# DETECTING VERSION NUMBER ATTACKS IN RPL-BASED NETWORKS USING A DISTRIBUTED MONITORING ARCHITECTURE

**ABSTRACT**

The concept of Internet of Things involves the deployment of Low power and lossy Networks (LLN) allowing communications among pervasive devices such as embedded sensors. The IETF designed the Routing Protocol for Low power and lossy Networks (RPL) for supporting these constrained networks. Keeping in mind the different requirements of such networks, the protocol supports multiple routing topologies, called DODAGs, built using different objective functions, so as to optimize routing based on several metrics. A DODAG versioning system is incorporated into RPL in order to ensure an optimized topology. However, an attacker can exploit this mechanism to damage the network and reduce its lifetime. The unique aspects of our work can be seen in our analysis of a realistic network topology that has both static and mobile nodes with different cardinalities for which our inspiration came from the IETF routing requirement documents. The version number attack can misuse a RPL feature which is normally used for ensuring a loop and error free topology. A malicious node modifies the version number associated to a topology, thereby forcing a rebuild of the entire routing tree. Since the version number is included in control messages by parents, there is no mechanism provided by the standardized protocol to guarantee the integrity of the advertised version number. The proposed detection strategy based on a distributed monitoring architecture with dedicated algorithms that is able to identify malicious nodes performing such attacks in RPL-based environments. The performance of this solution is evaluated through extensive experiments and its scalability is quantified considering a monitoring node placement method.

## I.INTRODUCTION

The growing interest for the Internet of Things has resulted in the large-scale deployment of Low power and Lossy Networks. They enable new applications ranging from smart electricity grids [1] to home automation solutions [2] [3]. The constrained devices composing these networks can be integrated with the existing Internet infrastructure, so that they exploit software services already available coupled in conjunction with their control and data gathering capabilities. The Routing Protocol for Low-power Lossy Networks (RPL) was designed by the IETF RoLL working group to cope with resource constraints of embedded devices [4]. This

protocol not only organizes nodes into DODAGs (Destination Oriented Directed Acyclic Graphs) but also optimizes the topology for application specific objectives, e.g. energy conservation, by using metrics and/or constraints available to a device.

An RPL instance is a set of DODAGs, each with a specific objective function. Several RPL instances can be run within a network. A node can only join a single DODAG in one instance, however it can be part of several DODAGs only if they are in

different instances. A node's rank value represents its position with respect to the DODAG root. This value always increases in the downward direction. To avoid rebuilding the entire DODAG when a parent node disappears, two local repair mechanisms are introduced by the protocol. The first one allows nodes to temporarily route through neighbors of the same rank, while the other one consists in using an alternative parent. It also provides a global repair feature to rebuild completely the DODAG. The mechanisms that enable RPL to provide this level of flexibility could also be manipulated by malicious nodes to harm the network. In particular, the version number attack can misuse a RPL feature which is normally used for ensuring a loop and error free topology. A malicious node modifies the version number associated to a topology, thereby forcing a rebuild of the entire routing tree. Since the version number is included in control messages by parents, there is no mechanism provided by the standardized protocol to guarantee the integrity of the advertised version number. A forced rebuild can cause increased overhead, depletion of energy reserves, channel availability issues and even loops in the routing topology. Previous studies show that such attacks have a significant impact on RPL networks and highlight the importance of addressing them [5], [6]. That architecture propose a solution based on a distributed monitoring architecture to detect version number attacks in RPL-based environments and identify the malicious nodes involved. Our main contributions are (1) the design of a detection strategy for these attacks and its associated algorithms, (2) the deployment and instantiation of the strategy using a distributed passive monitoring architecture, (3) the performance evaluation of our solution through extensive experiments and (4) the quantification of the proposed solution scalability in line with a node placement method.
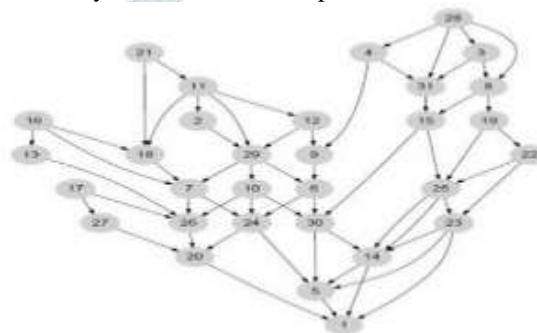


**FIG.1.DODAG TREE**

## II.RELATED WORK

Version number attacks have already been analyzed in our previous studies such as [5] and [6]. We have shown that this type of attacks have severe consequences for RPL network causing significant control message overhead and building loops in the network which leads to a reduced lifetime for the

network and the loss of data packets. Since many loops are built, the end-to-end delivery ratio decreases also. Authors of [6] have proposed to investigate these attacks under mobility with a probabilistic attacker model. They have also analyzed the impact of these attacks on nodes energy consumption and show that the batteries of the nodes were severely reducedby the attack. These analyses have confirmed the need for detecting and remedying these attacks.

In that context, the Version Number and Rank Authentication (VeRA) approach aims at preventing compromised nodes from impersonating the root and from sending an illegitimateincreased version number [7]. It provides integrity of version numbers and ranks advertised in control messages via hash and signature operations. Their approach is shown to be faultyby the authors of [8] and [9], and another mechanism called TRAIL that uses the root as a trust anchor and monotonically increases node ranks is also proposed by them. Both approaches require maintaining state information on nodes that is likely to reduce already constrained computing resources. Several intrusion detection systems have also been proposed for RPL-based networks [10], [11]. The first solution [10] is a specification-based IDS relying on a finite state machine implemented in each monitor node. The second IDS called SVELTE [11] is composed of three modules. One is responsible for rebuilding the topology at the sink nodes using requests, the second one carries out the intrusion detection process and the last one is a mini distributed firewall. However, none of them proposes to detect version number attacks. In order to prevent depleting the scarce resources of devices and provide a security-oriented monitoring solution, we propose a passive distributed monitoring architecture [12] which relies on higher order devices typically used in AMI1 networks. We also prove that this solution is efficient to detect DAG inconsistency attacks. However, none of these solutions address version number attack properties.

## III.VERSION NUMBER ATTACKS IN RPL NETWORKS

The RPL protocol is vulnerable to version number attacks, which exploit the global repair mechanism to overload the network. The root initiates a global repair, when too many inconsistencies are detected in the network. It consists in rebuilding the entire DODAG by incrementing the version number of the DODAG [4]. This number is carried in a type of control messages called DIO[2]. Each receiving node compares its existing version number against the one received from its parent. When the received version is higher, it must ignore its current rank information, reset trickle timers and initiate a new procedure to join the DODAG. This global repair mechanism guarantees a loop free topology, but is also quite costly. An older value of the version advertised in DIO messages indicates that the node did not migrate to the new version of the DODAG. Such a node should not be chosen as preferred parent by other nodes. Two versions of a DODAG can exist at the same time during a global repair. However, in order to avoid loops, data packets from the old version are allowed to transit in the new version but not the other way. As the convergence of the network has not been reached, the old version is no longer a DAG and loop free topologies cannot be guaranteed in this situation.

To avoid possible inconsistencies in the network, the version number should be propagated unchanged through the DODAG. However, there is no mechanism in RPL to ensure the integrity of the version number in received DIO messages. A malicious node may change this value in its own DIO messages to harm the network. Upon receiving a malicious DIO with a new

version number, nodes reset their trickle timer, update the version and advertise this new version through DIO messages to their neighborhood as well.

This can cause the illegitimate version number to propagate through the network. Such manipulation of the version number in the DIO packets causes both an unnecessary rebuild of the whole DODAG, and generates loops in the topology. Furthermore, since the new version of the DODAG is not built from the root, the topology is no longer acyclic, allowing loops to occur. This can negatively impact energy resources of the nodes, routing of data packets and channel availability. The pattern of this attack makes it difficult for a node to detect it locally. Indeed a malicious D

IO packet coming from a parent seems to be legitimate for a node. When it comes from a child, then the node can consider this as due to an inconsistency in the network. Also localization of the malicious DIOs source is impossible in a purely local point of view, as nodes have only a view of their neighbors. They need to communicate with each other in order to find the origin of the attack.

## IV. DETECTION STRATEGY

In the following section, we present our detection strategy for identifying version number attacks in RPL networks. This strategy uses our distributed monitoring architecture [12] on which we have deployed detection algorithms specifically designed for the version number attack. We first detail the architecture components and then describe the different algorithms that support this detection.

### A. Security-oriented Monitoring Architecture

The strategy relies on a distributed monitoring architecture for the Internet of Things that passively observes the network based on dedicated nodes. This architecture uses RPL protocol mechanisms to perform monitoring and detection operations. Two types of nodes participating in the network compose.

**Fig.2.Detection strategy based on our monitoring architecture.**

this architecture, monitored nodes, also called regular nodes, plotted in white in Figure 1, and monitoring nodes plotted in blue which implements the detection solution.

The monitored nodes, noted $V = fv_i$ g, are highly constrained devices that are typical C0 or C1 devices [13]. Their function is to carry out their sensing or actuation task and they constitute the so called regular network. The monitoring nodes ($V^0 = fv_k^0$ g) are on the other side, higher order devices that are at least C2 [13] or better. Since they have higher capabilities, they can perform monitoring and detection activities without impacting their ability to route information in the regular network. They are able to intercept and analyze packets sent by regular nodes and record necessary information. A monitoring node $v_k^0$ can only monitor its neighborhood $N_{vk}0$ which is

composed of all nodes in its communication range. However, network-level monitoring information is necessary to follow the topology and detect inconsistencies in the network such as maliciously incremented version number. As such, these monitoring nodes periodically forward the collected monitor-ing data towards the sink which can perform a distributed detection.

In order to preserve regular nodes resources, the monitoring nodes form a second routing topology, called monitoring network, as illustrated by the upper plane of Figure 1. This network has access strictly limited to monitoring nodes and is used to send collected information and results of detection algorithms. We exploit the multi-instance feature of RPL to build the two networks: one instance for the regular network noted $I_R$ and one for the monitoring instance $I_M$. Figure 1 represents those two instances running at the same time. The two are completely independent which means that if

Algorithm LOCAL ASSESSMENT potential att =NULL; for each DIO received by $v_k^0$ from $v_i \in N_{vk}0$ do

if ($VN_{vi} > VN_{vk}0$) and (potential att == NULL) then potential att = $v_i$

    send root($M_k = (VN_{vi}, v_i, N_{vk}0)$)

  end if

end for

**LOCAL ASSESSMENT algorithm** implemented on monitoring nodes except the root.

The regular network breaks down at some point because of regular node failure or attacks, the monitoring network can still operate normally.

**B. Detection Algorithms**

This section details the different algorithms used in our strategy for detecting version number attacks considering that only one attacker is present in the network at a given time. Due to the fact that an incremented version number is propagated in the entire graph, a monitoring node cannot decide by itself if this is the result of an attack or not. The monitoring nodes must share monitoring information to identify the malicious node. Our monitoring architecture is designed to allow monitoring nodes to collaborate together thanks to the monitoring instance network. Also, the monitoring nodes can track information regarding their neighborhood, so the regular nodes do not have to carry out this task. To detect an attack and identify malicious nodes, we propose detection and location algorithms described in Figures 2, 3 and 4. The local assessment algorithm presented in figure 2 is deployed on monitoring nodes except the root and allows monitoring nodes to report to the root the sender of an incremented version number in their neighborhood. The algorithms presented by Figures 3 and 4 are implemented on the root node. The first one detects the attack and gather all monitoring node information into tables. The last algorithm performs the attacker identification by analyzing the collected information. In the LOCAL ASSESSMENT algorithm, a monitoring node $v_k^0$, upon receiving a greater version number $VN_{vi}$ from $v_i$ than its own version number $VN_{vk}0$, sends to the root a message containing the address of the sender $v_i$ and the list of its neighbors $N_{vk}0$ obtained from the different received RPL control messages. The monitoring node only sends a message the first time it receives an incremented version number. Indeed, since the attacker is in the direct neighborhood of at least one monitoring node there is no need in sending further messages because senders of other incremented version number messages are relays. We also consider the other neighbors of the monitoring node as safe. Complementary to the algorithms, the root has the possibility to send a signal message indicating that the monitoring nodes should

reset the potential att value, in order to restart the detection process, in case another attacker appears in the network.

Algorithm DISTRIBUTED DETECTION anomaly detected = 0

if ($VN_{vj} > VN_{vl}0$ in DIO received from $v_j$ anomaly detected = 1
add(potential att list, $v_j$)

add(neigh list, $fN_{vi}0$ g)

start(detection timer)

end if

if ($VN_{vi} > VN_{vl}0$ in $M_k$ received) and (anomaly detected == 0) then

anomaly detected = 1

start(detection timer)

end if

while (potential att list.nb != card($V^0$)) or (!timer expired(detection timer)) do

for each message $M_k$ received from $v_k^0$ add(potential att list, $v_i$)
add(neigh list, $fN_{vk}0$ g)

end for
end while

LOCALIZATION()

**DISTRIBUTED DETECTION algorithm** implemented on the root.

This procedure exploits the two previous lists in order to produce two new lists: att list list composed of nodes considered as malicious and the safe list list containing all nodes classified as safe. The objective of this procedure is to compare neighborhoods of monitoring nodes in order to eliminate potential attackers. At initialization, the first element of the potential attacker list is added to the attacker list, and the other neighbors of the corresponding monitoring node are added to the safe list.

Algorithm LOCALIZATION
att list = NULL
  safe list = NULL

  for (i=0, i<potential att list.nb, i++) do if (att list == NULL) then

    add(att list, potential att list[i])

    add(safe list, fneigh list[i] n potential att list[i]g else

    if (potential att list[i] 2 att list) then

    add(safe list, fneigh list[i]npotential att list[i]g

    else if (potential att list[i] 2 safe list) then add(safe list, fneigh list[i]npotential att list[i]g

    else
add(att list, potential att list[i])

add(safe list,fneigh list[i] n potential att list[i]g) end if

if (neigh  list[i] \ att list  =  vm;  vm  6=  ;) then remove(att list,vm)

end if
   end if
      end for

### Localization algorithm implemented on the root

The distributed detection algorithm (see figure 3 is supported by the root. Upon receiving either a monitoring message or an incremented version number, the root starts a detection timer to allow all monitoring nodes to send their messages. Two lists are managed by the root node: the potential att list list which is composed of all $v_i$ nodes reported by the different monitoring nodes and the neigh list list which is composed of each monitoring node neighbors from the attacker list. In order to illustrate these algorithms, we provide two examples describing the different possibilities using the topol-ogy presented in Figure 5. The first scenario shows our detection strategy functioning under normal conditions. The second scenario is used to present a use case where the detection strategy produces false positive results (normal node considered as malicious). In the first scenario (see Figure 5a), the attacker is located at position 11, it sends DIO malicious messages to all its neighborhood (plain red arrows) which are relayed by other nodes (in purple dotted arrows). The different monitoring nodes report to the sink the sender of abnormal messages and the list of their neighbors.

### V.PERFORMANCEEVALUATION

We have evaluated the performance of our detection strategy through experiments by implementing a Proof of Concept prototype. The section details our

### FIG.3.(a) Configurations with 4 monitoring nodes. (b) 5 monitoring nodes.

| Attacker Position | Series 1 | Series 2 | Series 3 |
|---|---|---|---|
| V5 | V5,V9 | V5,V9 | V5,V9 |
| V9 | V5,V9 | V5,V9 | V9 |
| V18 | V5,V18 | V18 | V18 |

### TABLE 1: Attacker detection results

experimental setup, the selection process for the placement of monitoring nodes and the the performance results of our detection algorithms.

### A.SIMULATION SETUP

In these experiments, we have set up a grid topology of 20 nodes corresponding to the lower plane of Figure 1. The grid topology was chosen because it allows relocation of the attacker to multiple positions easily, making it possible to study the performance of our detection strategy from different locations and neighborhood scenarios within a network. The Contiki 2.7 operating system was used to implement the sink, regular nodes

and monitoring nodes. We have considered the attacker implementation proposed in [5]. The Cooja tool [14] was used to run the simulation with the compiled binaries of the different nodes. The radio model used was the DGRM model (Directed Graph Radio Medium) to emulate the links as shown in the lower plane of Figure 1: regular nodes can communicate with their neighbor horizontally and vertically while the monitoring nodes can also listen diagonally. Across all experiments, node $v_1^0$ is the DODAG root, acting as the sink to which all other nodes send messages every twenty seconds to generate a background traffic. The attacker is designed to constantly send incorrect version numbers, which are greater than the root's version. Each simulation has lasted ten minutes which is enough to test our detection algorithms since only the first attack message is required for the detection as previously explained. The location of the attacker has been set to one of regular nodes, such that at least one simulation with the attacker located at every regular node is executed. This entire set of simulations is repeated three times for accuracy reasons. Attacks start after five minutes of simulation time, so that the network has enough time to settle and reaches a stable RPL topology. Not only the location of the attacker has been varied but also the location and the number of monitoring nodes. Indeed, we have seen in Section IV-B that it was possible to encounter false positives results depending on the fact that a node is monitored by one or several monitoring nodes. The next section details how and why different monitoring nodes configurations were chosen to evaluate the number of false positives.

### B.MONITORING NODE PLACEMENT SELECTION

Since the designed detection solution depends on the cover-age of regular nodes by monitoring nodes, we defined the fol-lowing metrics: (i) $Cov_i$ representing the percentage of regular nodes covered by exactly i monitoring nodes (i $\in$ [1; M]; M is the number of monitoring nodes); (ii) $Ca_i$ representing the percentage of regular nodes covered by at least i monitoring nodes, e.g. $Ca_2 = Cov_2 + Cov_3 + Cov_4$ for M = 4. In all cases, we target $Ca_1$ equals to 100% because all regular nodes should be covered by at least one monitoring node since the architecture is able to monitor all nodes. As shown by the second scenario in Section IV-B, $Ca_2$ is an important parameter for selecting the configurations to be considered, because the number of false positive depends on the neighborhood overlapping of the monitoring nodes. Therefore, monitoring nodes configurations have been selected for different $Ca_2$ values in order to quantify the impact of the $Ca_2$ value on the number of false positives. Five different $Ca_2$ values have been chosen including the lowest and the highest possible values for 4 and 5 monitoring nodes in the considered topology. The minimal number of required monitoring nodes is 4 so that $Ca_1$ equals to 100%. This value is given by the resolution of an Integer Linear Program (ILP) with our grid topology under the constraint that the sink, $v_1^0$, is a monitoring node. The rest of the monitoring nodes are chosen among all the other nodes. A particular $Ca_2$ value corresponds to several combination of $Cov_i$. Therefore, one configuration of each combination has been chosen for the simulations. For 4 monitoring nodes, the number of possible configurations so $Ca_1$ = 100% is 24. We have also selected configurations with 5 monitoring nodes because the obtained $Ca_2$ values allow us to have zero false positive as illustrated by Figure 7b. For 5 monitoring nodes, 427 configurations can be run. We have simulated 29 configurations corresponding to the selected $Ca_2$ values. The different chosen $Ca_2$ values can be seen on Figure 7.

**FIG.4. False positive rates for different location of the attacker when configuration is the topology of 1.**

For each simulated scenario, the false positive rate (FPR) was calculated according to Equation 1, where F P and T N are respectively the number of false positives and the number of true negatives. A false positive is a node which has been incorrectly detected as malicious by our detection solution (the node is actually safe). A true negative is a node which has been properly considered as safe.

$$FPR = \frac{FP}{FP+TN}$$

## C.DETECTION RESULTS

Across all experiments, our detection strategy has successfully located the attacker, but other regular nodes were sometimes detected as malicious too. Figure 6 details false positive results for the topology presented in the lower plane of Figure 1 where the monitoring nodes are $v_1^0$ ; $v_7^0$ ; $v_{13}^0$ and $v_{15}^0$ and the $Ca_2$ is 43,75% (maximum value for 4 nodes). We can observe that the FPR is 0 for 13 positions of the attacker Details about the detection results when the FPR is higher than 0 are given in Table III. When the attacker corresponds to node $v_5$, node $v_9$ is always detected as malicious too, because node $v_9$ is each time the direct relay of the attacker $v_5$ and is monitored by only one monitoring node ($v_{13}^0$ ). No other monitoring nodes could have exonerate it. This is also the case for other positions of the attacker. However, attack relays were not considered as malicious each time. This can be explained by the fact that the attack relays can change depending on the timing for each simulation. For example, when the attacker is $v_{18}$, $v_5$ is considered as malicious only once, this is because monitoring node $v_1^0$ receives only once the attack relay message from $v_5$. The other times, the relay node $v_6$ is also monitored by $v_7^0$ which exonerates it. Similar results have been obtained for the other 35 configurations.
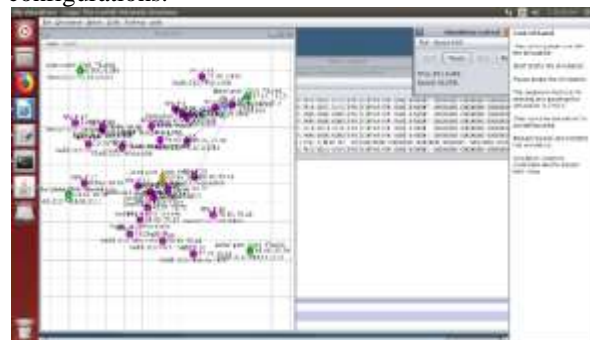


**FIG.5.Simulation process in contiki.**

## VI.SCALABILITY EVALUATION

We have also analyzed the scalability of our solution in line with the considered node placement. We have represented the problem of having at least C% of the nodes covered by at least two monitoring nodes using an optimization model. This constraint can be transformed into having at most (100 C)% of the nodes covered by exactly one monitoring node which can be

formulated as follows: for a given topology, a given connectivity matrix for all possible monitoring nodes placement in this topology, a given number of monitoring nodes and a given value C, find a configuration of monitoring nodes placement that minimizes the number regular nodes monitored by only one monitoring nodes so that at most (100 C)% regular nodes are covered by strictly one monitoring node.In that context, we have considered four parameters detailed in Table IV, as inputs to solve this problem. The first parameter is the size of the topology N. The second one is the connec-tivity matrix detailing the links of possible monitoring nodes with other nodes, $A_{i;j} = 1$ if node $v_i$ can listen to node $v_j$. We set the diagonal of this matrix to 0, i.e. 8i; $A_{i;i} = 0$ which means that we consider that monitoring node does not cover itself. The third parameter is the number of monitoring nodes M. The last parameter is the percentage of regular nodes we want to be monitored by at least two monitoring nodes C. The variables used are Y which represents if node $v_i$ is monitoring node ($Y_i = 1$) or not ($Y_i = 0$), W indicating if node $v_i$ is covered by monitoring node $v_j$ ($W_{i;j} = 1$) or not ($W_{i;j} = 0$). The last variable is Z and represents if node $v_i$ is covered by exactly one monitoring node ($Z_i = 1$) or not ($Z_i = 0$). The total number of variables for this problem is $N(N + 2)$. is used to set $v_1^0$ , the root, as a monitoring node, it is possible to set another particular node to be a monitoring node according to the topology specifics. Equation 3 indicates how many monitoring nodes we choose. The constraint $Ca_1 = 100\%$ is given by Equation 4. Equation 5 calculates variable W which is used in Equation 6 to compute Z. The right part of this equation forces $Z_i = 0$ if $v_i$ is a monitoring node or else $Z_i = 1$.
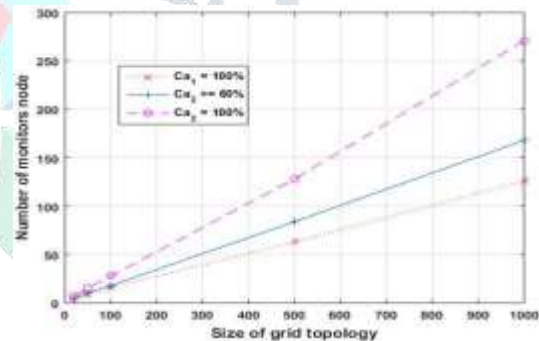


**FIG.6.Number of monitoring nodes needed to have ca1=100%, ca2 = for different topologies.**

## VII.CONCLUSION

We have proposed in this paper a detection strategy with dedicated algorithms to address version number attacks in RPL networks. We have instantiated this solution based on our distributed monitoring architecture which preserves constrained nodes resources. We have exploited monitoring nodes collaboration to identify the attacker, the attacker localization process being performed by the root after gathering detection information from all monitoring nodes. We have evaluated our solution through experiments and have analyzed the performance according to defined metrics. We have shown the false positive rate of our solution can be reduced by a strategic monitoring nodes placement. We have also considered the scalability issue by proposing an optimization problem which can be easily adapted to different topologies. By resolving this problem, we have quantified the number of required monitoring nodes to ensure an acceptable false positive rate for a given size of topology. As future work, we are interested in performing complementary experiments in real infrastructures with

additional classes of devices implementing the RPL protocol. We also want to evaluate and extend our solution to the case of attacker coalition where are several malicious nodes are involved at the same time in the network. We are also planning to enhance our architecture with other detection modules for addressing additional attacks [17].

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