Implementation of RPL in OMNeT++

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Abstract—The growth and evolution of Internet of Things (IoT) is now of paramount importance for next-generation networks, including the upcoming 6G. In particular, there is a set of constrained IoT nodes that comprise the Low-Power and Lossy Networks (LLNs), which have very particular requirements. The current standard for routing in those networks is RPL, which was defined less than a decade ago and still needs improvements in terms of scalability or integration with other networks. Many researchers currently need an implementation of RPL to evaluate their works and, for that reason, among others, we implemented it in the OMNeT++ simulator. The results of this implementation show that is an easy way to check prototypes in their very initial develop phases, and its code is publicly available for the research community.

Index Terms—Network simulation, OMNeT++, IoT, RPL, 6G

I. INTRODUCTION

The future sixth generation of mobile/wireless networks, also known as 6G, is envisioned to cause a tremendous growth in the number of connected devices (that is, Internet-of-Things (IoT) nodes) in order to achieve diverse applications of smart environments, fostered by Artificial Intelligence (AI), such as Agriculture 4.0 or Industry 4.0 [1]. However, still many challenges need to be tackled, like the seamless integration of IoT in virtualized and programmable environments required by 6G [2].

IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [3] is an standard for routing in Low-Power and Lossy Networks (LLNs). LLNss consist of a set of constrained IoT nodes interconnected by limited links. The constraint is due to processing, memory, and sometimes energy resources of the nodes and high loss rates, low data rates, and instability of the links [3]. Currenly, there are many efforts to align RPL to the requirements of these 6G networks and, therefore, there are many proposals enhancing RPL in different ways.

In our specific case, our research team wanted to implement an alternative protocol for LLNss. To evaluate it and compare it with RPL, we decided to first implement RPL in OMNeT++. This served as an initial step to prove our designed prototype, and we hope it also helps future researchers trying to design additional protocols and enhanced versions of RPL.

Our article is structured as follows. In Section II, we first provide a summarized overview of RPL, explaining its main Mode of Operations (MOPs) and its design implications. Afterwards, in Section III we analyze the diverse network simulators and emulators, and explain our reason to choose OMNeT++ as the implementation platform for our initial prototype. In Sections IV and V we describe the main characteristics of the implementation, and how to install it, respectively. In Section VI we examine the obtained results and expected impact of our implementation. Finally, we conclude the article Section VII providing some research directions as well.

II. RPL OVERVIEW

In order to explain the design decisions made along the implementation of RPL in the OMNeT++ simulator, we will first provide a quick overview about the protocol.

Each RPL-based network can operate in one of three modes illustrated in Table I [3]. Upward routes are established based on a common routing used in all MOPs in the standard. These routes are used for multipoint-to-point (MP2P) traffic type. Therefore, we could say that MOPs are defined in terms of whether the Downward routes are used to enable a network to route point-to-multipoint (P2MP) and point-to-point (P2P) traffic types or not, and also based on how RPL populates the routing/source routing tables of each node in the network.

| MOP # | Description of MOP |
|-------|--------------------|
| 0     | No Downward routes maintained by RPL |
| 1     | Non-Storing Mode of Operation |
| 2     | Storing Mode of Operation with no multicast support |
| 3     | Storing Mode of Operation with multicast support |
| Other values | Unassigned |

A. MOP 0

When RPL uses MOP 0, all nodes can only use Upward routes and MP2P traffic type from a node to the Destination-Oriented DAG (DODAG) root along the DODAG. Therefore, all non-root nodes can send their traffic, called multipoint, to a root node, called point, in the network. Since in this MOP routing is unidirectional, P2P traffic type cannot be used to communicate two non-root nodes with each other (particularly when the nodes are not neighbors of each other). In this regard, there are some schemes to improve and optimize P2P traffic type in RPL [3].
In this MOP, all nodes excluding a DODAG root node maintain a routing table to store a default route to specify a next hop to reach the DODAG root (Fig. 1). Upward routes and DODAG are constructed and maintained by propagating DODAG Information Object (DIO) messages. When a child node receives a DIO message, the child node selects the sender of the DIO message as a parent node and creates a default route to the parent using the link local address of the parent in the routing table if the DIO message passes the rules specified in the standard such as having a valid version number, rank, DODAG ID and etc. After constructing the Upward routes, if a child node wants to send a data packet to a DODAG root, it routes the packet to a default route specifying the DODAG root.

**B. MOPs 1 and 2**

Both MOP 1 and 2 use Downward routes in addition to the Upward routes. Using Downward routes enables the protocol to route P2MP traffic type, that is, to route data packets downward from a DODAG root to other child nodes along the DODAG. Since these MOPs can route both Upward and Downward routes, they can route P2P traffic type along the DODAG in different ways. Downward routes are established and maintained by propagating Destination Advertisement Object (DAO) messages upward along the DODAG.

More specifically, MOP 1 applies source routing to route data packets downward. As shown in Fig. 2, DODAG root node only maintains a table, called source routing table, and other child nodes do not store any routing entries to route packets downward, hence this MOP is also known as **Non-Storing Mode of Operation**. To establish routes, DAO messages are sent as unicast messages by child nodes to a selected parent node(s). When a DAO message is sent to a selected parent node, the parent node creates an entry in its routing table. We encounter the concepts of the forwarder and generator nodes in this MOP. The generator node creates the DAO message and puts its global address as the destination advertised address field in the message and inserts its link local address as the sender address in the packet, then it sends the message to the selected parent node. The parent node creates an entry in its routing table after receiving the message. The entry includes the sender’s address as the next hop field and the destination advertised address as the destination field. Briefly, the parent node updates the sender address of the packet to its link local address, then it forwards the message to its selected parent. This process continues until the message reaches the DODAG root.

**III. NETWORK SIMULATORS AND EMULATORS**

In order to implement RPL to evaluate it and compare it with other enhanced or new competing protocols, we first assessed the different network simulators and emulators, commonly leveraged in the field for this purpose.

In this sense, the most popular platform for IoT environments is **Contiki-NG** [4]. Contiki-NG is an open-source operating system implementing the standard protocol stack containing IPv6/6LoWPAN, 6TiSCH, RPL, and CoAP for...
next-generation IoT devices and low-power communication. Contiki-NG includes real platforms such as the Sky mote [6]. Because of RAM and ROM limitations, the Sky mote cannot run implementations which have a lot of code. Furthermore, Contiki-NG includes a virtual platform, called Cooja mote, which is a fast mote not constrained in memory, although simulation with Cooja mote is not perfectly time-accurate. In addition to compile and load implemented code in a real device, Contiki-NG includes a simulator, called Cooja [6], which can emulate real modules and simulate virtual platforms to run and test the implemented code. Additionally, motes programmed with Contiki-NG can be easily deployed in large IoT environments and testbeds like FIT IoT-LAB [7], which increases accuracy. In add.

Another two well-known simulators are ns-3 [8] and OMNeT++ [9]. On the one hand, ns-3 is a discrete-event network simulator for Internet systems and RPL is available for this simulator too [10]. On the other hand, OMNeT++ [9] is a discrete-event simulator in which several frameworks (such as INET [11], MiXiM [13]) can be executed. Kermajani et al. [13] implemented a preliminary version of RPL. This implementation only supports MOP 0 to construct Upward routes. In this regard, both of them are packet-based simulators and we could say –in a very simplistic way– that OMNeT++ is usually easier to program as it provides a higher-level view, while ns-3 has a better overall performance.

Additionally, there is a third library for simulation that is worth mentioning, in this case event-based, which is called SimPy [14]. As the name indicates, it is based on Python and allows the implementation of high-level simulations (e.g., flow-based) in a fast and easy way.

Up to this point, all described platforms are used to implement different protocols in a distributed manner, i.e., the logic of the protocol is implemented as the logic of a network node, which is later on deployed in a network scenario. However, there is an alternative centralized approach that can be followed by applying the Software-Defined Networking (SDN) [15] paradigm, which is not only an architecture, but also another mean of testing and validation of protocols. Although SDN is leveraged in many implementations for realistic developments based on a centralized logic developed in the form of a software, most of the current platforms are mainly focused on non-constrained wired network devices, which makes it difficult to apply in LLNss. There is a current effort to implement a platform to test these networks called Mininet-WiFi [16], which is an extension of Mininet [17], and also some frameworks like SDN-WISE [18] try to integrate both Contiki-NG motes and SDN.

A. Reason to select OMNeT++ as implementation platform

In our case, we wanted to test a completely new protocol to be compared with RPL. As the protocol was designed from scratch and not as an extension of RPL, we believed the first step was to validate it with a simple and fast prototype. In this regard, although the multiple benefits of Contiki-NG are apparent, this environment might be slightly harsh for beginners, and the implied effort is high if we consider we just want to validate an initial idea. For this reason, we thought OMNeT++ was the simplest way for this initial step, because it was simpler than ns-3 and Contiki-NG, while keeping more realistic than SimPy (which is not packet-based).

For the implementation of RPL we took the work from Kermajani et al. [13] as a reference. Since the MiXiM framework was not updated because it is not supported by the new versions of OMNeT++, we implemented RPL in OMNeT++ 5.2.1 and the INET 3.6.3 framework [19] instead. This implementation had to support other MOPs applying the Downward routes, ICMPv6 messages for transmitting the RPL control messages, the interface and routing table. In particular, our implementation followed the standard [3], the implementation of RPL in MiXiM [13], and Contiki-NG [4]. Unlike Contiki-NG, the simulation runs a single instance and DODAG of RPL.

IV. IMPLEMENTATION

Since our objective was to fully implement the routing functionality of RPL, according to the definition of RPL provided in Section I, we implemented the three MOPs: 0, 1 and 2. In particular, we focused on the network layer, while the link and physical layers were kept simple (though extensible in the future if required).

As a departing point, we considered the original INET framework and we modified it accordingly. In the following paragraphs, we explain the applied changes and the expected (and resulting) behavior.

Fig. 4 illustrate an outline of the original Network Layer module defined in INET (Fig. 4c) compared to the implemented extension of it, which comprises the definition of RPL (Fig. 4b). We added three submodules to module IPv6NetworkLayer: (1) ParentTableRPL maintains parent node information, (2) sourceRoutingTable maintains source routing entries in MOP 1, and finally, (3) RPLUpwardRouting is a submodule to implement the routing functionality of Upward routes for all MOPs. Since...
the upward routing functionality was more complex than the downward one and, at the same time, to decrease the complexity of the ICMPv6 submodule, we separated the functionality from this ICMPv6 module. In addition to the newly added submodules, we also updated some existing modules of INET shown in Table II.

As mentioned in the previous section, we use both link local and global addresses to form the DODAG. Upward and Downward routes. To assign addresses to each node, we updated the IPv6NeighbourDiscovery module in INET to IPv6NeighbourDiscoveryRPL in our implementation. One of the updated changes is to statically assign a link local address to each node. In order to assign a global address to each node, we first check whether a global address has been assigned to the node or not. If there is not any assigned global address to the node, we assign a global address to the node. The prefix of the global address is fd00::/64, which is the prefix used in Contiki-NG, and its suffix is a sequence of last 64 bits of the link local address. Since the functionality of the global address assignment is the same function in the three simulated MOPs of RPL, we placed the function in the RPLUpwardRouting module.

### A. Message propagation and processing (Network layer)

1) **DIO:** First, the DODAG root node propagates a DIO message. Then, other nodes which receive the message, update the message and schedule a timer to send it if some situations are satisfied (e.g., avoiding a loop, receiving invalid messages by checking the version, etc.). Submodule rplUpwardRouting performs the operation.

When the Network Layer receives a DIO message from the MAC Layer, the message is first sent to submodule ipv6. In the submodule, the message is duplicated. Then, a copy of the message is sent to submodule neighbourDiscovery to update the submodule’s entries based on rules, and the original message is sent to submodule icmpv6. Since the DIO messages are used for constructing Upward routes, submodule icmpv6 sends the message to submodule rplUpwardRouting, where needed processes are done (e.g., if needed to update parentTableRPL or not, adding a default route to module routingTable or not, etc.). These operations are done for all MOPs.

2) **DODAG Information Solicitation (DIS):** If non-root nodes have not joined to a DODAG after some specified time, submodule icmpv6 schedules a DIS message to be sent.

Like the received DIO message, when the Network Layer receives a DIS message from the MAC Layer, the original message is sent to submodule icmpv6, and a duplicated copy is sent to submodule neighbourDiscovery. Unlike the received DIO message, submodule icmpv6 processes the DIS message since the process is not complex.

3) **DAO:** After receiving a DIO message which introduces a new parent node, a DAO message is scheduled to be sent.

When the Network Layer receives a DAO message from the MAC Layer, different actions are performed in each MOP. In MOP 0, no routing operations are performed for Upward routes, so no DAO messages are propagated in MOP 0. In MOP 1, the message is routed to the DODAG root node by the default route dedicated to the DODAG root, so it is sent to the parent node. Simultaneously, submodule ipv6 sends a copy of the message to submodule neighbourDiscovery. Finally, the DODAG root node creates an entry in the source routing table based on the message’s originator, as the child node, and the parent of the originator, as the DAO parent node when receiving the message. In MOP 2, a duplicated copy is sent to submodule neighbourDiscovery and the original one is sent to submodule icmpv6. Like a DIS message, submodule icmpv6 processes the DAO message to update/add an entry in the routing table and sends a DAO message to a parent node sometimes when some conditions are satisfied.
TABLE II: Updated modules/classes in the implementation

| Module                  | Updated module       | Functionality description                                      |
|-------------------------|----------------------|----------------------------------------------------------------|
| IPv6                    | IPv6RPL              | To implement the Downward routing for MOP 1 and 2              |
| ICMPv6                  | ICMPv6RPL            | To define the ICMPv6 RPL control messages                      |
| ICMPv6Message           | ICMPv6MessageRPL     | To maintain neighbors discovered by the RPL control messages   |
| IPv6NeighbourDiscoveryRPL | IPv6NeighbourDiscoveryRPL | To maintain neighbors discovered by the RPL control messages |
| IPv6NeighbourCache      | IPv6NeighbourCacheRPL| To handle the ICMPv6 RPL control messages                      |

B. MAC and Physical layers

We designed a simple ideal MAC and Physical layers to check RPL functionality in ideal conditions. IEEE802.15.4 is easily replaceable with the ideal MAC Layer by putting "*.wlanType = "Ieee802154NarrowbandNic" in the .ini file of an OMNeT++ project.

V. HOW TO INSTALL AND USE THE IMPLEMENTATION

The implemented code is openly available in GitHub [20]. To install it, the next steps should be followed:

- Install OMNeT++
  - Download OMNeT++ 5.2.1 [9].
  - Let OMNeT++ install and use its compiler.
  - After extracting and before installing OMNeT++, change "PREFER_CLANG=yes" to "PREFER_CLANG=no" in the "configure.user" file in your OMNeT++ installation folder.
  - Install OMNeT++.
  - To check whether OMNeT++ correctly works or not, run an example of OMNeT++ such as dyna, aloha, tictoc, etc.
- Install INET
  - Download INET 3.6.3 [19].
  - Install and build INET.
  - To check whether INET correctly works, run an example of INET such as inet/examples/adhoc/ieee80211, etc.
- Install the RPL implementation
  - Since the simulation files only include implementation code, the project may not be probably imported by the IDE, and a new OMNeT++ project must be manually created. Therefore, please follow the next substeps:
    - Click on the menu of "File".
    - Select "New".
    - Select "OMNeT++ Project".
    - Type the name of project.
    - Click on "Next".
    - Select "Empty Project".
    - Click on "Finish".
    - Copy all files/folders in the folder to the created project folder.
    - Introduce INET to the project as a reference/library. Therefore, please follow the next substeps:
      - Right-click on the project in "Project Explorer" window.
- Select "Properties".
- Select "Project Reference" in the left list.
- Select "INET" in the right list.
- Click on the "Apply and close".
- Build and run the project.

VI. RESULTS, EXPECTED IMPACT AND CONTRIBUTIONS

The implementation of RPL in OMNeT++ allowed our team to quickly evaluate and compare this protocol with our own proposal, entitled IoTorii [21]. We created scenarios of up to 50 motes to have initial results regarding different parameters such as number of table entries and convergence time, which helped to polish the design of our protocol, which was eventually implemented in Contiki-NG, obtaining very similar results. Therefore, this implementation helped immensely to prove the initial design and analysis of our protocol, in a fast and easy way. However, the main shortcoming is related with the physical layer, which is currently ideal and does not reflect completely realistic scenarios in that regard.

As previously mentioned, the code is publicly available in GitHub [20] and some other researchers are already using and testing it, as it can be observed in their public forums. The simulations support more than 200 motes, which can be useful for big scenarios, before testing them with Contiki-NG, which might required more computational resources. For this reason, we expect some impact in the upcoming years from the usage of our implementation.

However, the OMNeT++ and INET frameworks evolved rapidly, and it is difficult to keep all versions up to date. Although the current version of the code is still usable, we kindly invite any researcher to clone the code and update it or extend it, as any contribution would be probably highly appreciated by the research community.

VII. CONCLUSION AND FUTURE WORK

In this article, we have presented the background and design decision of our implementation of the RPL protocol in the OMNeT++ simulator. Although our research team has experience in all the aforementioned platforms (Contiki-NG, ns-3, SimPy, and SDN-related platforms like Mininet or the Ryu and ONOS controller), our conclusion is that OMNeT++ is an ideal first step to test very conceptual research approaches (particularly if based in in designs from scratch) and for beginners in the field. For that reason, we have made the code publicly available.

As future work, we would like to extend the implementation to include a realistic physical layer, as this is particularly relevant in LLNss. Moreover, we would like to
invite any researcher in the field to use and contribute to our code if willing to.

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