# Securing RPL using Network Coding: The Chained Secure Mode (CSM)

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Abstract—Considered the preferred routing protocol for many Internet of Things (IoT) networks, the Routing Protocol for Low Power and Lossy Networks (RPL) incorporates three security modes to protect the integrity and confidentiality of the routing process: the Unsecured Mode (UM), Preinstalled Secure Mode (PSM), and the Authenticated Secure Mode (ASM). Both PSM and ASM were originally designed to protect against external routing attacks, in addition to some replay attacks (through an optional replay protection mechanism). However, recent research showed that RPL, even when it operates in PSM, is still vulnerable to many routing attacks, both internal and external. In this paper, a novel secure mode for RPL, the Chained Secure Mode (CSM), is proposed using the concept of intra-flow Network Coding (NC). The CSM is designed to enhance RPL's resiliency and mitigation capability against replay attacks. In addition, CSM allows the integration with external security measures such as Intrusion Detection Systems (IDSs). An evaluation of the proposed CSM, from a security and performance point of view, was conducted and compared against RPL in UM and PSM (with and without the optional replay protection) under several routing attacks: the Neighbor attack (NA), Wormhole (WH), and CloneID attack (CA), using average packet delivery rate (PDR), End-to-End (E2E) latency, and power consumption as metrics. It showed that CSM has better performance and more enhanced security than both the UM and PSM with the replay protection while mitigating both the NA and WH attacks and significantly reducing the effect of the CA in the investigated scenarios.

*Index Terms*—IoT, Security and Privacy, Secure Routing, RPL, Routing Attacks, Chained Secure Mode, CSM.

#### I. INTRODUCTION

The Routing Protocol for Low Power and Lossy Networks (RPL) [1] has attracted a great deal of attention since it became a standard in 2012. The security aspect of RPL has been of a special interest, including different routing attacks the protocol is susceptible to [2]–[4], mitigation methods and Intrusion Detection Systems (IDSs) [5]–[7], and performance evaluation of some of RPL's security mechanisms [8]–[10].

Our previous work [8], [9] showed that RPL's secure modes, while providing reasonable mitigation of some external attacks, are still susceptible to many routing attacks (both internal and external) (see §IV-A), especially the replay attacks such as Neighbor attack (NA) and Wormhole (WH) attack.

This paper presents a significant extension to our previous conference paper [11], where we devised a proof-of-concept

prototype of Chained Secure Mode (CSM). In this work, We added a proper Secret Chaining (SC) recovery mechanism to CSM and the capability to integrate external security measures (e.g., IDSs) into CSM. Then, a thorough evaluation of the improved CSM was executed against the other RPL secure modes in the presence of several routing attacks - see §V.

Our contributions can be summarized as follows:

- A novel secure mode for RPL, the CSM, was designed and complemented with a proper recovery mechanism and integration capability with external security mechanisms. CSM makes use of the idea of intra-flow NC to create a linked chain of coded RPL control messages between every two neighboring nodes (see §IV-B). The effect of the linked chain can limit adversaries' ability to launch some routing attacks, e.g., identity-cloning and replay attacks (e.g., WH and NA attacks) [2].
- A prototype of the proposed CSM was designed and implemented in Contiki Operating System (OS) [12], including the newly-added features mentioned above.
- Using 350 simulation experiments, and to demonstrate the capabilities of the CSM prototype, a security and performance comparison between RPL in CSM and Preinstalled Secure Mode (PSM) (with and without the optional replay protection) against the NA, CloneID attack (CA), and WH attacks was conducted using several metrics.
- For the internal adversary cases, the results showed that CSM is capable of mitigating both the NA and WH attacks with less latency ( $\approx$ 95% less) and power consumption ( $\approx$ 13-28% less) than PSM with replay protection. In addition, CSM showed enhanced security and was able to significantly reduced the impact of CA on the network (PDR is 5-18% higher, E2E latency is  $\approx$ 95% less, and with comparable power consumption to that of PSM, compared to all other secure modes. See §VI.)
- For the external adversary cases, the results showed that CSM is the only secure mode capable of mitigating the WH attack with PDR ≈95-99%, E2E latency between 5-10 milliseconds, and power consumption similar to the normal operation of RPL in UM. See §VII.

The remainder of this paper is structured as follows: the next section describes the related works. Section III presents an overview of RPL and its security mechanisms. Section IV presents the proposed CSM. The experimental setup and assumptions are described in section V. Sections VI and VII present the evaluation results and analysis, respectively, which is followed by a discussion in Section VIII. Section IX presents the conclusion drawn from the proposed CSM.

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# II. Related Works

An implementation of PSM for RPL was provided by Perazzo et al. in [13], along with the optional replay protection, the Consistency Check (CC) mechanism. This implementation was based on ContikiRPL (Contiki OS version of RPL). The authors evaluated their implementation, and compared RPL's performance between PSM and UM. Their evaluation results showed that the replay protection mechanism introduced higher network formation time and increased power consumption. In an effort to enhance the CC mechanism, an optimized version of it was introduced in [10] 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. It was shown in our work in [8] that, based on the authors' implementation, PSMrp is still vulnerable to replay attacks, specifically the WH attack where the adversaries will replay the CC messages between the victim nodes.

Airehrour *et al.* in [14] proposed a modified version of RPL, named *SecTrust-RPL*, which used their devised SecTrust framework [15]. In the SecTrust framework, 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, *SecTrust-RPL* 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 E2E latency.

#### III. RPL BRIEF OVERVIEW

Being a distance-vector routing protocol, RPL arranges the network nodes into a Destination Oriented Directed Acyclic Graph (DODAG) [16]: a network of nodes connected without loops with the traffic directed toward one *root* node [1], [17]. The creation of DODAGs and how parents are selected depends on two aspects: the *Objective Function* (*OF*), which defines the used RPL configurations, and the node's *rank*<sup>1</sup>.

The DODAG in RPL is built by exchanging control messages, which have five types; four of them have two versions (base and secure versions), and the last one has only a secure version. Enabling any of the secure modes of RPL (explained later in this section) switches the control messages to their secure versions. The secure control messages 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]. As stated in the RPL standard [1], 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].

The five types of RPL control messages go as follows [1]: DODAG Information Object (DIO) and DODAG Information Solicitation (DIS) messages are used for the creation and maintenance of the upward DODAG, while the Destination Advertisement Object (DAO) / DAO Acknowledgement (DAO-ACK) pair of messages are used to create the downward routing table. Finally, the CC messages are the basis for the optional replay protection mechanism, where non-repetitive nonce values are exchanged and used to assure no DIO message replay had occurred [1], [14].

RPL standard currently offers three security modes to ensure control messages' confidentiality and integrity [1], [13]: (i) *UM*, where no RPL security features are enabled and only the link-layer security is applied, if available (default mode); (ii) *PSM*, in which preinstalled symmetrical encryption keys are used to encrypt RPL control messages; and (iii) *ASM* where two keys are used within the network: preinstalled keys are used by nodes for joining the network as leaf nodes, after that all routing-capable nodes must acquire new keys from an authentication authority after being authenticated. The new keys are used between the routing nodes only. However, the RPL standard [1] leaves all the details of ASM (e.g., how the authentication is performed, the exchange of the new encryption keys, etc.) for a future specification that has not been worked out yet.

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], [14].

It is worth mentioning that all of the popular Internet of Things (IoT) operating systems (e.g., Contiki OS [12] and TinyOS [18]) have implemented RPL in UM only. To the best of our knowledge, ASM has never been implemented, and it was not until recently that PSM was implemented by Perazzo *et al.* [13], albeit in an experimental form.

#### IV. THE PROPOSED CHAINED SECURE MODE (CSM)

## A. Motivations

Our work in [8], [9] examined RPL secure modes' performance under several routing attacks, and have shown that PSM (and by extension, ASM) can mitigate most of the external attacks<sup>2</sup>. However, it does not increase RPL's security against internal attacks<sup>3</sup>. In addition, we showed that replay attacks could still be triggered by external adversaries, even when PSMrp is used (e.g., in the case of the WH attack.)

Further, we have investigated RPL standard [1] and found out that it only provides confidentiality and integrity of its control messages, without any verification of their sender's

<sup>&</sup>lt;sup>1</sup>The rank of a node represents its distance to the root node based on the routing metrics defined by the OF

<sup>&</sup>lt;sup>2</sup>External attack is launched by an adversary who is not part of the network, e.g., it does not have the encryption key used by the legitimate nodes for RPL in PSM, or runs RPL in UM.

<sup>&</sup>lt;sup>3</sup>An internal attack is launched by an adversary who is part of the network, e.g., it has the encryption key used by the legitimate nodes for RPL in PSM.

TABLE I List of Used Abbreviations for CSM

Abbreviation	Description
SC	Secret Chaining
xC	Either Unicast (UC) or Multicast (MC) flow
ER	Emergency flow
TX	Transmitting
RX	Receiving
SRRxx	SC Recovery control message, either Request (SRReq) or Response (SRRes)

authenticity. It means that the door is wide open for attacks such as the Sybil, identity-cloning, eavesdropping, and replay attacks [2] to be launched regardless of the secure mode RPL is running. For example, a *Neighbor attack* - see §V-B - can be easily launched from an external adversary simply by checking the "*Type*" and "*Code*" fields in any ICMPv6 message header to identify RPL's DIO messages<sup>4</sup>, without the need to decrypt the actual message [8].

The lack of sender authentication in RPL control messages motivated us to devise an innovative method to overcome this problem. Integrating the intra-flow NC scheme into RPL provides a proof of message authenticity for any receiving node, assuming that the first message truly came from the original sender. This scheme stands true for most attacks as the adversaries mostly join the network after it has been initiated and established.

#### B. Brief Review on Network Coding

Since its first proposal be Ahlswede *et al.* [19], NC has received a great deal of research attention, as many researchers investigated NC schemes (e.g., *XOR*, *Random Linear NC*, etc.) to improve network efficiency (e.g., throughput, reliability, and E2E delay) on different communication technologies (wired, wireless, or ad hoc networks) [20].

NC's basic idea 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. At the receiver's end, and upon receiving enough information, the combined information is decoded to recover the original data.

The simplest NC scheme is XOR. For example, 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 [19].

Implementation-wise, NC can be applied to either (i) *inter-flow* traffic; for which NC applies coding to packets from different traffic flows (see Fig. 1b), or (ii) *intra-flow* traffic, whereas NC applies coding to packets of the same traffic flow [21], [22] (see Fig. 1c), creating a *chain* of messages. Interflow 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.

This paper proposes an innovative secure mode for RPL, the CSM, using the intra-flow NC. The *chaining* effect from this method adds sender authenticity to RPL (assuming that the first message came from the original sender) and increases its resilience against several routing attacks (e.g. replay attacks). For concept demonstration only, we make use of the simplest NC scheme, the *XOR*. However, more sophisticated NC schemes can be used for higher level of security.

Throughout this paper, a *flow* is defined as the stream of RPL control messages from a node toward a specific Internet Protocol version 6 (IPv6) address. This can be for a Unicast (UC) transmission (a unicast IPv6 address of a certain neighbor of the node) or a Multicast (MC) transmission (a multicast IPv6 address.)

## C. How CSM Operates

First, the used abbreviations are listed in Table I. The design of CSM is based on the following points:

- Adhering to the RPL standard by maintaining the same procedures used for PSM.
- Using intra-flow NC to provide broad replay-attacksmitigation capability as part of RPL standard.
- Allowing external security measures to integrate with CSM by controlling how RPL trusts nodes.
- CSM's primary focus is on protecting static networks, as they constitute the majority of current IoT applications. However, mobility can be supported using the external security measure integration mentioned above.

To implement the intra-flow NC, and instead of using the entire previous control message for the *encoding / decoding* of the current one (see Fig. 1c), CSM uses the **Secret Chaining (SC)** values which are sent within the previous control message. These SC values are 4-byte unsigned, randomly generated integer numbers (for each sent control message), and are locally unique for each neighbor.

Since RPL sends its control messages as either Multicast (MC) or Unicast (UC) messages, CSM considers them two independent flows: an MC-flow and a UC-flow. Hence, every node in the network should maintain a table (the *SC table*) of the following SC values for each neighbor, in order to successfully encode and decode their control messages:

- SC\_UC\_RX: The SC value used to decode the next incoming UC-flow message from the neighbor.
- SC\_MC\_RX: The SC value used to decode the next incoming MC-flow message from the neighbor.
- SC\_UC\_TX: The SC value used to encode the next outgoing UC-flow message to the neighbor.
- SC\_ER\_TX: The SC value used to encode the next outgoing Emergency (ER)-flow message to the neighbor see §IV-D.

In addition, each node should maintain the next SC value for its next MC-flow transmission (SC\_MC\_TX) and ERflow reception (SC\_ER\_RX) – see §IV-D. For simplicity, the current CSM design uses *zero* as a value for the SC used for the first transmission in each flow.

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 are used to provide (or request) information to (or from) the receiver. CSM

<sup>&</sup>lt;sup>4</sup>(Type = 155) means this is an RPL message. (Code = 1 or 129) means it is a regular or secure DIO message, respectively.



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 parts are added by CSM.



(b) Receiving an RPL message

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

adds three 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, (SC\_MC\_NEXT) is for the SC value to be used for the next MC-flow message, and (SC\_ER) is for the SC value to be used for the next ER-flow message – see §IV-D.

When a node wants to send an RPL control message (whether for the UC-, MC, or ER-flow), it will follow the following steps (see Fig. 3a):

- 1) Prepare the message as per the standard PSM procedures.
- 2) Generate a new SC value to be sent within the corresponding RPL option. The generation process also ensures that the generated SC values, when used to encode the ICMPv6 Code field (see step 4), will not result in one of the valid values of the RPL message type identifier. This step is not performed for SC Recovery Request/Response (SRR) messages see §IV-D.
- 3) Adding the (SC\_xC\_NEXT) and (SC\_ER) new control message options, as per the RPL standard. CSM should add both the (SC\_UC\_NEXT) and (SC\_MC\_NEXT) 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.
- 4) 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. The only exception is the *SRR* messages, which keep their designated ICMPv6 "Code" value without encoding – see §IV-D. Since the Code field is one byte long, its encoding will be a sequential one, i.e., it is encoded first with the first byte of the SC value, then the result is encoded with the second byte of the SC value, and so on.

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



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.

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. The whole message then is decoded using the same SC value and is processed based on PSM's procedures. If the *Code* field cannot be decoded, the message will be discarded without processing. Fig. 3b shows a flowchart for message reception in CSM.

Fig. 4 shows a few examples of the normal CSM operations. Parts (a) and (b) represent the first MC transmissions, where the sender node generates a new SC\_MC\_TX value (to be used for its next MC transmission) and SC\_ER\_RX. Then, it adds the newly-introduced SC\_xC\_NEXT and SC\_ER RPL control message options (which includes the generated SC values) to the sent message before encoding it with zero (this is the very first MC transmission). At the receiver side, once the message is decoded successfully (using zeros for the SC value as it is the first MC message from the sender), the receiver adds an entry to its SC Table for the sender with the SC values it extracts from the received message, e.g., node B will store the value A020 in the SC MC RX field of node A's entry. A similar situation is shown in parts (c) and (d) for the first UC transmission. However, the difference here is the inclusion of both the UC and MC SC values in the sent message, which means all SC values of the sender will be updated. Finally, parts (e) and (f) show how the subsequent UC and MC transmissions will update the SC Table at the nodes. For example, in part (e), node B will use the stored SC\_UC\_RX for node A (8B5E) to decode the received UC message, then updates node A's entry with the extracted SC values, e.g., SC\_UC\_RX will become DBA0.

## D. SC Recovery Mechanism

Our initial work [11] showed that CSM requires a proper recovery mechanism when a control message from any NC flow is missed or lost, otherwise all subsequent communications in that flow will be discarded due to not having the correct SC value to decode it.

As CSM is designed for the static networks, there are two cases where nodes can loose track of the SC values:-

- Node Reset: When a node is reset for any reason (e.g., battery replacement, firmware upgrades, etc.), it will lose all stored SC values and start from scratch. For this, CSM assumes that the OS will periodically save all SC values (node's own and SC table) to the filesystem, and loads them at boot-up time, so the node can resume from the point just before the reset.
- 2) Lost or Corrupt Messages: Missing a control message is normal for lossy networks such as the ones RPL is designed for [1]. However, in CSM this means breaking the message-chain for one of (or both) flows, resulting in discarding all subsequent messages of the broken flow.

To recover from the second case mentioned above, CSM implements a special recovery mechanism, dubbed the *SC Recovery*. This recovery mechanism applies only to the neighbors that are already in the SC table. To secure the recovery process, the SC values are not sent as clear text. Instead, a challenge/response exchange is performed based on the concept of solving Linear Algebra equations that involves the missing SC values. In general, assuming that node (A) is the receiver of the "non-decodable" message and node (B) is the original sender, node (A) will send an SC Recovery Request (SRReq) message to node (B) containing the coefficients of a system of linear equations, to which node (B) will use the coefficients and its next SC values to calculate the results of the

linear equations. These results are replied to node (A) inside an SC Recovery Response (SRRes) message. Now, node (A) will use the provided information to solve the linear equations and extracts the missing SC values for node (B). The reason behind this procedure is to raise the bar for the adversaries to launch attacks against (or abusing) the recovery mechanism.

Based on the above-mentioned concept, The SC recovery mechanism goes as follows:

- A new NC flow is added to CSM, the *Emergency (ER) flow*, to be used when exchanging the SRR messages. Each node will maintain an SC value (SC\_ER) for this flow, and exchanges it through the (SC\_ER) option in every message of the other flows – see §IV-C. However, the SC\_ER only updates after a successful recovery.
- When a message is received, if the decoded "Code" field at the ICMPv6 header of the received message does not represent an RPL control message, the following methods are performed to recover the missing SC value:
  - If the received message was from the MC-flow, a regular UC-DIS message is sent to the sender. As per RPL standard, the sender must reply with a regular UC-DIO, which will have all the correct SC values for the next message in all the flows.
  - If the received message was from the UC-flow, the SC recovery mechanism is conducted:
    - 1) The received message will be discarded.
    - 2) The receiver sends a UC-SRReq message to the original sender, containing the randomly-generated coefficient values to be used by the original sender as explained above. The SRReq is encoded with the original sender's SC\_ER value.
    - 3) Once receiving the SRReq message, the original sender will calculate the results of the linear equations, then it sends them within a MC-SRRes message to the receiver, encoded with the receiver's SC\_ER value. Since this is a multicast message, the SRRes message contains the IPv6 address of the node that is supposed to process it. In addition, the original sender will update his SC\_ER and send it within the corresponding RPL option.
    - Now, the receiver will use the coefficients and the received results to solve the linear equations and update its SC table with the extracted SC values.

#### E. The CSM-Trust Integration Interface

To allow integration with external security measures, CSM provides a trust-based control interface for such security systems called the *CSM-Trust* interface, which uses the *TrustVal* value (as part of the SC table) to define the trust-worthiness of each of the node's neighbors. Hence, the acceptance or rejection of RPL's control messages from that neighbor.

The *CSM-Trust* interface allows external security measures to set and use the *TrustVal* value according to their needs. For example, an external security mechanism (such as an IDS) would set the boundaries for *TrustVal*; the maximum (*TrustValMax*) and minimum (*TrustValMin*), and the trigger value (*TrustTrig*) that, if *TrustVal* went below it, CSM will drop



Fig. 5. CSM-Trust interface conceptual diagram.

any RPL control messages from that neighbor. the conceptual diagram of *CSM-Trust* interface is shown in Fig. 5.

In addition, the calculation of *TrustVal* is left to the external mechanism and can be dynamic to allow for larger flexibility to different applications and scenarios. For example, an IDS can use its own methods (e.g., special messages, monitoring the traffic, etc.) to determine the neighbor's trustworthiness, then it updates *TrustVal* in the SC table, which tells CSM if it should accept or reject control messages from that neighbor.

## V. EVALUATION OF THE CHAINED SECURE MODE

To evaluate our proposed CSM, we conducted a comparison on security and performance 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.* [13] implementation). All secure modes were evaluated against three routing attacks (NA, CA, and WH).

## A. Evaluation Setup and Assumptions

The default simulator for Contiki OS [12], Cooja, was used for all the simulations (with simulated motes). The topology used in our evaluation is shown in Fig. 6, and simulation parameters are listed in Table II.

As the chosen metrics for the evaluation, the average data PDR, average data E2E latency, and the average network power consumption per received data packet were all used for the comparison.

The following assumptions were used in our evaluation: For all the evaluated secure modes, the default OF for RPL was used, i.e., Minimum Rank with Hysteresis Objective Function (MRHOF) [23]. Settings of Contiki OS's uIP stack were as follows: IEEE 802.15.4 [24] for the Physical layer and



Fig. 6. Network topology used for the evaluation. The adversaries' locations are represented by a dark-purple circle (No Attack, NA, and CA scenarios) or the light-purple ones (WH scenario.)

Medium Access Control (MAC) sublayer, ContikiMAC [25] and NullRDC [12] for the Radio Duty-Cycle (RDC) sublayer (see below), IPv6 and RPL at the Network layer, and UDP for the Transport layer. To keep the focus on RPL, we assumed neither security measures nor encryption were enabled at the Link layer. Data packets are sent toward the root by legitimate nodes only and at a rate of 1 packet/minutes per node.

As explained in our previous work [8], Contiki OS supports several RDC protocols [12], with the ContikiMAC and Null-RDC being the most common ones. The main difference between the two is that ContikiMAC is designed to aggressively conserve energy more than NullRDC, at the expense of having longer E2E latency [8], [26]. In this paper, the implementation of the WH attack is based on our work in [8]; hence, it is only available using NullRDC protocol.

The data traffic model used for the evaluation, as described above, is a deterministic one that mimics a typical sensing-IoT network, where nodes send their sensor readings toward the root node at predetermined periods.

To test the external mechanism integration capability of CSM, the following simple, proof-of-concept, external security mechanism was implemented (only in CSM experiment):

- *TrustValMin*, *TrustValMax*, and *TrustTrig* were set to 0, 100, and 50, respectively.
- For the first RPL message from a neighbor, a successful reception will set *TrustVal* to *TrustValMax*.
- Afterward, *TrustVal* will increase or decrease based on the successful (or unsuccessful) decoding of the received RPL control messages. The increment/decrement amount was set to 10.

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

# B. Adversary Model and Attack Scenarios

The following attacks were chosen due to the low 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

 TABLE II

 List of Simulation Parameters (per RDC protocol)

Description	Value
No. of simulation sets	Two: one for each adversary type (Internal and External) (See $V-B$ )
No. of experiments per set	Four: one for each secure mode (UM, PSM, PSMrp, and CSM)
No. of scenarios per experiment	3 (ContikiMAC) / 4 (NullRDC) - See §V-A
Sim. rounds per scenario / time	10 rounds / 20 min. per round
Node positioning	Random distribution
Deployment area	210m W x 150m L
Number of nodes	28 (29 for the WH scenario) includes 1 adversary (2 for WH)
Sensor nodes type	Arago Sys. Wismote mote

these attacks can be significant on the network. The location of the adversary(ies) was chosen to present the most prominent effect of the investigated attacks [27]–[29].

All the secure modes were evaluated in both normal operation (*No Attack*) and against three replay routing attacks [2], [28] (the following depicts our implementation of the attacks):-

- Neighbor attack (NA): Whenever the adversary hears a DIO message from any neighbor (regardless of its destination), it will replay it (as a multicast) to all its neighbors without modifications or processing, deluding them to think that the original sender is within their range. If the original sender has a better rank (see §III), the receivers of the replayed message will select it as their preferred parent, which may result in lost data packets and longer E2E delays [8]. The objectives of this attack [2] are the disruption of data packets transmission and the disconnection of the routing topology.
- 2) CloneID attack (CA): The adversary will clone the identity of another node, in our case node (25), by changing its IPv6 and MAC addresses to match that of the cloned node (by monitoring its frames and RPL messages). In addition, it will follow and copy the cloned node's rank by reading its DIO messages. Our implementation combined CA with a Selective-Forward (SF) attack (that only drops data packets passing through the adversary) to better show how the CA changed the DODAG around the adversary. The main goals of this attack [2] are to disrupt the routing topology and manipulate any reputation-based IDS.
- 3) Out-of-Band Wormhole (WH) attack: Two adversaries (connected by an out-of-band link) will forward and replay all RPL control messages they hear from their neighbors between the two locations where they reside. Due to simulation limitations [8], this attack scenario is only available in the NullRDC set of experiments. The attack aims [2] to increase data packets' latency, disrupt the routing topology, exhaust the victim nodes' energy, and disconnect parts of the network.

For the adversaries, they run in the same RPL secure mode as the legitimate nodes. However, they have two types: *Internal* adversaries, where they have the proper preinstalled encryption



Fig. 7. Simulation results for the four experiments (three attacks scenarios - internal adversary), using ContikiMAC RDC protocol.



Fig. 8. Simulation results for the four experiments (four attacks scenarios - internal adversary), using NullRDC RDC protocol.

key for PSM, PSMrp, and CSM experiments; and the *External* adversaries, which do not have the required encryption key. Also, it is worth mentioning that the external and internal versions of the adversaries in UM scenario are the same.

In all cases, the adversary starts as a legitimate node, tries to join the network, then launches the attack after two minutes. For the Wormhole attack, the two adversaries are always in promiscuous mode and never participate in the DODAG.

# VI. RESULTS FOR INTERNAL ADVERSARY SETS

#### A. Effects on the Data PDR

Looking at Fig. 7a (ContikiMAC) and Fig. 8a (NullRDC), it is clear that PSMrp and CSM (for both ContikiMAC and NullRDC) successfully eliminated the NA effect, with both of them having almost 100% PDR. UM and PSM suffered more (PDR $\approx$  80-90%) as the adversary actually was able to become part of the network.

For the CA scenario, it is noticeable that the attack was able to confuse the surrounding nodes and in many cases it successfully switched their preferred parent to the adversary for the UM, PSM, and PSMrp. This shows in the lower PDR (PDR $\approx$  80-85%) for all secure modes except CSM. On the other hand, CSM was able to reduce the effect of the attack (PDR $\approx$  85-95%), albeit the reduction here is caused by CSM's integration with the external security mechanism, which acted as a dynamic blacklist and "*untrusted*" both the legitimate and cloned nodes after several unsuccessful recovery attempts.

Finally, CSM outperformed the other secure modes in the WH attack scenario, where it was able to mitigate the attack (PDR $\approx$  95-99% compared to 75-80% for the other secure modes). This is mainly due to CSM policy of dropping, without processing, RPL control messages from new neighbors if they were encoded with unknown SC values. Hence, the routing topology will not change due to the WH attack.

#### B. Effects on the Data E2E Latency

Looking at Fig. 7b (ContikiMAC) and Fig. 8b (NullRDC), it can be seen that NA has been mitigated by both PSMrp and CSM (latency  $\approx$  a few milliseconds), and that it introduced higher E2E latency to the network for the other secure modes ( $\approx$ 40-70 seconds), confirming our previous findings in [8], [9].

The results for the CA shows the significant effect of the attack on the network, where the latency is in the (100-200) seconds range for UM and PSM, while PSMrp varies between 20 seconds (NullRDC) to 100 seconds (ContikiMAC). This variation is caused by ContikiMAC as its energy-conservative mechanism amplifies any latencies due to transceiver extended *sleep* times [8], [26].

Further proofing CSM's ability to mitigate the WH attack, latency is kept to minimum (<5 seconds) compared to the other secure modes ( $\approx$ 80-200 seconds), for both RDC protocols.

## C. Effects on Power Consumption

Comparing Fig. 7c (ContikiMAC) and 8c (NullRDC), it can be seen that all secure modes have similar patterns, where



Fig. 9. Simulation results for the four experiments (three attacks scenarios - external adversary), using ContikiMAC RDC protocol.



Fig. 10. Simulation results for the four experiments (four attacks scenarios - external adversary), using NuIRDC RDC protocol.

the CA scenario has the higher power consumption in the ContikiMAC set, and the WH attack scenario has the highest power consumption in the NullRDC set. However, CSM has the lowest power consumption in every situation when compared to other secure modes. This is more prominent in the WH attack scenario. It is worth mentioning that power readings for NullRDC are higher than the ones for ContikiMAC, as the transceiver is always on for the former while it is off most of the time for the latter [8], [9].

## VII. RESULTS FOR EXTERNAL ADVERSARY SETS

#### A. Effects on the Data PDR

Fig. 9a (ContikiMAC) and Fig. 10a (NullRDC) show that PSM, PSMrp, and CSM are capable of mitigating both NA and CA, with the latter having a slightly more effect in the case of ContikiMAC set (PDR  $\approx$  90-99%). However, CSM was the only secure mode that mitigated the WH attack with (PDR  $\approx$  98%) compared to ( $\approx$  70-75%) for the other secure modes.

To explain the effect of the CA attack on the network when ContikiMAC is used, we must first understand the way RPL decides on selecting the preferred parent or switching to another parent. In general, RPL depends on neighbors' statistics, which are provided by RPL itself, IPv6 Network Discovery protocol [30], and Link-layer protocols. In ContikiMAC, the Link-layer statistics depends on the successfully-received frames, probing frames, and acknowledgment frames from these neighbors, among other factors [31]. Now, when RPL operates on top of ContikiMAC, it will use these statistics, besides its own, to decide if the neighbor is still "*fresh*" or not; hence, if it should keep it in its possible-parents list or even as the preferred parent [1]. However, NullRDC does not provide such statistics, leaving RPL only to use its statistics.

Since the dropped RPL control messages are still successfully received by ContikiMAC, it will affect RPL's decision on keeping the victim node (and the cloned node - adversary) as the preferred parent at the neighboring nodes. In many cases, it will prolong the time required to switch to another parent until RPL's statistics point to a communication failure and force the switch, unlike the case for NullRDC where RPL quickly detects the communication failure and switch to another parent.

## B. Effects on the Data E2E Latency

similar to the analysis of PDR, Fig. 9b (ContikiMAC) and Fig. 10b (NullRDC) show that the three secure modes have successfully mitigated the NA, while the CA still has an effect in the case of ContikiMAC for the same reason mentioned above. Again, CSM shows as the only secure mode capable of mitigating the WH attack, with minimum E2E latency.

# C. Effects on Power Consumption

The results for ContikiMAC (Fig. 9c) shows similar patterns among all the secure modes and for all attacks as a proof of significant attacks' mitigation. However, PSM, PSMrp, and CSM do have a slightly more power consumption than UM in the No Attack scenario, due to the additional security measures. This case is reversed for the CA attack scenario, as the UM was the only mode fully affected by the attack.

Fig. 10c show that all three secure modes have similar patterns for the NA and CA scenarios (significant mitigation of the attacks) under NullRDC. While, for the WH attack, CSM has the lowest power consumption (matching the No Attack scenario), due to the mitigation of the attack.

## VIII. DISCUSSION

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

#### A. 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, providing a means of sender authentication which limits the adversaries' ability to eavesdrop on, manipulate, forge, and replay RPL control messages.
- ii) Encoding of the *Code* field of the ICMPv6 header in CSM means that 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 currently encoded with zero see Fig. 4c. Hence, external replay attacks that target specific RPL control messages (e.g., NA) can be mitigated by using CSM.
- iii) Unlike PSMrp, CSM provides mitigation to both "oneway" and "two-way replay attacks (e.g., the NA and WH, respectively), due to the chaining of the control messages (by the SC values) that acts as a sender authentication mechanism, without the need for a challenge/response mechanism as in PSMrp.

Due to the characteristics of the intra-flow NC, there is one case where an internal adversary can launch one of the investigated attacks, which is if it is able to extract and track all the SC values from the exchanged RPL control messages between the adversary's neighbors, which requires the adversary to be around the victim nodes when the network starts operating. However, tracking all the SC values for all the neighboring nodes' communications (and in other parts of the network for a WH attack) would require a tremendous amount of resources (e.g., processing power, memory/storage capacity, and fast transceiver) to be available to the adversary. The amount of the required resources depends on the IoT network size, the location of the adversary, the number of victim nodes, and the type of attack desired.

## B. CSM Reduction of the In-threat Period

The in-threat period for a replay-attack adversary 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 replay 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 always **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 from 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, due to the lack of the used encryption key.

As CSM enhances RPL security through the intra-flow NC, it limits the adversaries' ability to launch several internal and external attacks that require identifying and understanding RPL control messages. Hence, CSM significantly reduces the in-threat period to either:

- The time between receiving the first MC and the first UC messages for all internal adversaries. During this period, the adversary will try to intercept the first UC control message (which is encoded with zeros and has the SC values for both UC and MC flows), so it can use the included SC values to decode (then decrypt) the following message from any flow. However, the adversary needs to continuously intercept and decode all messages from its victims in order to keep up with used SC values, which significantly raises the cost of any attack's launch.
- Zero for all external adversaries, due to the lack of both the used encryption key and the correct SC values. In addition, CSM's encoding of the "Code" field of the ICMPv6 header makes it harder to the adversary to identify the type of RPL control message; hence, more difficult to launch message-specific replay attacks.

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

## C. Trades-offs for CSM

It is clear from the analysis of the power consumption patterns (Figures 7c, 8c, 9c, and 10c) that CSM power consumption is slightly higher than UM and PSM when there is no attack. This is mainly due to the SC recovery mechanism, which was triggered several times during the experiments, mainly when there is a lot of traffic (e.g., at the network initialization phase or when there is an active attack), due to the increased number of lost/corrupt control messages. All of the reported results include the overhead of running the SC recovery mechanism. On the advantage side, the evaluations proved the superiority of CSM at mitigating the investigated attacks with higher data PDR, lower data packet latency, and lower average power consumption compared to the other secure modes when under attacks.

## IX. CONCLUSION

In this paper, we proposed a novel secure mode for RPL, the Chained Secure Mode, that is based on the concept of intraflow 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 prototype of CSM was devised, and its security and performance were evaluated against the currently implemented secure modes of RPL (UM, PSM, and PSMrp) under three replay routing attacks (NA, CA, and WH attack). It was shown that CSM successfully mitigated the replay attacks (NA and WH attack) while significantly reduced the effect of CA, all with latency and power consumption less than the other secure modes. Also, it was shown that CSM has a significantly smaller in-threat period than all other secure modes. In addition, the ability to integrate external security mechanism opens the door to further enhance RPL security through future expansions. For example, it is possible to support mobility vie suitable external security mechanism that would allow CSM to trust the mobile nodes, which is left for future work.

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