TRAIL: Topology Authentication in RPL

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Abstract—The IPv6 Routing Protocol for Low-Power and Lossy Networks was recently introduced as the new routing standard for the Internet of Things. Although RPL defines basic security modes, it remains vulnerable to topological attacks which facilitate blackholing, interception, and resource exhaustion. We are concerned with analyzing the corresponding threats and protecting future RPL deployments from such attacks.

Our contributions are twofold. First, we analyze the state of the art, in particular the protective scheme VeRA and present two new rank order attacks as well as extensions to mitigate them. Second, we derive and evaluate TRAIL, a generic scheme for topology authentication in RPL. TRAIL solely relies on the basic assumptions of RPL that (1) the root node serves as a trust anchor and (2) each node interconnects to the root in a strict hierarchy. Using proper reachability tests, TRAIL scalably and reliably identifies any topological attacker without strong cryptographic efforts.

Keywords: IoT, routing security, mobile security, topology verification

I. INTRODUCTION

RPL [1] has been designed as an efficient and scalable routing protocol for low-power and lossy networks (LLN). It promises to reduce the overall power consumption by minimizing the control traffic, which is a major requirement for the energy constrained devices envisioned in the future Internet of Things (IoT). Such tiny intercommunicating devices like sensor nodes used in (home) automation, smart grids or surveillance systems are expected to massively populate our environment soon.

RPL constructs one or several tree topologies oriented towards a single root node. Each node in the RPL routing graph has a rank derived from its parent relationship that describes the topological distance to the root. Every node joining the topology calculates a higher rank than its parent, lower ranks are used for default upstream. This proactive organization leads to a Destination Oriented Directed Acyclic Graph (DODAG) topology, from which RPL is able to detect and remove inconsistencies reactively.

Control traffic in this topology consists of DODAG Information Objects (DIOs). A DIO advertises parameters and constraints for a specific DODAG that is uniquely identified by a version number. A node uses the information obtained from a DIO to select a parent node, compute its rank and join the DODAG, from which it inherits an upward route towards the root node. An optional upwards advertisement of Destination Advertisement Objects (DAO) generates downward-oriented routes to children of a subtree. Depending on the mode of operation, these routes are either maintained and stored at each node (storing mode), or forwarded to the root node and collected there (non-storing mode). The integrity of distribution trees is essential for RPL, as an inconsistent hierarchy will lead to traffic redirections and a loss of routes to the root. In addition, RPL will attempt to cure tree deficiencies by reorganization, and a node that will hold up failures of the routing hierarchy may trigger repeated reconfigurations that drain resources of the network.

RPL offers basic protection against external attackers breaking into the topology [1]. However, as nodes may be captured and security keys can be extracted from them, the RPL topology is threatened by various attacks from inside the network. The rank of a node and the DODAG version number are focal attributes in the topology. Known attacks are foremost based on them. A false rank of a node forges the relative topological distance to the root and thus disarranges the hierarchy. An inconsistent version breaks the reference to the topological graph and causes the network to rebuild its routing graph. Corresponding protections are not part of the current RPL specifications.

Recently, VeRA [2] has been proposed to fix these two classes of vulnerabilities by adding reverse hash chaining to DIO messages. Receivers shall be enabled to verify the advertised hierarchy. However, in the following we can show that VeRA remains vulnerable to rank attacks by forgery and replay. We analyze its incompleteness of message-rank-authentication, and present enhancements to VeRA for repair. Leaving aside the complexity of VeRA, our remaining work concentrates on a generic scheme for verifying RPL topologies. We design and evaluate TRAIL (Trust Anchor Interconnection Loop) that can discover and isolate bogus nodes while they attack the RPL routing hierarchy. TRAIL is derived of first hand principles and shall resolve the issues of topological infringements. It has been implemented and made openly available on the RIOT platform [3].

The remainder of this work is structured as follows. Section [I] discusses the problem of securing RPL, common attacks and related work. The incompleteness of VeRA is examined in Section [II]. Countermeasures for fixing VeRA are presented in Section [III]. Section [IV] introduces TRAIL, our generic solution for topology authentication. Finally, we conclude in Section [V] and look out on future work.

II. RPL SECURITY CHALLENGES & RELATED WORK

RPL constructs a reverse path forwarding hierarchy by announcing tree parameters in the downward direction, starting
from the root node. A node that successfully joined the tree advertises its rank towards its potential children in so called DIO messages, while unconnected nodes select as parent the neighbor of lowest rank, i.e., in closest position to the root. Following this algorithm, a fully connected graph of unambiguous hierarchical relations is created in compliance to wireless reachability. Each of such DODAGs is associated with a unique version number to survey consistency.

RPL specifies secured control plane messages for authenticity, integrity, and optional confidentiality [1]. Even though these basic security features defend against external attackers [3], RPL remains unprotected against adversaries from inside the network [2], [5]. Capturing a node and extracting security credentials enables an attacker to gain access to the control plane and to modify the routing topology. The rank and the version number are the key information for defining the structure of the routing system. The essential challenge for securing the routing topology thus is to protect rank and version number from any unwanted modification. Next, we introduce the core attacks against the RPL topology and the assumptions made on the attacker.

A. Attacker Model

We assume the presence of one or multiple attackers that physically captured and compromised multiple, arbitrary nodes on the network. The attacker has access to all available keys on the captured nodes, which include all information for joining and participating in the DODAG without restrictions. The compromised nodes are successfully integrated in the network and are thus authorized to transmit authenticated messages. Furthermore, the attacker is limited by the resources and constraints of the captured nodes. Hence, we assume that the attacker cannot install directed antennas or create multiple identities [6] to seemingly use several malicious nodes with one physical interface or to establish out-of-band channels. The attacker aims at maximizing his impact on the network, for example by attracting as much traffic as possible for eavesdropping or sink-holing, or by affecting the operational conditions of as many nodes as possible.

B. Topology Attacks

1) Version Number Attacks: The version number of the DODAG is increased by the root node, whenever a global repair is needed. This occurs, if inconsistencies cannot be repaired locally. In a version number attack [2], an attacker illegally increases the version number of the DODAG. Publishing a higher version number will lead to a reconstruction of the RPL topology. This either serves as a preparation for a following attack such as on the rank, or can be repeatedly executed to disturb the network and drain the resources of nodes.

2) Rank Spoofing Attack: In a rank spoofing attack [2], a malicious node propagates an incorrect rank to change its position in the routing tree. Commonly, an attacker will choose a lower rank to improve its position in the hierarchy and achieve larger impact on the network. In response to forged rank advertisements, neighboring nodes select the attacker as parent and forward traffic towards it. Fig. 1(a) visualises the topological manipulations caused by a strict rank decrease. The attacker M propagates the lowest rank of the vicinity and attracts all its neighbors. In this example, the parent node H is also attracted by the malicious node M, which creates a sinkhole. Node 3 correctly selects M as parent, but unknowingly propagates the illegal rank downtree. Thus, 3 and its parents potentially attract even more children and increase the number of nodes that forward traffic towards the attacker M.

3) Rank Replay Attack: An attacker who learned a valid rank from a (potential) parent may replay this value in its own advertisements and pretend to run at one hierarchy level above the proper value. This special case of a rank spoofing will not disconnect the attacker from the root as visualised in Fig. 1(b) In contrast to arbitrary rank forgery, the replay allows a malicious node to re-use a proper rank, even if rank verification schemes apply. We will show in the following section that present protection schemes are vulnerable to rank replay attack.

C. Related Work

Up until now, only limited work has addressed the security of the RPL routing system. A security threat analysis for LLNs by the IETF [4] focuses on potential threats and attacks. However, the analysis solely proposes generic countermeasures to the described attacks. Some attempts have been made to deal with topology attacks [7], [2], [8], [9]. The authors in [7] propose an Intrusion Detection System to mitigate the rank attack and a local repair mechanism by installing additional monitoring nodes. VeRA addresses the rank and version number attacks by adding a rank and version control obtained from hash chaining [2], [10]. While successfully
mitigating a version number attack, the VeRA approach is still subject to two topology attacks [11]. As we will work out in the following section, the first attack is a general rank spoofing, which allows an attacker to pretend any rank and therefore any position in the DODAG. The second attack is a rank reply attack, which allows an attacker to claim one level closer to the root by replaying its parent’s rank. Weekly and Pister [9] concentrate on the evaluation of sinkhole attacks and their impact on the data throughput in RPL. They utilize a rank authentication based on VeRA and introduce a parent fail-over technique to blacklist sinkhole nodes. The root maintains a list of nodes that go below a threshold, which defines the minimum expected data receptions for each node. A node that finds itself on the list, blacklists its default next-hop towards the root, since some node on the path seems to not forward traffic. The authors observe that an adversary can attack VeRA by replaying the rank of his parent. Similarly, Wallgren et al. [9] propose to maintain a whitelist in combination with a heartbeat protocol in which the root periodically sends echo requests to each node to check the connectivity. A node that does not respond is considered malicious and is thus removed from the whitelist.

Our work goes beyond mitigating sinkhole attacks. By performing generic topological tests, we inquire on the integrity of the routing hierarchy, identify and isolate individual attackers. The rank protection approaches discussed above rely on the authentication of digital signatures. Authentication in RPL is implemented either by an asymmetric signature scheme like RSA [12], or a symmetric message authentication code like CBC-MAC [13] with a pre-shared key. Even though the complex use of asymmetric cryptography in wireless LLNs is not per se feasible [14], [15], [16], it adds the advantage to unambiguously authenticate the sender of a message. Conversely, when a MAC is created from a group key, it suffers the disadvantage of authenticating any sender from that group. Recent work on pre-computation techniques [12] strengthened the case for standard signature deployment on sensor nodes. In this work, we rely on the RPL root node as a trust anchor, since it is commonly deployed as a more powerful gateway node. Signature creation remains bound to this RPL root.

III. ATTACKING VERA

A. VERA in a nutshell

VeRA is performed in two steps: initialization and version number update. The scheme assumes that the nodes are given a public key $pk$ for a public key signature scheme like RSA, and the corresponding secret key $sk$ is known only to the DODAG root.

Initialization: The DODAG root generates the hash chains to be used for securing version number and rank updates. For $n$ version updates, the root picks a random number $r$, a secure hash function $h$, and computes a hash chain, \{$r, V_i\}_{i=0,\ldots,n}$, with $V_i = h^{n+1-i}(r)$. Additionally, the root generates a rank hash chain of size $l + 1$ for each version $V_l$. Let $R_{i,j}$ denote the rank hash chain for $V_l$. Then, its elements are computed as $R_{i,j} = h^{j+1}(x_i)$, where $x_i$ is a random number. Subsequently, for bootstrapping the security, the root broadcast an initialization message \{$V_0, V_{N_0}, MAC_{V_1}(R_{i,1}), \ldots\}$ to all nodes in a DIO message. Thereby, $V_{N_0}$ denotes an initial version number chosen by the root and $\sigma = Sig_{sk}(V_0, V_{N_0}, MAC_{V_1}(R_{i,1}))$ the signature. Each node stores this message after verifying the signature using the public key $pk$.

Version number update: To update the version of a DODAG from $V_{N_{i-1}}$ to $V_{N_i}$, the root sends a DIO message \{$V_{N_i}, V_i, MAC_{V_{i+1}}(R_{i+1,1}), R_{i,\text{Rank}_{\text{sender}}}\}$, where $Rank_{\text{sender}}$ is its new rank. Each intermediate node receiving this message checks first whether the new version number is higher than the current one, i.e., if $V_{N_i} > V_{N_{i-1}}$. If this is the case, it continues to verify that the version update was indeed initiated by the root by checking if $V_0 = h(V_{N_{i-1}}) = h^i(V_i)$ holds. If any of these verifications fails, the node terminates the version update operation. Otherwise, it proceeds with verifying the rank of its parent by checking the hash chain consistency, i.e., $MAC_{V_i}(h^{\tau-Rank_{parent}}(R_{i,\text{Rank}_{\text{parent}}})) = MAC_{V_i}(R_{i,\tau})$. Note that $MAC_{V_i}(R_{i,\tau})$ was received in the previous update, while $V_i$ is received in the current update. Finally, the child node calculates its own rank $\tau$ using the objective function and forwards the received DIO message to nodes lower in the topology with the corresponding rank chain element $R_{i,\text{Rank}_{\text{sender}}} = h^{\tau-Rank_{\text{sender}}}(R_{i,\text{Rank}_{\text{parent}}})$.

B. (In)Security of VERA

The security of VeRA relies on the assumption that increasing the version number or decreasing the rank value requires an attacker to compute the pre-image of a hash chain element. However, due to the stateful nature of the VeRA protocol, the pre-image resistance of the hash chains alone are not sufficient for security. VeRA is a stateful protocol, since the security of each version update relies on the parameters revealed in a previous update. Although, the initialization message is signed, as shown in Section III-B1, it is not sufficient to mitigate rank chain forgery performed by malicious insiders or when jamming attacks are considered. Hence, additional

\[ R_{i,\text{Rank}_{\text{sender}}} = h^{Rank_{\text{root}}(x_i)}. \]
methods preserving backward secrecy of the rank hash chains are needed to mitigate VeRA against such attack.\footnote{Solutions based on time synchronization are not considered in this work.} Within the scope of the VeRA protocol, we give the following definitions:

**Definition Perfect-backward-secure version update protocol:** A version update protocol is perfect-backward-secure if an adversary cannot efficiently calculate a valid rank hash chain \( \{x'_i, R'_i, l\}_{i=\{n,...,1\}} \) with \( x_i \neq x'_i \) even if it is given all elements of the version hash chain, i.e., \( V^i \), the corresponding rank hash chains \( \{x_i, R_i, l\}_{i=\{n,...,1\}} \), and the signature \( \sigma \). A hash chain \( \{x'_i, R'_i, l\}_{i=\{n,...,1\}} \) is valid, if its verification in the \( i \)th version update, i.e., \( \{V^i\}_{i=\{n,...,1\}} \), at any receiving node returns a success.

**Definition \( \lambda \)-backward-secure version update protocol:** A version update protocol is \( \lambda \)-backward-secure if an adversary cannot efficiently calculate a valid rank hash chain \( \{x'_i, R'_i, l\}_{i=\{n,...,1\}} \) with \( x_i \neq x'_i \) even if it is given up to \( \lambda < n \) elements of the version hash chain, i.e., \( V_i \), the corresponding rank hash chains \( \{x_i, R_i, l\}_{i=\{n,...,1\}} \), and the signature \( \sigma \). A hash chain \( \{x'_i, R'_i, l\}_{i=\{n,...,1\}} \) is valid, if its verification in the \( i \)th version update, i.e., \( \{V^i\}_{i=\{n,...,1\}} \), at any receiving node returns a success.

**Lemma** The VeRA protocol is a \( \lambda \)-backward-secure version update protocol.

**Proof (Sketch):** Consider a VeRA setting for \( n = 3 \). Furthermore, consider the version hash chain \( \{r, V_3, V_2, V_1, V_0\} \), and the rank hash chains \( \{(x_3, R_{3,l}), (x_2, R_{2,l}), (x_1, R_{1,l})\} \). Given the version hash chain element \( V_2 \), the adversary can calculate a valid hash chain \( \{x'_2, R'_2, l\} \) by simply picking a random number \( x'_2 \) and subsequently authenticating \( R'_2 \) with the MAC using \( V_2 \) as the key. This rank hash chain would be verified as valid in a version update \( V_2 \). Hence, the VeRA protocol is 2-backward-secure version update protocol. That is, it remains secure against rank hash chain forgery as long as no version hash chain element \( V_{\lambda > 2} \) is compromised. \( \blacksquare \)

**Remark** Praxis relevance of backward-secrecy: RPL is a routing protocol for LLNs. A typical characteristic of such networks, such as WSNs, is that they are often deployed in public and even in hostile environments. Hence, they are typically easy to access by attackers. Wireless communication used in such networks allows an attacker to disrupt and even entirely block the communication between nodes. For instance, (selective) jamming attacks allow to partition a network. Similarly, selective-forwarding attacks allow the attacker to drop selected packets during routing. Such attacks allow the adversary for decreasing its own rank and, hence, the rank of those nodes located in its sub-DODAG if the version update protocol used is only \( \lambda \)-backward-secure like VeRA. In the following, we describe a practical rank chain forgery attack in existence of e.g., selective-forwarding or jamming attacks.

1) **Rank hash chain forgery attack:** VeRA is only 2-backward-secure. Hence, it is vulnerable to rank chain forgery. Such an attack might be performed as follows. The DIO messages for two subsequent version updates \( V_N i \) and \( V_N i+1 \) are prevented from being received by all or some of the nodes within the network. This can be achieved e.g., through a selective-forwarding or (selective-)jamming attack on the DIO messages of the version updates. After receiving the hash chain element \( V_{i+1} \) in the version update \( V_N i \), the attacker calculates a bogus hash chain \( \{x_{i+1}'', R_{i+1}'\} \) by simply picking a random number \( x''_{i+1} \) and subsequently authenticating it with the MAC using \( V_{i+1} \) as the key. Subsequently, the blocked version update \( V_N i+1 \) is resumed by forwarding the DIO message containing the MAC of the forged rank hash chain \( MAC_{V_{i+1}}(R_{i+1}'\}) \). Finally, once the version update \( V_N i+1 \) is completed, the version update \( V_N i+1 \) is initiated, in which the attacker can claim an arbitrary rank value.

2) **Rank replay attack:** In each rank update, VeRA discloses the cryptographic credentials needed for verifying the advertisements from parents to each node. These credentials are not bound to any sender-specific attributes. Hence, a malicious node can transparently forward them down the tree to decrease its rank. As visualized in Fig. \( \textsf{1(b)} \), a malicious node \( M \) receives valid rank announcements from the honest node \( H \). This includes the version hash \( V_i \), its rank \( j \), and the associated hash element \( R_{i,j} \). It can simply re-use them in its own rank advertisements to nodes \( 1 . . . 4 \) for gaining one hierarchy level. In consequence, the honest nodes \( 1, 2, 3 \) and \( 4 \) can verify the bogus rank announcements and prefer \( M \) over \( H \) due to better connectivity. Node 3 correctly selects \( M \) as parent, but calculates a falsely improved rank. All children of \( M \) propagate maliciously lowered ranks down the sub-DODAG.

IV. Fixing VeRA

We introduce two countermeasures to fix VeRA against the described attacks. Our first countermeasure makes the VeRA approach perfect-backward-secure and, hence, it mitigates the rank hash chain forgery attacks. Our second countermeasure is a simple challenge-response procedure proposed for mitigating the rank replay attacks.

A. VeRA++: Perfect-backward-secure VeRA

VeRA authenticates a rank hash chain for a version \( V_i \) using a MAC keyed with \( V_i \). In each version number update a MAC key is revealed. Hence, VeRA provides only the \( \lambda \)-backward-secrecy. To achieve the perfect-backward-secrecy, we propose to authenticate the rank hash chains using an encryption chain instead of MACs. In the following, we first describe the construction of the proposed encryption chain. Subsequently, we describe the VeRA++ approach, i.e. an extension of VeRA with the proposed encryption chain. Finally, we show that VeRA++ provides the perfect-backward-secrecy.

1) **Construction of the encryption chain:** After generating the version number hash chain and the rank hash chains \( \{x_i, R_i, l\}_{i=\{n,...,1\}} \) as described in Section III-A, the root node computes the (rank) encryption chain \( \{c_i\}_{i=\{n,...,1\}} \) as follows:

\[ c_0 = \text{last element of rank hash chain for } V_n, \quad \text{i.e., } \quad c_0 = R_{n,1}. \]

Subsequent elements of the encryption chain \( c_i \) are calculated by encrypting the last element of the corresponding rank hash chain \( R_{i,l} \) using \( c_{i+1} \) as the encryption key.
is, \( \{ c_i = \text{enc}_{c_{i+1}}(R_{i,1}) \}_{i=n-1, \ldots, 1} \), where \( \text{enc} \) is a symmetric key encryption scheme such as AES.

2) Extension of VeRA with the encryption chain: In VeRA++, the initialization and version number update steps are performed slightly differently than in VeRA. In the initialization step, the root broadcasts the initialization message \( \{ V_0, V_{N_0}, c_1, c_0, \sigma \} \) to all nodes in a DIO message. Thereby, \( \sigma = \text{Sig}_{sk}(V_0, V_{N_0}, c_1, c_0) \). As in the VeRA, each node stores this message after verifying the signature with \( pk \).

In the version number update step, to update the version of DODAG from \( V_{N_i-1} \) to \( V_{N_i} \), the root sends a DIO message \( \{ V_{N_i}, V_i, c_i, R_i, \text{Rank}_{next} \} \). Similar to VeRA, each intermediate node receiving first checks if the new version number is higher than the current one, i.e., if \( V_{N_i} > V_{N_i-1} \). If this is the case, it continues to verify that the version update was indeed initialized by the root by checking if \( V_0 = h(V_{N_i} - V_{N_0}) (V_i) = h^i (V_i) \) holds. If one of these verifications fail, the node terminates the version update operation. Otherwise, it proceeds with verifying the rank of its parent.

Assume that the parent node claims to have the rank value \( \text{Rank}_{\text{parent}} \). The child node verifies its validity by checking if \( h^{i-\text{Rank}_{\text{parent}}} = \text{dec}_{c_i}(c_{i-1}) \). Note that \( c_{i-1} \) was received in the previous update. A successful verification implies that the rank of its parent is increasing monotonically. Subsequently, the child node calculates its own rank \( \tau \) using the objective function and forwards the received DIO message to the nodes lower in the topology as in VeRA.

3) Security of VeRA++: We show that the VeRA++ approach is a perfect-backward-secure version update protocol.

**Proposition:** The VeRA++ approach described above is a perfect-backward-secure version update protocol if the underlying encryption function \( \text{enc} \), the signature scheme \( \text{Sig} \), and the hash function \( h \) are cryptographically secure.

**Proof (Sketch):** Assume that the VeRA++ approach a \( \lambda \)-backward-secure version update protocol. Then, according to our definition, given a hash chain element \( V_i \) with \( \lambda < n \) and the encryption chain \( \{ c_i \}_{i=\lambda, \ldots, 1} \) and the rank hash chains \( \{ x_i, R_{i,1} \}_{i=\lambda, \ldots, 1} \) and the signature \( \sigma \), there exist an efficient algorithm that calculates a forged rank hash chain \( \{ x'_i, R'_{i,1} \} \) with \( x_i \neq x'_i \) which is valid for a version update \( \{ V_{N_i} \}_{i=n, \ldots, 1} \).

- \( i = 1: \ c_1 \) is signed. Thus, there is only one possibility for calculating a forged rank hash chain \( \{ x'_1, R'_{1,1} \} \) with \( x'_1 \neq x_1 \). All the adversarial needs to find a \( c'_1 \) such that \( R'_{1,1} = \text{dec}_{c'_1}(c_1) \) for an arbitrarily chosen \( x'_1 \). The probability of finding such inputs \( (c'_2, c_1, x'_1) \) is negligible if the underlying encryption function \( \text{enc} \) is secure and the hash function \( h \) is pre-image resistant and the signature scheme is secure.

- \( i = \lambda: \) For calculating a forged rank hash chain \( \{ x'_1, R'_{1,1} \} \) with \( x'_1 \neq x_1 \), the adversary needs to find a \( c'_{\lambda+1} \) such that \( R'_{1,1} = \text{dec}_{c'_{\lambda+1}}(c_\lambda) \) for an arbitrarily chosen \( x'_1 \). However, the probability of such inputs \( (c'_{\lambda+1}, c_\lambda, x'_1) \) is negligible if the underlying encryption function \( \text{enc} \) is secure and the hash function \( h \) is pre-image resistant and the signature scheme is secure.

4In the last version update, no decryption is required since \( c_n = R_{n,1} \).

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B. Countermeasure against Rank Replay Attacks

To mitigate rank replay attacks, we introduce a challenge-response scheme based on the rank hierarchy implemented by RPL. A malicious node, claiming a lower rank value than its actual value, is challenged to prove that it has a parent node of lower rank than the claimed.

1) General Idea: Each RPL node receives the rank hash chain element of its parent to verify the parent’s rank as well as to calculate its own rank. A parent node, claiming to have the rank one lower in a version update \( i \), sends the hash chain element \( R_{i,j-1} \) to its children. Each child receiving this message verifies it by checking if \( R_{i,j-1} = h^{i-1}(R_{i,j-2}) \) holds. However, due to pre-image resistance of the hash function \( h \), they cannot calculate \( R_{i,j-2} \), i.e., the hash chain element valid for their grandparent nodes. Our scheme relies on this one-way property of the rank hash chains. That is, any node claiming to have a rank \( j \) knows (or can calculate) the hash chain element of their parents, their own, and their children only, i.e., \( \{ R_{i,k} \}_{k=j-1, \ldots, j} \). The hash chain elements for lower ranks (e.g., for their grandparents) \( \{ R_{i,k'} \}_{k'=1, \ldots, j-2} \) remain unknown to them (or cannot be calculated by them). Hence, any node claiming to have a rank \( j \) must be able to encrypt a challenge message using \( R_{i,j-1} \) as the key, correctly. An attacker that incorrectly replays the rank hash chain element of their own cannot encrypt a challenge such as, since it needs to know the key \( R_{i,j-2} \) in such a case.

2) Challenge-Response Scheme: Assume that the node \( M \) depicted in Fig. 2 is suspicious of replaying the rank \( j \) of its parent \( H \) to obtain an improved position in the DODAG topology. To verify the rank of \( M \), the parent node \( H \) constructs a challenge message \( \langle ID_M, r \rangle \), which includes the host ID of \( M \) \( ID_M \) and a random number \( r \). This message is to be encrypted by \( M \) with \( R_{i,j-1} \). \( M \) shall reply with \( \text{enc}_{R_{i,j-1}}(\langle ID_M, r \rangle) \) to \( H \). \( H \) can then check whether \( M \) holds the correct rank. If \( M \) cannot solve the challenge, it has no valid parent of the claimed rank and incorrectly announced \( j \).

3) Applying the Challenge-Response Scheme: The challenge-response scheme is initiated by a RPL node...
that complies with two requirements: (a) it is at the same rank level as claimed by the attacker, (b) it is within the transmission range of the attacker. The first requirement allows for self-organization among RPL nodes according to correct and incorrect ranks (i.e., who initiates the challenge). The second requirement is necessary to react on suspicious rank announcements (i.e., observing rank upgrade). It is noteworthy that these requirements fully comply to the RPL protocol message design.

Our approach detects the potential attack by requiring each node to multicast its rank to all neighbors. If a parent $H$ detects an inconsistent routing state, which is not removed by a local repair, the suspicious node is challenged to proof its rank. If the node does not pass the challenge, either the sub-DODAG can simply be excluded from upward routing, or the root node can be included in the validation process. The root creates a validation packet for the children of the malicious node $M$. This gives each node the ability to independently react and for example discard $M$ as a routing node. Note that the root node can trust $H$ after the update is delivered successfully and the replay detection is applied recursively from $H$ to the root.

Remark Our challenge-response scheme is not secure in existence of out-of-band channels or $k$ directly connected attackers. An attacker, who can obtain the rank hash chain element for a rank $j - \Delta$ through such a tunnel, can correctly respond any challenge issued for verifying the ranks $\leq j - \Delta$. Another limitation of this approach is that the children of a malicious cannot be reliably notified about an attack. Introducing a white- or blacklist containing benign or malicious nodes respectively, as proposed in [9] and [8], holds the drawback of straining the entire network with local information. Hence, in the next section we propose TRAIL which inverses the direction of rank validations.

V. TRAIL – TRUST ANCHOR INTERCONNECTION LOOP

We introduce TRAIL, our generic approach to detect and prevent topological inconsistencies. In contrast to the previous approaches, each node is enabled to validate its upward path to the root and to detect rank spoofing on it. Our test furthermore identifies the largest sub-DODAG(s) affected by non-monotonous rank order. Having learned such inconsistency, the root of that sub-DODAG may either trigger a local repair, or disconnect its malicious sub-tree and rely on alternate paths.

A. TRAIL Idea: Path Validation

The key idea of TRAIL is to validate upward paths to the root using a round trip message. Without relying on encryption chains as in VeRA++, a node can conclude rank integrity from an recursively intact upward path.

A child node that received a rank advertisement from its parent initiates a positive attestation of the rank as follows. It sends a test message with a random nonce $\eta$ upwards to its parent. The parent adds its rank $j$ and forwards the test message $(j, \eta)$ upstream towards the root. At each intermediate hop, the receiving upper node verifies that (a) the rank in the test message is higher than its own, and (b) the rank of the sending node lies in between the rank of the test message and its own. If a rank violation is observed, the test message is discarded and the sub-DODAG gets either disconnected or a local repair is started (see Fig. 3). The test message eventually arrives at the root, which adds the current version number to the test message and signs for its way back to the initiating client. Every forwarding node verifies if the signed message contains the scribed rank $j >$ its own rank before forwarding it. A violated relation stops the propagation of the message. On reception, the client verifies the signature, matches its...
nonce, and obtains evidence of the current version number and the rank advertised by its parent. As the rank announcement had consistently travelled to the root, no honest node on the path had observed a rank violation and the upstream is valid. A child not receiving the reply, continues without positive attestation of its parent. It may choose another upstream, if available, or apply additional measures for transport security.

After all nodes have applied this test recursively down the hierarchy with success, it is assured that none of the nodes has a parent that illegally lowered its rank. The highest ranked node that unsuccessfully performs the test identifies the root of the largest sub-DODAG affected by rank spoofing. It should be noted, though, that a directly connected chain of \( k \) malicious nodes can secretly replay rank values \( k-1 \) times so that they are counted in the test as one node. However, this costly attack does not decrease rank values of the attackers, but solely extends the wireless reach of the malicious group and cannot be observed without surveillance of the wireless geometry.

As every node in the network needs to inquire with the root individually, the overhead in messages and signature processing grows linearly with the network size. Hence, this simple scheme of path validation suffers the obvious drawback of scalability. In the following, we will present an aggregated scheme that keeps messages per node and signature computation constant.

### B. Scalable Path Validation

1) **Rank Attestation Scheme:** The path validation can be turned into a scalable procedure by aggregating all client-specific inquiries into a single message exchange. Starting from the leaf nodes of a DODAG, we design a convergecast that reaches up to the root. The root node receives and signs a single, converged request that serves as a universal path attestation message when distributed downstream via multicast.

After a leaf node \( N_{l,k} \) of the DODAG has received the rank advertisement of its parent (and discovered that it has no further children), it issues a nonce \( \eta_{l,k} \) to its parent. The parent node collects the nonces \( \{\eta_{l,k}\} \) of all children and writes them into a single array element. For space efficiency, the parent combines the nonces in a Bloom filter \[20\]. Note that this Bloom filter can be very short, as the number of entries is limited by the number of children per node. This array element containing a single Bloom filter is sent upstream to the grandparent and saved by the node.

From each of its children, the grandparent receives such an array of Bloom filters together with an individual nonce. It should be noted that these arrays need not be of equal lengths, as the tree may be unbalanced. The grandparent aligns every array on the position below the child node rank and merges the entries of equal index using the scalable Bloom filter technique of Almeida et al. \[21\]. In detail, the grandparent node extracts all first index elements \( A_i(1) \), merges them and writes the result to a new output array \( B \) at the index 2 (incremented by one). In general, \( \{A_i(1)\} \) are merged into \( B(k+1) \), if existent. Finally, the node adds the Bloom filter that aggregates all nonces of its immediate children to the array element \( B(1) \) forwards the array \( B \) upwards together with its own nonce and saves both \( B \) and its nonce.

As depicted in Fig. 4 in proceeding this way stepwise towards the root, an array is created whose index represents the rank and whose values are merged Bloom filters of all nonces issued at a specific rank. Thereby array elements are of variable length, each accommodating the concatenated Bloom filters as generated according to the shape of the tree. Additionally every node on the path saves the array and nonce they forward for latter validation. The root node adds the current version number and signs the data structure consisting of the Bloom filter array and the version number. Thereafter, the signed data is distributed via multicast down the tree.

On the reception, each node can verify the version, and the rank of its parent. It accesses the corresponding array element to match its nonce in the Bloom filter and verifies that no further array element contains the same nonce. Finally, it verifies that the signed Bloom filter array does not contain less nonces than the previously saved array. Note that the probability of a false positive hit can be chosen sufficiently low when configuring the Bloom filter. A successful match testate that ranks have increased monotonically from the root downwards and that the array and contained nonces have not been manipulated or reordered. Whenever the matching fails, monotonic rank order has been violated on the upward path from the current node to the root. The highest ranked node detecting such violation forms the root of an inconsistently connected sub-DODAG. Any node experiencing such inconsistency may choose another upstream, if available, or apply additional measures for transport security.

2) **Security Proof:** We show that a malicious node cannot improve its rank by modifying the data structure, and that improper modifications are detected in the verification phase.

**Assumptions:** We rely on the attacker model specified in Section II-A. In particular, we refer to an attacker that has no means to establish an out-of-band communication channel. A chain of \( k \) malicious neighbors is considered as one attacker with an extended wireless reach. Distributed attackers scattered among different hierarchy levels communicating out-of-band channel cannot be detected and are not considered in our model. However, non-collaborating attackers distributed in the topology are considered. Finally, we ignore the false positive rates on queries to bloom filters as they can be made arbitrarily small by choosing appropriate parameters.

**Proof:** We consider the security of TRAIL in existence of i) multiple non-collaborating malicious nodes and ii) multiple malicious nodes with limited collaboration:
i) Multiple non-collaborating malicious nodes: Since the nodes are not allowed to collaborate, they can be considered as multiple single attackers. For simplicity, we provide the analysis for a single malicious node. A malicious node receiving a topology test message \( \langle \eta, A \rangle \) from its child(ren) has the option to (1) not include its child(ren) in the message array or to not merge-and-forward the array \( A \) at all. It may as well (2) rearrange the array, and in particular include the nonces of its child(ren) at a wrong array position. It may (3) attempt to exclude itself from the attestation hierarchy by not submitting its nonce value to its parent. These four choices of malicious nodes will lead to the following conditions:

1. By not forwarding the test nonces of its children or the attestation array, the malicious node causes its immediate detection. When receiving the signed attestation message of the root, the child(ren) of the malicious node will test for its nonces without success and detect the inconsistency.

2. The best a malicious node can do to its children is writing nonces at the foreseen position. Any misplacement will move data of the children to a lower rank position and thus cannot be aligned with a malicious rank upgrade. Other rearrangements of the array will change the data positions for nodes lower in the tree. This implies that affected nodes are not within the wireless transmission range of the malicious node – they had chosen the better rank of the malicious node otherwise. As the malicious node cannot coordinate rank advertisements outside its wireless reach, nodes will remain unaware of their nonce moving to other rank positions. Nodes will thus search at the original rank position in the attestation message and corresponding tests will fail.

3. If the malicious node withholds its own nonce, but cooperates in traversing the merged filter array, its honest parent will merge the data with data from its other children and insert at the proper position. Not delivering the nonce will simply lead to a Bloom filter that does not contain the nonce of the malicious node. Hence, an malicious node causes nothing but excluding itself from the verification process.

ii) Multiple malicious nodes with limited collaboration: We mean by a limited collaboration that multiple attackers know in advance their position in the topology and the desired rank which they want to claim during an attack. This can be realized by configuring them accordingly during their deployment. Limited indicates that once they are deployed, those malicious nodes, which are not within each other’s communication range, cannot communicate anymore. TRAIL mitigates such attacks as follows: A malicious node close to the root merges array elements on behalf collaborating malicious nodes lower in the topology that claim a false rank. Consequently, nonces of honest nodes that are affected by the rank spoofing, are moved to the correct array element. However, due to the malicious merging of array elements, these nonces exist multiple times. Such a duplicate either denotes a fraud or a false positive. Given a false positive rate of \( f \), we detect the attack with probability \( 1 - f \). Deleting nonces from filters will cause that an honest node on the path will detect the attack by comparing the forwarded array with the signed one.

In any of the cases, forgery will not comply to a rank decrease and will be detected, whenever it affects third party nodes. All parents of a malicious node will always exclusively write to the lower rank-test positions, which is the obvious protection from rank spoofing in this procedure.

3) Details of the Bloom Filter: We use Bloom filters [20], a space-efficient random data structure, to reduce message lengths in our attestation scheme. A Bloom filter is defined as a bit-vector, \( v \) of \( m \) bit and represents a data set. By using \( k \) independent hash functions, each element of a set of \( A = \{a_1, \ldots, a_n\} \) is mapped to \( k \) bits in \( v \). By these means, the size of each input element is reduced to at most \( k \) bits. Due to randomized overlapping of bits from different elements, the size may be reduced even further, but this may return a false positive result of a query. Essentially, there is a linear relation between number of bits used for storing each element, and the false positive rate. Mitzenmacher [23] could show that properly designed Bloom filters can be compressed even further by about 30% at a given false positive rate. Almeida et. al. [21] designed a scalable extension of Bloom filters that linearly add filter elements with increasing set sizes.

In TRAIL, we require tiny Bloom filters that store nonces from the children set of a single node. For a commonly small fanout of \( k \) nodes and a false positive rate below 1%, an appropriate bit-size \( m \) of the (compressed) Bloom filters can be estimated as \( m = 6k \) [bits].

C. Evaluation

For the evaluation of our RPL security scheme, we have implemented TRAIL authentication as an extension to the RPL protocol on the RIOT platform [3] and performed experiments on the DES Mesh Testbed of FU Berlin [23]. For the sake of brevity, we concentrate on the overhead cost and the temporal performance of the routing protocol.

Critical cost metrics for wireless sensor nodes relate to over the air transmission, e.g., the number of messages sent, as well as message lengths. Hence, we first analyze the message characteristics of TRAIL as a function of the network size. The critical resource consumption of TRAIL is given by the sizes of the test messages. As nodes need to accumulate nonce values of their parent nodes, the attestation array grows with increasing network sizes. While messages are tiny at the leaf nodes, the array gets larger towards the root node. Fig. 5 visualizes the average message sizes for different fanout degrees \( k \) of the tree nodes as functions of the total network size. For simplicity, we assume balanced \( k \)-ary trees, but results are not strongly dependent on tree shapes. It is clearly visible that small message sizes compliant to 6LowPAN MTUs constrain network dimensions by about \( \approx 250 \) nodes. The characteristic performance aspects of TRAIL for different network sizes and tree configurations are summarized in Table I.

Our second evaluation targets at the temporal performance of route convergence. We deployed TRAIL on 25 MSBA2 nodes distributed in the sensor network testbed. RPL/TRAII
Our first contribution in this paper was to analyze and improve VeRA, a cryptographically centered protection scheme. We identified new attack vectors and modified VeRA to withstand them. While returning to the topological core of the problem, our second contribution introduces TRAIL. TRAIL defines a test procedure to inquire on the actual path properties of the routing system. This generic approach is built on firsthand principles and – different from VeRA – requires almost no cryptography. Its main cryptographic workload is carried out by the root node, which acts as a (stronger) gateway in typical RPL deployments. TRAIL is designed to minimize network message exchanges and node resource consumption. Our evaluations revealed that the transmissions of bits required by TRAIL remain feasible for typical challenged environments, and that a testbed of typical shape can well operate TRAIL with limited additional effort. Future directions of this work are twofold. First, we will further optimize our algorithms to reduce dependency on network sizes. Second, we intend to apply the TRAIL approach proposed for RPL to other routing protocols.

VI. CONCLUSIONS & OUTLOOK

This work focuses on routing security of RPL, a new routing protocol for the emerging Internet of Things. Intrinsically, RPL is vulnerable to topology attacks. Its rank and version number need particular protection, since by spoofing version and rank an attacker can obtain dominant impact on the network. The current state of the art leaves relevant security issues unresolved.

Fig. 5. TRAIL MESSAGE SIZES: Average message size distribution for varying fanout degrees \( k \) as functions of the network size.

| \( k \) | \( h \) | \( \# \) Nodes | \# Msg. per node | Average Size | Max. Size |
|---|---|---|---|---|---|
| 3 | 15 | 2 | 3.5 | 10.5 |
| 2 | 4 | 31 | 2 | 7.5 | 22.5 |
| 5 | 63 | 2 | 15.5 | 46.5 |
| 3 | 85 | 2 | 12.6 | 63 |
| 4 | 4 | 341 | 2 | 51 | 255 |
| 5 | 1365 | 2 | 204.6 | 1023 |

TABLE II
MESSAGE OVERHEAD FOR DIFFERENT NETWORK SIZES: \( k \) = number of children, \( h \) = height of the tree
Fig. 6. Per node performance in joining the DODAG comparing pure RPL with the TRAIL overhead as observed in the testbed.

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