplest XOR NC scheme. To add extra security against replay attacks that target certain types of RPL messages, CSM also encodes the "Code" field of the ICMPv6 header of the control message using the same secret value.

C. How CSM Operates

The simplest implementation of intra-flow NC is to *encode* the current packet with the previous one from the same flow using a simple XOR NC scheme – as in Fig.1c. Here, the

receiver node should always keep the previous packet so it can *decode* the incoming message and retrieve the new packet.

A problem that arises when implementing the aforementioned concept in an IoT network is the limited resources available for the nodes, which renders such implementation impractical. As an example, if a node has 30 neighbors, it should store the last 30 messages from these neighbors. Assuming the average size for RPL control messages is 80 bytes [1], the receiving node has to reserve 2400 bytes (≈ 2.4 KB) from its limited memory so it can decode any received message properly.

To overcome this problem, CSM uses the Secret Chaining (SC) values instead of the entire previous packet for the encoding/decoding process. These SC values (currently in our prototype design) are 4 bytes unsigned, randomly generated integer numbers, and are locally unique for each neighbor. Compared to the example mentioned above, the receiving node will store 120 bytes only of the SC values instead of 2400 bytes for all the thirty neighbors. This is a huge saving for the resource-constrained IoT nodes.

Since RPL sends its control messages as either an MC or UC messages, CSM considers them as two independent flows: an MC-flow and a UC-flow. Because of that, every node in the network should maintain a table of the following SC values for each neighbor, to be called the *SC table*:

- 1) **SC_UC_RX**: The SC value used to decode the next incoming UC-flow message from the neighbor.
- 2) **SC_MC_RX**: The SC value used to decode the next incoming MC-flow message from the neighbor.
- 3) **SC_UC_TX**: The SC value used to encode the next outgoing UC-flow message to the neighbor.

In addition, each node should maintain the next SC value for its next MC-flow transmission (**SC_MC_TX**). For simplicity, the current proof-of-concept design uses *zero* as a value for the SC used for the first transmission in each flow. Examples of the SC Table are used in Fig.4.

To exchange the SC values used to encode the next control message, CSM employs the *RPL Control Message Options* from the standard [1]. These optional add-ons contain pieces of information that informs the receiver(s) about routing metrics, updates, or to request information. CSM adds two new options to accommodate the transmission of the next SC used for each flow: the (**SC_UC_NEXT**) option includes the SC value to be used for the next UC-flow message, and (**SC_MC_NEXT**) is

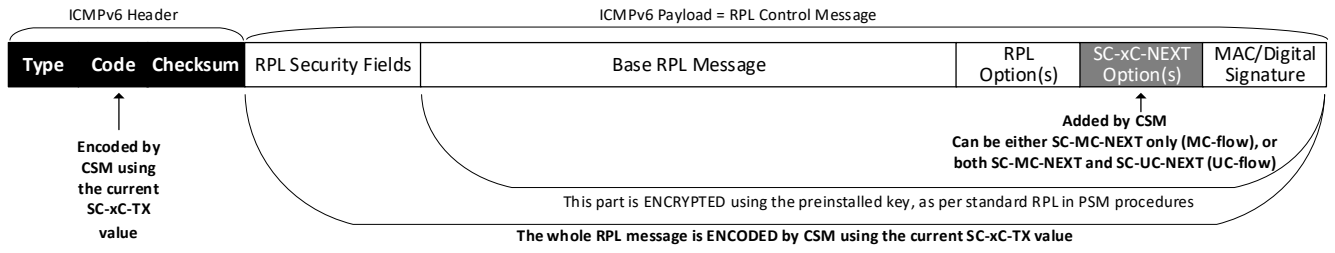


Fig. 2. Format of an RPL control message, as constructed by the proposed CSM. The black parts represents ICMPv6 header, the white parts are standard RPL in PSM fields, and the grey part is added by CSM.

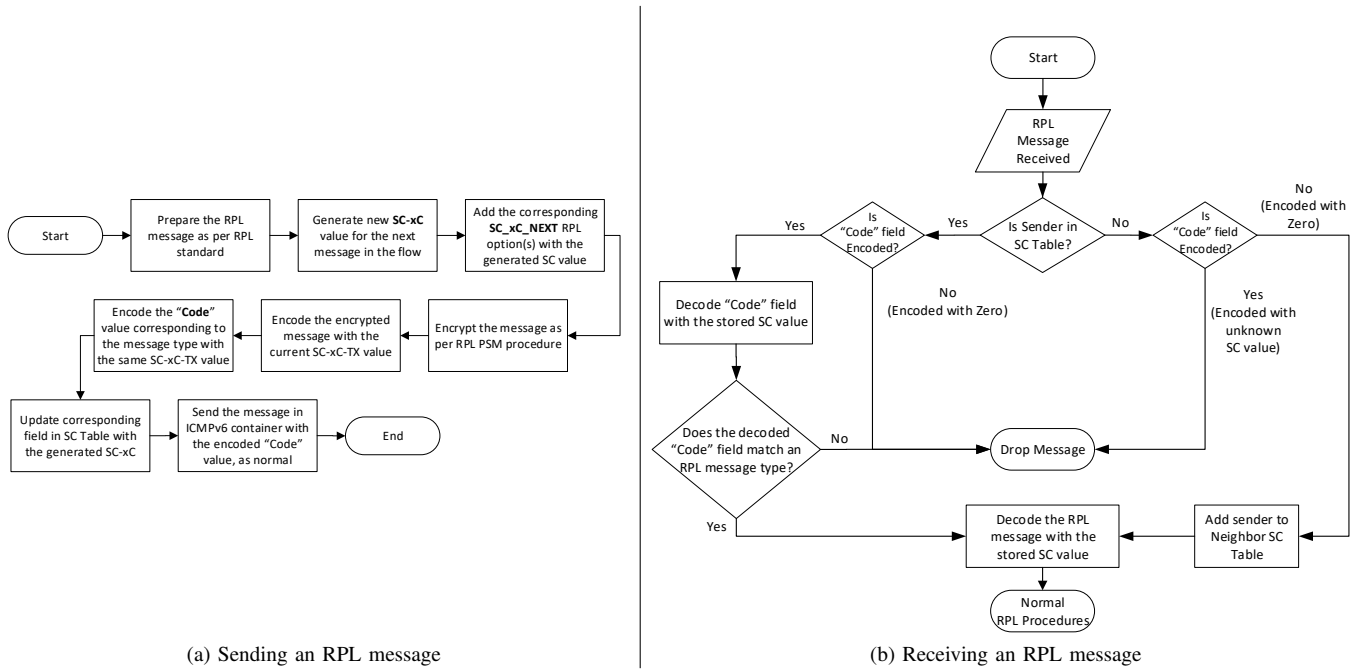


Fig. 3. Flowcharts represent the sending and reception procedure of an RPL message in the current CSM prototype.

for the SC value to be used for the next MC-flow message.

When a node wants to send an RPL control message (whether for the UC- or MC-flow), it will prepare the message as per the standard PSM procedures. Further, two additional steps are performed by CSM before encrypting the message with the preinstalled key:

- The *Code* field of the ICMPv6 header is encoded using the corresponding *SC_UC_TX* or *SC_MC_TX* value to mitigate the security vulnerability addressed in §IV-A.
- Adding the (*SC_UC_NEXT*) and (*SC_MC_NEXT*) new control message options, as per the RPL standard. CSM should add both options for UC-flow messages and only the (*SC_MC_NEXT*) for the MC-flow messages. The use of both options for the UC-flow allows for quicker recovery from message chain breakage in the MC-flow.

After encrypting the message (according to standard PSM procedures), CSM will encode the whole message using the corresponding SC value then send it as usual. Fig.2 depicts how CSM constructs an RPL message, while Fig.3a represents a flowchart of RPL message sending procedure in CSM.

At the receiving node, the decoding SC value is found from

the SC table using the sender IP address. The found SC value is used to decode the *Code* field of the ICMPv6 header to identify the type of RPL message, then the whole message is decoded using the same SC value and is processed as per PSM procedures. Any message with a non-decodable *Code* field will be discarded without processing. Fig.3b shows a flowchart for message reception in CSM.

Except for the above-mentioned requirements and procedures, CSM follows the same rules dictated by the RPL PSM standard. Fig. 4 shows examples of CSM normal operation.

V. EVALUATION OF THE CHAINED SECURE MODE

To evaluate our proposed CSM, we conducted a security and performance comparison between our devised prototype of CSM and the currently implemented secure modes: RPL in UM (vanilla ContikiRPL), PSM, and PSMrp (both according to Perazzo *et al.* [16] implementation). All the secure modes were evaluated in both normal operation and with an external adversary launching a Neighbor attack [2] (as an example of replay attacks – see §IV-A). Hence, two scenarios with four experiments each were performed.

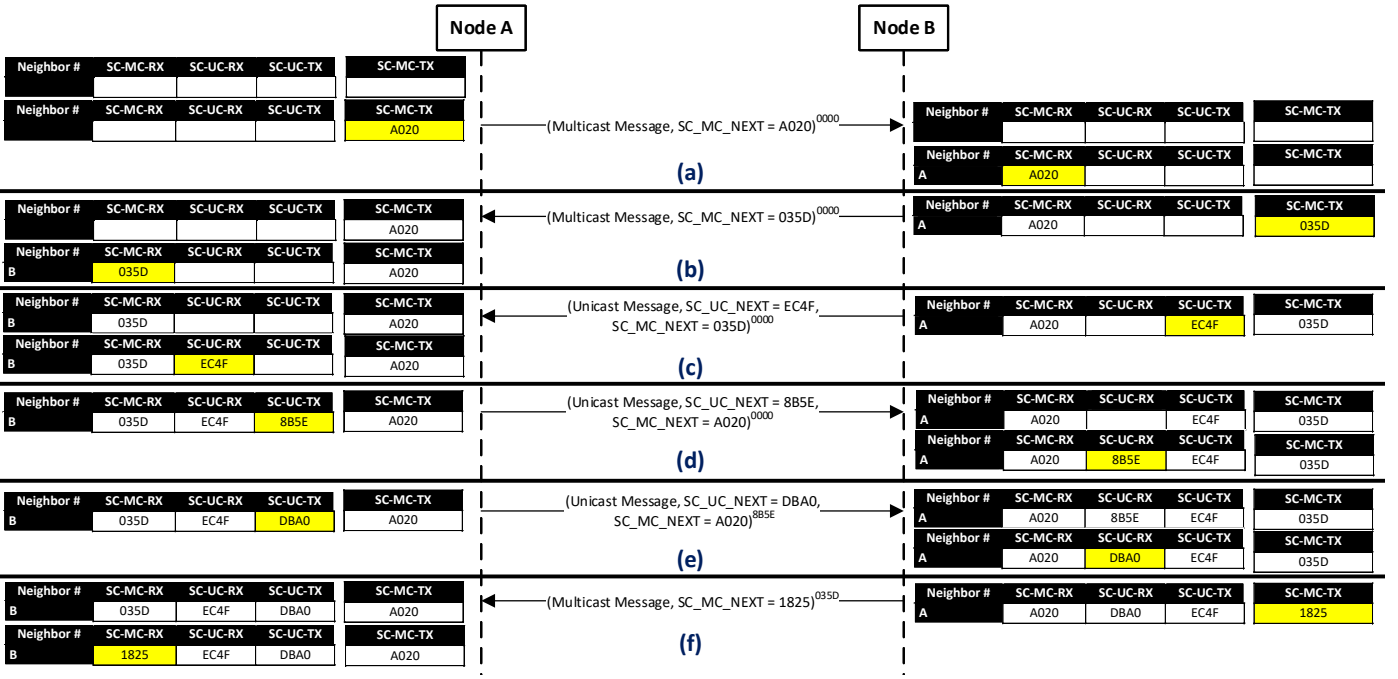


Fig. 4. Examples of normal CSM operation in chronological order (the number on the top-right of the brackets represents the SC value used to encode that message): (a and b) the first message in the MC-flow, (c and d) the first message in the UC-flow, (e) subsequent messages of the UC-flow, and (f) subsequent messages of the MC-flow. The yellow color highlights a creation or a change of an SC value in the SC table.

Cooja, the simulator for Contiki OS [15], was used for all the simulations (with simulated motes). Fig.5 shows the topology used in our evaluation. A list of simulation parameters is provided in Table I.

For the purpose of the evaluation, the following metrics were used: the average data packet delivery rate (PDR), average data E2E latency, the number of exchanged RPL control messages, and the average network power consumption per received data packet.

The following assumptions were used in our evaluation: all the legitimate nodes send data packets toward the root at a rate of 1 packet/minute per node, while the adversary does not send any data packets. For all the evaluated secure modes, RPL is set up with the default OF, namely the Minimum Rank with Hysteresis Objective Function (MRHOF) [22]. Contiki OS is using the default settings for its uIP stack: IEEE 802.15.4 [29] for the Physical layer and Medium Access Control (MAC) sublayer, ContikiMAC [30] for the Radio Duty-Cycle (RDC) sublayer, IPv6 and RPL at the Network layer, and UDP for the Transport layer. To keep the focus on RPL at the Network layer, we assumed neither security measures nor encryption was enabled at the Link layer.

For the adversary, it operates in the same RPL secure mode as the legitimate nodes, but without the required preinstalled encryption key (for PSM, PSMrp, and CSM experiments). The adversary starts as a legitimate node, tries to join the network, then launches the attack after two minutes.

The results obtained from the simulations were averaged over ten rounds per experiment with a 95% confidence level.

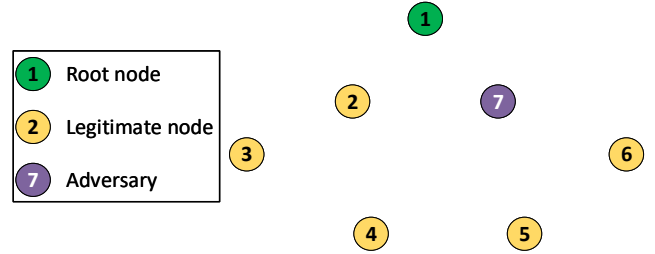


Fig. 5. Network topology used for the evaluation.

TABLE I
LIST OF SIMULATION PARAMETERS

Description	Value
No. of scenarios	Two (No attack + Neighbor attack)
No. of experiments per scenario	Four (See §V)
No. of sim. rounds per exp. / time	10 rounds / 20 min. per round
Node Positioning	Tree topology (single DODAG)
Deployment area	60m W x 85m L
Number of nodes	7 (adversary included)
Sensor nodes type	Arago Sys. Wismote mote

VI. RESULTS AND ANALYSIS

The results for the experiments are shown in Fig.6. It is worth mentioning that we are evaluating a proof-of-concept prototype of CSM that is not fully optimized.

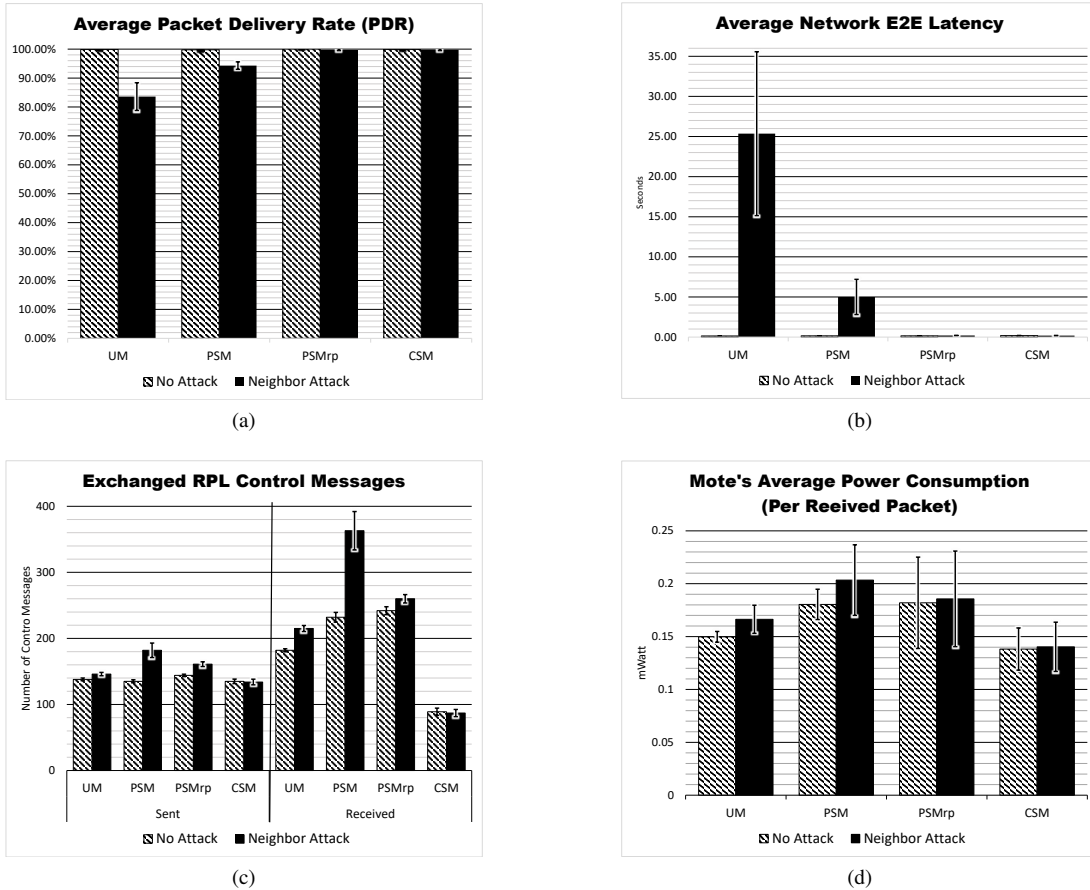


Fig. 6. Simulation results for the two scenarios and the four experiments.

A. Analysis of the Results

Effects on the data packet delivery rate (PDR): Looking at Fig.6a, it is clear that PSMr and CSM successfully eliminated the Neighbor attack effect, with both of them having almost 100% PDR. UM suffered the most (PDR \approx 80%) as the adversary actually was able to become part of the network, while PSM was affected by a small margin (PDR \approx 92%) as the adversary affected only one node (node 5) when it replayed the DIO messages it heard from nodes (1 and 2).

Effects on the data E2E latency: as pointed out in [9], [10], Fig.6b confirms that the Neighbor attack introduces higher E2E latency to the network. This is clear in the cases of UM (latency \approx 25 sec.) and PSM (latency \approx 5 sec.). On the other hand, both PSMr and CSM were able to mitigate the attack and kept the latency to its minimum (in the milliseconds).

Effects on the exchanged number of RPL's control messages: As seen in Fig.6c, the number of control messages sent in the network is almost the same for all the secure modes, with the attack increasing the number slightly. Under the Neighbor attack, nodes running PSM are receiving way more control messages than the other secure modes, due to the many MC DIO messages from the nodes 5 and 6 to the "ghost" parents (nodes 1 and 2). PSMr nodes had a bit more control messages received when the Neighbor attack is commenced,

compared to the no-attack scenario, due to the exchange of the CC messages.

On the other hand, our CSM prototype has the least number of received control messages, even less than what it had been sent originally. It was observed that this is due to some unicast DAO/DAO-ACK messages being lost (e.g., lossy wireless connections), which broke the UC message flow and resulted in having less received control messages than the sent.

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.6d shows the average network power consumption per received packet, as it gives a more accurate look into the effect of the attack on the power consumption than just using the regular average power consumption readings [9], [10]. We can see that the power consumption patterns for RPL in UM, PSM, and PSMr are very similar, with the attack slightly increasing the power consumption due to the undelivered data packets. However, it is noticeable that our CSM prototype is using less power than the other modes. From our observation, this behavior is because of the dropped control messages (whether they are the replayed messages or due to the message chain breakage).

B. Observations

Our observations from the evaluation experiments can be summarized in the following points:

1) **Enhanced Security Features of CSM:** Those can be summarized as follows:

- i) CSM adds an extra layer of security by encoding the control messages and chaining them with the SC values, which limits the adversaries' ability to eavesdrop on, manipulate, forge, and replay RPL control messages.
- ii) Because of the encoding of the *Code* field of the ICMPv6 header in CSM, external adversaries cannot identify the type of RPL control messages by reading the ICMPv6 header, except for the first message of each message flow as it is encoded with zero - see Fig.4c. Hence, external replay attacks that target specific RPL control messages (e.g., the Neighbor attack) can be mitigated by using CSM.
- iii) The PSMrp mitigates only "one-way" replay attacks, which only replay RPL control messages from a node but not any correspondence. This proved to be inefficient with enhanced "two-way" replay attacks such as Wormhole attacks [9]. Because CSM uses the chaining of the control messages (by the SC values) as a message authentication mechanism, all messages encoded with unknown SC values will be discarded without the need for a challenge/response mechanism as in PSMrp.

2) **CSM Reduction of the In-threat Period:** The *in-threat* period can be defined as "*the time duration in which an adversary can overhear and understand the whole (or a part of) the exchanged RPL control messages and launch attacks*". This period ranges between **zero** (*the adversary cannot launch attacks successfully*) to **infinity** (*the adversary can launch attacks at any time*), depending on the secure mode used, the adversary type, and the attack.

For UM, the in-threat period is **infinity** as the adversary can understand RPL messages and launch attacks at any time. On the other hand, the in-threat period for PSM can be either:

- **Infinity** for all internal adversaries or external adversaries of replay/identity-cloning attacks. The former can decrypt the whole control message with the preinstalled encryption key at any time, while the latter can identify RPL control messages through the "Type" and "Code" fields of the ICMPv6 header, then replay them at any other time without the need to decrypt the message contents.
- **Zero** for external adversaries of attacks that require a full understanding of RPL control messages; e.g., rank or version attacks, because of the lack of the used encryption key.

Due to the enhanced security caused by using intra-flow NC, CSM limits the adversaries' ability to launch several internal and external attacks that are based on identifying and understanding RPL control messages. Hence, CSM significantly reduces the in-threat period to either:

- **The time period to receive the first UC message** for all internal adversaries. During this period, the adversary

will wait for the first UC control message (which will be encoded with zeros and has the SC values for both UC and MC flows), so it can use the included SC values to decode any following message from any message flow. After that, it decrypts the message with the preinstalled encryption key.

- **Zero** for all external adversaries, due to the lack of the used encryption key and the correct SC values.

To further reduce the in-threat period for CSM, RPL should be forced to send the first UC message as soon as it finishes processing the first MC message.

3) **The Necessity of Proper Recovery Mechanism:** For any message flow (UC or MC), once a message is lost for any reason, all the subsequent messages in that flow will be discarded due to the message chain breakage. This could lead to a disruption in the DODAG and suboptimal routes. On the other hand, exchanging the missing SC values as clear text would hinder the enhanced security of CSM and allows adversaries to acquire the SC values, thus enabling them to launch their attacks. Hence, a proper recovery mechanism that assures secure exchange for the missing SC values is needed.

An example of such a recovery mechanism would be using special (request/response) control messages that are encoded with a special SC value than the one used for broken control messages flow.

VII. CONCLUSION

In this paper, we proposed a novel and new secure mode for RPL, the Chained Secure Mode, that is based on the concept of intra-flow NC, to enhance RPL security and to build a mitigation capability of replay attacks into the protocol itself, without significantly changing the way RPL works. A proof-of-concept prototype of CSM was devised, and its security and performance were evaluated against the currently implemented secure modes of RPL (UM and PSM, the latter with and without the replay protection mechanism) under the Neighbor attack as a demonstration. It was shown that CSM successfully mitigate replay attacks (e.g., the Neighbor attack) with less overhead and power consumption than the other secure modes. Also, it was shown that CSM has a significantly smaller in-threat period than all other secure modes. However, our evaluation indicated a need for a proper recovery mechanism for message chain breakage situations.

We believe that the proposed CSM has a real potential to increase RPL's resilience against routing attacks. Our next steps include adding a suitable recovery mechanism and evaluating CSM's performance under other routing attacks.

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