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RPL-based networks in static and mobile environment: A performance assessment analysis

Hanane Lamaazi [a,*], Nabil Benamar [b], Antonio J. Jara [c]

[a] University Moulay Ismail, Faculty of Sciences, Meknes, Morocco
[b] University Moulay Ismail, High School of Technology, Meknes, Morocco
[c] University of Applied Sciences Western Switzerland (HES-SO) Sierre, Vallais, Switzerland

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ABSTRACT

The IPv6 Routing Protocol for Low Power and Lossy Networks (RPL) used in the Internet of Things has some shortcoming when the network is dense and with mobile environment. In this paper, we evaluate the performances of RPL in three configurations: network scalability, multiple sink and mobility models. To this end, two different scenarios are implemented using the Cooja simulator. The first one is based on group models. The second scenario is based on the entity mobility models. Our simulation results show that RPL performances are greatly influenced by the number of nodes, the number of sink nodes, and the mobility type. The scalability of the network increases all metrics while providing less packet loss. Additionally, the number of sink nodes directly affects the RPL performances. The energy consumption is reduced in the case of multiple sink nodes by 55.86%, which is less than the case of a single sink.

Contents

* Corresponding author.
E-mail addresses: lamaazi.hanane@gmail.com (H. Lamaazi), benamar73@gmail.com (N. Benamar), jara@ieee.org (A.J. Jara).
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1. Introduction

Internet of Things (IoT) (Díaz et al., 2016) is considered as the open door of the omnipresent Internet. The main objective of this new technology is to connect all devices to the Internet, including smaller and finer devices. Because of its wireless nature and environmental context, IoT, through some application domains, such as smart cities and healthcare monitoring, uses low-cost and low-power devices. However, IoT has some issues, particularly in regard to the routing of IP packets. After standardizing the 6LoWPAN protocol, which allows IPv6 to run over IEEE 802.15.4 links because of its adaptation layer (Lamaazi et al., 2013, 2014), the IETF (Palattella et al., 2013) developed RPL (Vasseur et al., 2011). RPL lets constrained devices, using a Low Power and Lossy Networks, to access the internet. Furthermore, the specification of designing RPL allows it to be very challenging and thus open to further improvement (Winter, 2017).

1.1. Motivation

RPL is the first routing protocol standardized to support Low Power and Lossy Networks. However, few studies have been interested in evaluating its performances. Hence, the assessment and understanding of RPL behaviour in different scenarios and environments are important to distinguish its requirement and constraint, which allow for ameliorating it.

In this paper, the performances of RPL are evaluated as a standard routing protocol for the Low Power and Lossy Networks. This work differs from the previous studies (Lamaazi et al., 2013, 2014) and contributes to the state-of-the-art in three aspects. First, it provides a deep assessment of RPL performances based on simulation and experimentation (Lamaazi et al., 2015). This study lets us extrapolate that RPL offers several gains adequate for the applications of LLNs. In contrast, it provides a set of limitations related to the selection of the best route to the sink node. These limitations cannot be suited to the antipathetic requirements of LLN applications. Second, to employ RPL in mobile scenarios, the paper presents a new study that uses a specific classification of mobility models that define two entities. The first one contains mobility models that use an entity movement. The second one describes mobility models based on group movement. This new study permits a comparison between mobility models and concludes regarding which one is suitable for RPL in different scenarios. However, improved performance for low power wireless networks is a significant challenge faced by many mobility applications that require the best communication guarantees in mobile conditions.

The remainder of this paper is as follows. Section 2 overviews the most important research related to the improvement of RPL standard specifications. In Section 3, we describe our performance assessment to show the pertinence of RPL behavior in different scenarios, and we present our new deployment of RPL in mobile scenarios using two repartitions of mobility models. Section 4 presents the analysis and results of the proposed approaches. Finally, Section 6 concludes the paper with discussions of the ongoing work and future directions.

2. Overview

2.1. RPL overview

RPL is an IPv6 Routing Protocol for Low Power and Lossy Networks that uses an optimized route for transmitting traffic from or to a central collector node called a root or sink node (Winter, 2017; Lamaazi et al., 2015). RPL was proposed by the IETF ROLL working group and is designed as a solution for finer and tiny devices to run in large-scale networks using low-power and low-cost communications. RPL has some specifics: it adopts some mechanisms that facilitate forwarding data and minimizing routing complexity, and it is recommended to reduce memory requirement and routing signaling overheads (Iova et al., 2015). RPL topology is organized as a Directed Acyclic Graph (DAG) divided into one or more Destination Oriented Acyclic DAGs (DODAGs). Each sink in the network has one DODAG (Lamaazi et al., 2015). Moreover, RPL supports three traffic flows: multipoint-to-multipoint (MP2MP), point-to-multipoint (P2MP), and point-to-point (P2P).

To maintain and identify a topology, RPL uses four values (Winter, 2017):

- The first value is RPLInstanceID, which is responsible for identifying one or more DODAGs. If there are multiple RPLInstanceIDs in the same network, it defines a set of DODAGs independently optimized for different Objective Functions (OFs). This set of DODAGs constitutes an RPL Instance on which all DODAGs use the same OF.
- The second is a DODAGID that is unique for a DODAG; its combination with RPLInstanceID can uniquely design a single DODAG in the network.
- The third is DODAGVersionNumber, which is incremented when a DODAG root reconstructs a DODAG. It can be used to identify a DODAG Version when it is combined with RPLInstanceID and DODAGID.
- The last one is Rank, which is used to identify the position of an individual node according to its position with respect to a DODAG root made during classification over a DODAG Version (Gaddour et al., 2015).

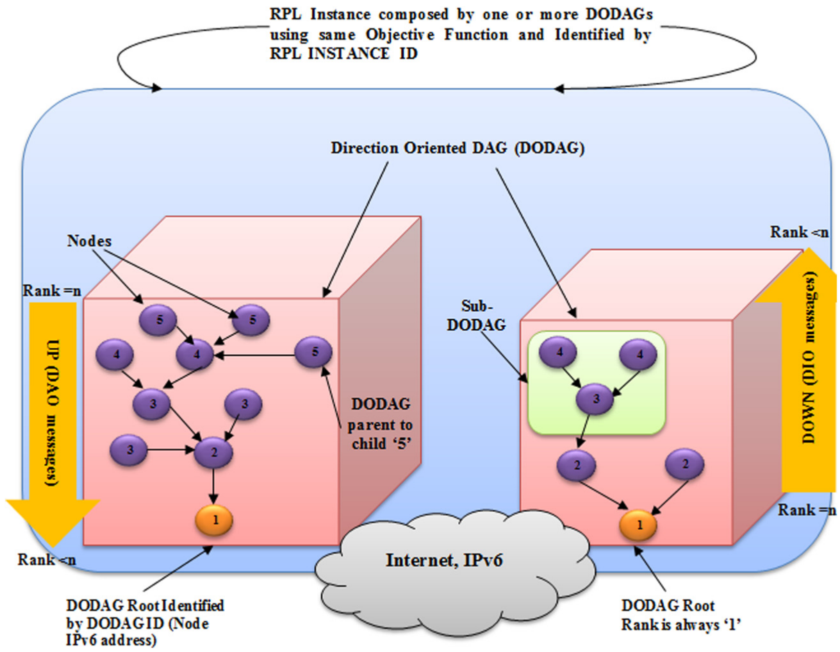


Fig. 1. Illustration of the different operations of the RPL mechanism.

In one instance, there are one or more DODAG roots, as illustrated in Fig. 1, which can coordinate over a network or operate independently. The RPL instance has as rule providing a route to a destination accessible via a DODAG root. Within an RPL Instance, the OF is carried out depending upon how RPL nodes select and optimize routes and select parents and translate one or multiple defined metrics into a Rank value. Then, the nodes calculate their own rank using the OF and start broadcasting DIO messages, which ensure the construction and maintenance of DODAG. Furthermore, with an OF, nodes are configured to use one or more metrics as hop counts, Expected Transmission Count (ETX) or other constraints. Moreover, RPL exchanges information associated with a DODAG according to a set of ICMPv6 control messages (Iova et al., 2015; Gaddour et al., 2015):

- DIO: DODAG Information Object (multicast) allows a node to discover an RPL instance.
- DIS: DODAG Information Solicitation (multicast) is used when a node joins the network.
- DAO: Destination Advertisement Object (unicast) is used to propagate destination information upwards along the DODAG. The node updates its routing table when it receives a DAO.

2.2. Overview of mobility models

Using the existing simulator as mentioned, simulations have been run for various simulation scenarios, as explained in the next subsection. The performances are observed for our proposed scenarios by considering the static and mobile environments. This subsection gives a brief introduction to the Mobility Models used in this study.

The mobility models can be applied for networks with frequent topology changes to be used with RPL protocol. We focus on the modeling and analyze the impact of the mobility model on routing protocol performances. We run several simulations by considering two repartitions of models: the entity and group mobility models. In the group models, we choose, in an arbitrary manner, RPG and Nomadic Model. The first one is the Reference Point Group Mobility Model (RPG), which can realize the movement of nodes inside the group and the movement of all groups (Patel Tushar et al., 2013). The second one is a Nomadic model; in this model, nodes move together, and each node inside the group defines its reference point according to the movement of the group (Bai and Helmy, 2004). However, for the entity models, we choose three models RWK (Random Walk), RWP (Random Waypoint), and SLAW (Self-similar least action walk). The RWK and the RWP act in the same way, where nodes move using a random distribution. However, RWK is different from RWP (Bai and Helmy, 2004; Atsan and Özkasap, 2006) in the context of the ability of RWK to calculate each step without depending on the previous one (Zhang et al., 2014). The last one is the Self-similar Least Action Walk (SLAW). This model illustrates human behavior; more specifically, it can generate synthetic walking traces of human movement (Kyunghan et al., 2009).

3. Related works

Over the next subsections, the main function of the RPL routing protocol and structure is presented. Then, the most recent works dedicated to the improvement of RPL standard specification are investigated, particularly in mobile conditions (Oliveira and Vazão, 2016; Bouaziz and Rachedi, 2016). The ROLL working group has proposed several drafts to improve the RPL implementation and design, which are still not sufficient. Outside the IETF work, several published articles have evaluated the RPL performances to resolve its issues.

3.1. RPL with stationary nodes

In (Iova et al., 2015), the authors applied their proposed Expected Lifetime metric (ELT) to minimize the time until the node runs out of energy. Additionally, they featured the DAG structure to forward the traffic to multiple parents, which allows for expanding both network lifetime and routing reliability. However, this solution was tested in the case where there is no packet fragmentation. Such approach needs to be extended to improve network reliability. Additionally, computing the expected lifetime of a node is based on the current traffic conditions, which can impact the ELT convergence in a varying radio channel. In Tang et al. (2014), the authors designed a new multipath routing protocol based on RPL, named M-RPL. This new design aims to reduce packet loss rate and to abate network congestion using a lowly link quality and by running on a high-loading LLN network. This optimization mechanism has considerably improved LLN performance and can be better used for the network congestion and links instability case. However, this approach has not yet been tested in mobile conditions, which makes its efficiency unknown in these cases. Another study of RPL has been made with regard to smart grid communication running on AMI networks (Parnian et al., 2014). The authors used a new Objective Function based on the Hop Count metric and compared it to the existing objective functions that use Expected Transmission Count as a metric to calculate the preferred parent. This optimization offers better performances in terms of end-to-end delay and packet delivery ratio (PDR). Similarly, the authors of (Xiao et al., 2014) suggested a new optimization of the Minimum Rank Hysterisis Objective Function (MRHOF) named PER-HOP ETX. It can resolve the problem of a long single hop caused by both the MRHOF and OF0 (Objective Function zero) when the network is dense. This proposed amelioration provides better parameters compared to the OF0 and MRHOF in terms of energy consumption, latency and packet delivery ratio. However, PER-HOP ETX can consume more energy in a small network, which means that this solution is not suitable for networks presenting low nodes density.

Table 1 summarizes all related works discussed in the subsection above and also includes our proposal.

3.2. RPL under mobility

Many researchers are interested in finding a solution for mobile nodes based on RPL in a mobile environment. Olfa et al. (Gaddour et al., 2015) suggested a new extension of RPL (Co-RPL) based on the corona mechanism. This proposed extension allows for localizing nodes movement. In comparison with the RPL standard, Co-RPL is more optimal for application in mobile networks. This optimization is tested with only random mobility models. It is based on the simple concept of dividing the network area into coronas, which allows for concluding whether this approach preserves its efficiency when it is used with another mobility model, such as the Reference Point Group Mobility Model.

Fotouhi et al. (2015) proposed a new extension of RPL (mRPL) to resolve the problems of high overhead, high packet loss and latency in mobile conditions. They ensured a hand-off mechanism in RPL, which preserves the overdue compatibility with regards to the standard protocol. In Ko and Chang (2014), the authors proposed a new mobility support layer (MoMoRo) for Low Power Wireless Sensor Networks that can be applied to data collection protocols already in use based on fuzzy logic to estimate link quality and then collect information from the neighborhood. As a result, a mobile node in the MoMoRo RPL network can retain its connectivity during its movement. Additionally, the MoMoRo node can reach up to 96% of the packet reception ratio (PRR), which is not possible with the RPL standard specification. This proposition is limited to a specific type of mobility: the human mobility model, which makes it inadequate for other mobility models. Furthermore, in Heurtefeux et al. (2013), the authors presented a new study of RPL behavior in terms of robustness, dynamics, delivery ratio, and control packet overhead. They applied two scenarios to obtain the results: converge cast traffic and high density. The results showed that the routing process preserves its stability even if nodes are moving in a random way. The paper is limited to the change of network topology by considering node state and does not consider the nodes mobility model. In Saad and Tourancheau (2011), the authors investigated the mobility of sink nodes in RPL by suggesting a new distributed and weighted moving strategy. The main goal of this study was to show that sink nodes can improve the network lifetime. The experiment results showed that the proposed approach provides better lifetime, lower energy consumption and a small overhead ratio. However, the mobility used for this strategy is limited to the random mobility model.

Similar to Section 3.1, Table 2 summarizes the related works based on mobility support, in addition to our proposed study.

As a conclusion, the evaluation of the RPL performances allows for finding the solution of some application requirements. However, most of the studies are focused on only a static case without considering mobility scenarios. This may also be incomplete if it does not take into consideration which mobility model should be used. In this paper, we propose evaluating and analyzing the RPL behavior in both static and mobile conditions. We are interested in assessing RPL performances in a diversity of mobility models by using two entities: group and entity mobility models.

4. Methodology and setup

In this section, a description of the design of our proposed scenario has been made based on static and mobile nodes. Moreover, the details of the mobility models used are given. All our simulations have been performed using the Cooja simulator version 2.7,

Table 1
Summary of works that study RPL in static environments.

	Contribution	Performance	Simulator
ELT (Iova et al., 2015)	Lifetime improvement	High reliability High lifetime Low DAG reconfiguration	WSNet
M-RPL (Multipath RPL) (Tang et al., 2014)	Multipath routing protocol	Low congestion Low packet loss ratio Low delay	Cooja
RPL over AMI (Parnian et al., 2014)	Hop Count Objective Function	High PDR Low Delay	Cooja
PER-HOP OF (Xiao et al., 2014)	Optimization of MRH Objective Function	Low latency High PDR Low energy	Cooja
Our proposal	-Network scalability -Sink nodes scalability	HC and ETX increase PDR decrease Overhead and Energy increase HC and ETX decrease PDR increase Overhead and Energy decrease	Cooja

Table 2
Summary of works that study RPL in mobile environments.

	Contribution	Strategy	Network	Simulator	Results
MoMoRo (Ko and Chang, 2014)	Packet Lost	Immediate Beaconing	VANET	TinyOS 2.X	High Overhead Low energy Low responsive
mRPL (Fotouhi et al., 2015)	Timers	Immediate Beaconing	WSN	Cooja	Low Overhead Low energy High responsive
Co-RPL (Gaddour et al., 2015)	Movement detection	Corona mechanism	MWSN	Cooja	Low packet loss Low energy Low delay
RPL Robustness (Heurtefeux et al., 2013)	RPL robustness assessment	Dynamic topology	LLNs	SensLAB platform	Stable path length Low PDR High overhead
RPL_Weight (Saad and Tourancheau, 2011)	Network lifetime with mobile sink	Weighted strategy	WSN	WSnet	High lifetime Low energy Low Overhead
Our proposal	Mobility support	Group/entity mobility models	LLNs	Cooja	PDR is better with group models Overhead and energy are better with entity models

which has been extensively evaluated in different works, i.e., (Dunkels et al., 2011; Osterlind and Dunkels, 2009; Kugler et al., 2013). We found that this version is more stable than the previous one. The results are averaged over 30 simulations with different random topologies; the different positions of the sink and senders are chosen randomly in the simulation area. In the physical layer, we chose to use the UDGRM model (Krishna et al., 2016). We used RPL-collect implementation to simulate our scenario. In this implementation, a connection between sink and sender nodes is initiated. The sink node establishes three phases: initializing the RPL DAG, setting up a UDP connection and then printing received packets from the sender on stdout. For sender nodes, it sets up also a UPD connection and then start to send packets to the sink periodically. When the sink node start the initializing, it tells the nodes "I am the sink" and then sends a DIO messages periodically. Moreover, after every transmission a time gap is increased with the help of a trickle timer.

Table 3 summarizes all the parameters used in the simulation.

4.1. Objectives of the simulation study

In fact, regarding the related work evocated in this paper, it is clear that all evaluations of RPL behavior cannot be applied to all of them in the same context. Some works evaluate the RPL in a special case (smart grid communication running on AMI networks) (Parnian et al., 2014), whereas others propose an extension of RPL to be used in a mobile network to make it reactive with an environment change (Fotouhi et al., 2015).

In all simulations, the default simulation testbed is used, which involves a large-scale network. We set a range of nodes that does not exceed 70 due to the PC capability and the RAM size of SKY motes. Nodes are disseminated randomly in the space to set up a wide network. The transmission range is set to 50 m, and the Unit Disk Graph Medium (UDGM) propagation model with Distance loss is used in the simulations (Krishna et al., 2016). Furthermore, the sink node acts as a root where all nodes send their packets. The communication between sink and senders follow multipoint-to-multipoint topology.

The objectives of these simulations are:

- To scrutinize the network behaviour of RPL standard specification. The use of RPL in static networks requires it to be extended to a mobile network to measure its power to keep its quality of performances in a topology change.
- To compare an entity mobility model with a group model using the RPL routing protocol, which allows for investigating the impact of each model on the network performances.
- To indicate the motif that influences the behavior of RPL in mobile Low Power and Lossy Networks.

4.2. Simulator

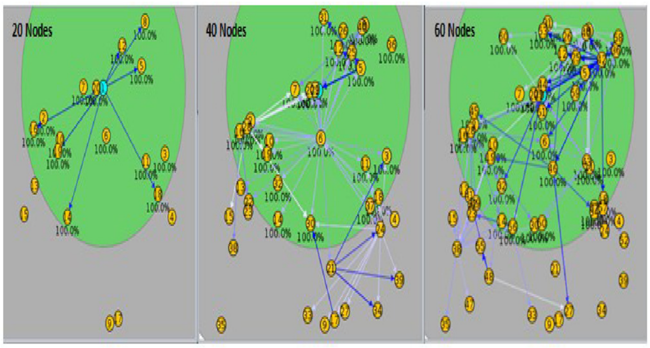
In this section, the different characteristics of the simulator are illustrated. The simulation model used in this work is based on the basic platform for the network simulator Cooja, which was designed as a simulator for IoT. This section gives an overview of Cooja version 2.7 (Dunkels et al., 2011), based on the Sky mote platform. We present the simulation model used in this work to evaluate the RPL performances under a set of simulation scenarios.

4.2.1. Cooja simulator:

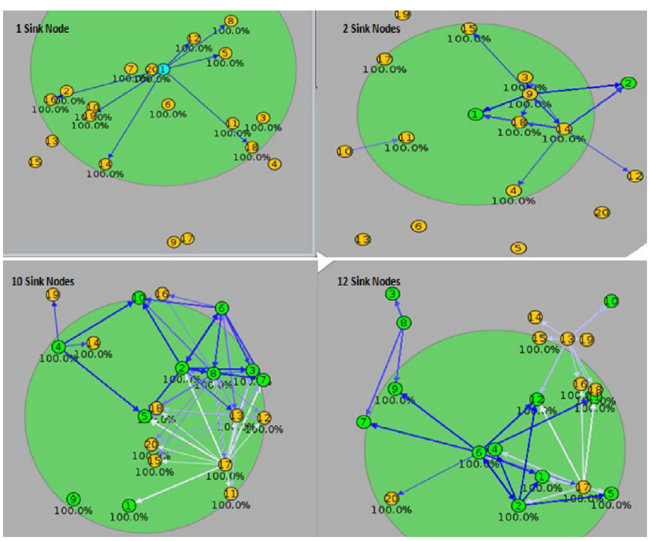
Cooja is a simulator based on the Contiki OS using sensor nodes (Dunkels et al., 2011). Cooja is an open source software, which is compatible with our needs for this study. Cooja offers the

Table 3
Cooja and Bonnmotion parameter setup.

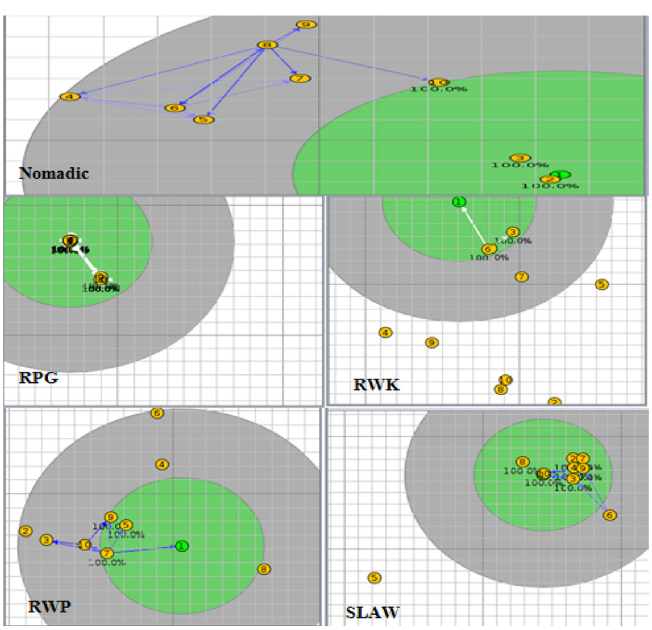
Cooja Parameters		Bonnmotion Parameters	
Settings	Table Value	Settings	Table Value
Propagation Model	UDGM with Distance Loss	Number of nodes	10, 20, 30
Mote Type	Tmote Sky	X; Y area	100 m
TX Range	50 m	Minimum speed	0
Total Simulation Time	1 h 16 min	Maximum speed	5 m/s
Number of Nodes	10, 20, 30, 40, 50, 60, 70	Simulation Duration	3600 s
Topology	Multipoint-to-multipoint	Minimum pause time	0
Nodes Position	Random	Maximum pause time	20 s
Speed	No limit speed		
Mobility Model	RPGM, Nomadic, RWK, RWP, SLAW		



a) Static Network Scalability



b) Use of multiple sink nodes



c) Mobility Models in Cooja simulator

Fig. 2. Screenshot of a simulation environment for the three scenarios.

possibility to simulate each node independently using either hardware or software. It can operate at the network level, the operating system level, and the machine code instruction level. It can run on different platforms such as Sky, TelosB, and native (etc.) and can simulate each node separately. The flexibility of Cooja makes it possible to add some extensions in the simulator (Dunkels et al., 2011). All parameters used in this study are described in Section 5. The Cooja simulator does not adopt any mobility model. For this, we use the Bonnmotion simulator (Aschenbruck, 2013) to generate the mobility pattern traces. After collecting generated mobility traces, we have developed a script that converts the extension obtained by Bonnmotion to another one used by cooja. Moreover, to use this file we have used the mobility plugin that we have added to cooja tools. This plugin allows attributing the mobility traces to nodes situated in the network.

4.3. Metrics of interest

In this section, five main metrics are identified to evaluate our study. Each metric provides important assets that have an impact on the routing process:

As described above, RPL has some specifications that make it more critical in its use in regards to the type of devices used. Our proposed scenario allows for discovering different changes in RPL behavior according to specific metrics. In what follows, we consider five important routing metrics for RPL assessment (Lamaazi et al., 2016):

- *Control Traffic Overhead:* This is the total number of control messages transmitted by nodes to build DODAG and to select the best parent between candidate neighbors.
- *ETX (Expected Transmission):* This represents a maximum number of the retransmissions of an individual packet to be successfully delivery over a wireless link to reach the destination.
- *Hop Count:* The hop count metric (HC) represents the number of hops between nodes (i.e., candidate neighbor) and the root (Khan, 2012).
- *Packet Delivery Ratio:* This illustrates the level of data delivered to the destination. Better performance of the protocol provides a greater value of PDR.
- *Node Energy:* This indicates the average energy measured from nodes in the network over the network lifetime. The formula used to calculate the energy of nodes is:

$$\text{Energy}\quad(\text{mJ}) = (\text{Transmit} * 19.5\,\text{mA} + \text{Listen} * 21.5\,\text{mA} + \text{CPU\_time} * 1.8\,\text{mA} + \text{LPM} * 0.0545\,\text{mA}) * 3\text{V}/(32768)$$

(Lamaazi et al., 2016)where: *CPU:* represents the power consumption during the full power mode. *LPM:* represents the power consumption during the low power mode. *Transmit* corresponds to the transmit operations while *listen* is for listening operations.

4.4. Scenarios

4.4.1. Realistic scenario

In this work, we undertake a pre-deployed IoT network in a small home of a size of 100 m ∗ 100 m that has a connected predeterminate set of sensor nodes (senders) and sinks. In the first step, we use a centric sink that collects data from senders around all parts of the house, where all nodes are static. In second step, a set of sinks nodes are distributed arbitrary with multiple sinks in the network. Finally, a set of senders are disseminated on a different entity in home who moves on entity or group way. The movement of these entities follow the different mobility models that we have used in our simulations. Parameters values used in our work are based on Tmote Sky platforms that can have different transmission range and power levels in order to realize devices heterogeneity. Inside a home, we didn't consider any obstacle that can disturbed communications.

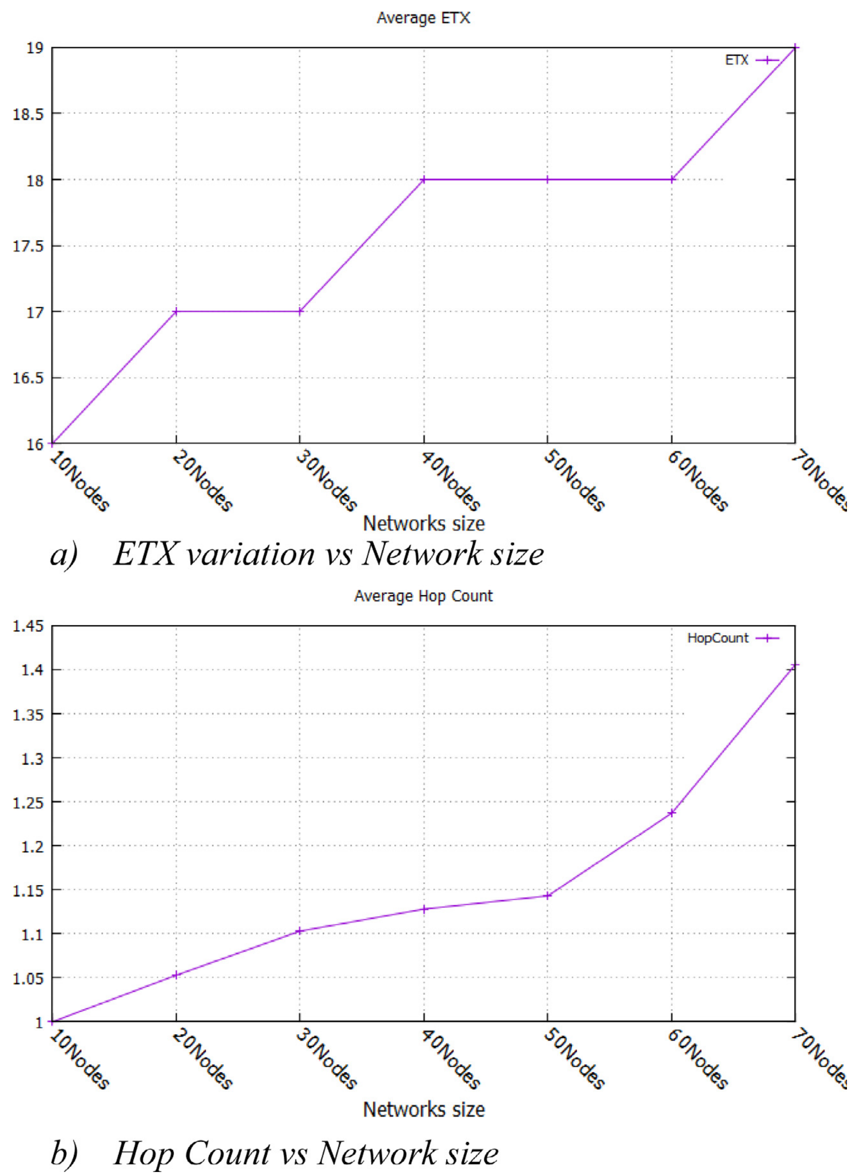


Fig. 3. Comparison of Hop Count and ETX metrics for different densities of networks.

4.4.2. Simulated scenario

This subsection presents the test scenarios adopted in this work. For the objective to observe RPL performances under our proposed scenarios, different topologies are created, considering point-to-multipoint and multipoint-to-multipoint topologies. To involve diverse scenarios to show the impact of different cases, the network size, the scalability of sink nodes and the mobility are considered.

In the static case, two scenarios are considered, as shown in Fig. 2. The two simple scenarios are tested to show how RPL performances change in such an event. The network size and the scalability of the number of sink nodes are depicted in Fig. 2(a) and (b), respectively. In both scenarios, two types of nodes are used: sink and sender. The sink node is the node that all sender nodes (end devices) transmit their data to and try to join. In the network size scenario, nodes increase by a factor of ten nodes in each network. In contrast, in the second scenario, we keep the same network size but with an increase of the number of sink nodes. We first consider a lower number of sink nodes than sender nodes, then an equal number of sink nodes and sender nodes, and finally a higher number of sink nodes than sender nodes, as shown in Fig. 2(b). This scenario makes it possible to discover the importance of sink nodes and how they can influence RPL behaviour.

In the mobile case, we follow the second repartition already explained above, which organizes mobility models using two classifications: entity and group mobility models. Moreover, we have chosen the RWK, RWP, and SLAW models, whereas, for the group models, we have used the RPG and Nomadic models (see Fig. 2c). In contrast with the majority of previous studies (Gaddour et al., 2015; Heurtefeux et al., 2013; Ko and Chang, 2014) that try to study RPL under mobility, we assess the RPL performances using a wide range of mobility models to show how RPL operates when the mobility model changes and which ones provide better performances.

To test our proposed scenarios, we configure a set of parameter settings using the Cooja and Bonnmotion simulators, which are described in Table 3. The trace file generated by the Bonnmotion simulator that allows for using mobility models is in the "if" extension. To use this file, we have developed a script that can convert this extension to another one used by Cooja. This makes it easy to use a set of models.

5. Results and evaluation

It is clear that each chosen metric offers an individual side to study the routing protocol. Moreover, the different scenarios used in this study also have an important impact on both protocol and network behaviour. It is, therefore, important to take into consideration all these metrics simultaneously to optimize the packets delivery and to select good routes without consuming more power. The aim of the simulations is to provide a basis on which we can analyze the performance of RPL, considering the number of received and lost packets, the number of hops, Expected Transmission (ETX), and Power Consumption. The results are also compared with two different mobility models. The simulation results show the performance of the mobility models with respect to the parameter that has been selected previously.

5.1. Network scalability

5.1.1. ETX and hop count

Fig. 3 compares the average hop count and the number of expected transmission counts of RPL. It is clear that HC and ETX increase with the case of a scalable network composed of a set of nodes up to 70 nodes. This can be justified by the availability of a set of a number of neighbours, which makes the choice of another parent easy, and the nodes can then use more HC to reach the destination. Additionally, in the case of a very dense network, the interference between transmitted packets increases, which pushes nodes to send more packets to increase their chances to be successfully received at the destination. This can also explain why ETX increases when network density increases.

5.1.2. Packet delivery ratio

Fig. 4 shows the packet delivery ratio of RPL compared to the network size. Simulation results show that the PDR decreases with the increase of the number of nodes. Thus, RPL performance is better in low-density networks with regards to the high PDR value that it provides. In contrast, for a high network density, nodes can lose more packets due to interference, where a node can send data to multiple destinations that have the same minimum rank. These parents can be congested and then drop these packets. In this case, the density of the network can provide a low link quality.

5.1.3. Control Traffic Overhead

Fig. 5 illustrates the Control Traffic Overhead of nodes. We note that in a low density network, the nodes provide fewer control messages than in a dense network. In a high-density environment, the nodes send more messages in multicast to build the routes and then to propagate the routing table. For this, more DAO messages should be sent to transmit the routing tables. The neighbor nodes generate more DIO messages to update the routing table information. All of these messages explain the higher value of Control Traffic Overhead when the network becomes denser. Moreover, the Control Traffic Overhead impacts the network stability and resources. The high value of these metrics means that the network is unstable. Additionally, in high-density networks, there is more congestion and collision between packets, which increases the transmission delay. This behaviour can be explained by the fact that nodes need to send more messages to check the availability of the network, which consumes more resources.

5.1.4. Energy consumption

We varied the network density to measure the consumed energy. Fig. 6 shows that the network consumes more energy when it becomes denser. This increase is mainly due to the number of transmissions of packets sent by nodes. The augmentation of the number of nodes from 10 to 70 nodes provides an augmentation of the energy of 89.38%. Indeed, an unsuccessful transmission provides an augmentation of energy consumption as opposed to a successful one.

5.2. Multiple sink

5.2.1. ETX and hop count

Fig. 7 shows that the number of HC decreases considerably when the number of sink nodes increases. This is justified by the fact that sink nodes collect data from the nearest senders. Moreover, the sender nodes send data to one or more sink nodes if they are in the same transmission range. This means that there are some

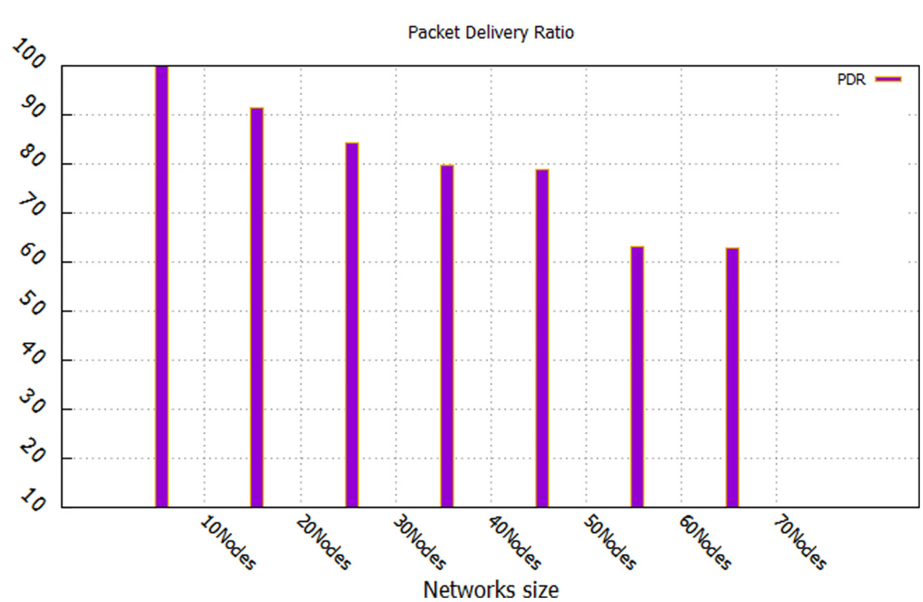


Fig. 4. Comparison of the Packet Delivery Ratio for different densities of networks.

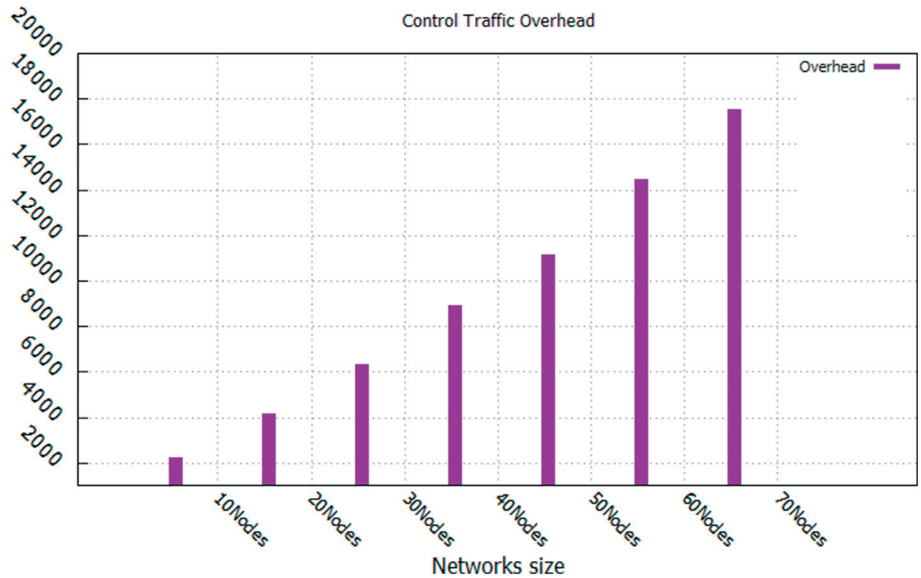


Fig. 5. Comparison of Control Traffic Overhead metric for different densities of networks.

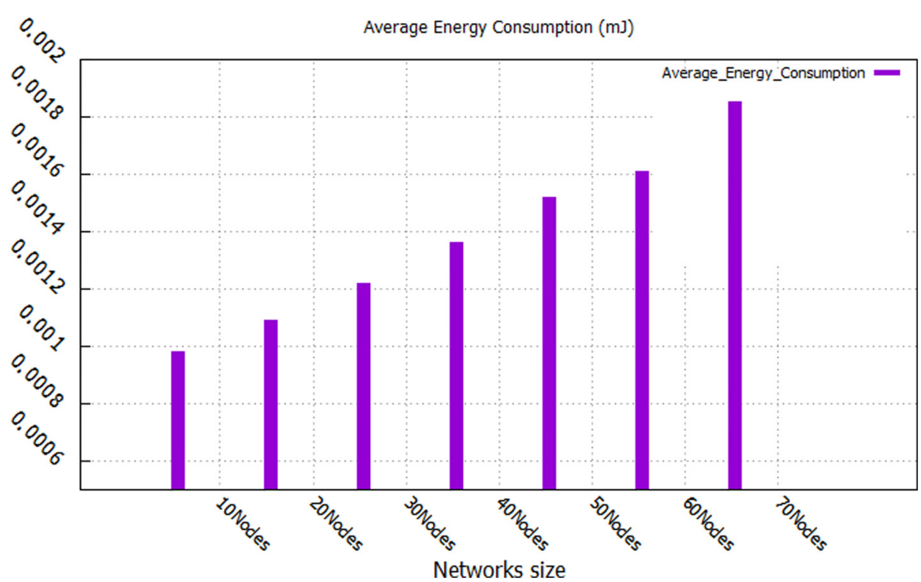


Fig. 6. Comparison of Energy consumption for different densities of networks.

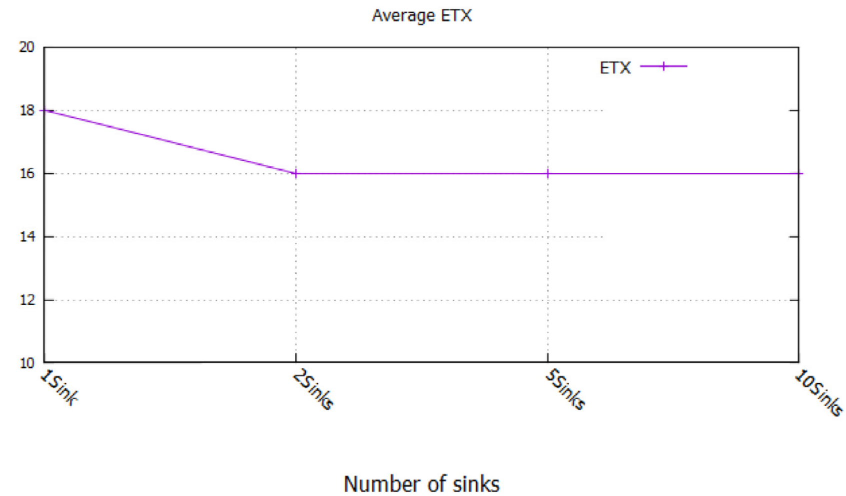
sink nodes that cannot receive any data if they are not in proximity to the senders. These results show that the number of sink nodes has a direct influence that can reduce the ETX and HC metrics. This result can be justified by the routing protocol behavior, which calculates these values only between the nearest sink node and all sender nodes. As a conclusion, this solution could be optimal for an application that uses a very high density with a distribution of area on which each sink node should collect data from a fewer number of sender nodes, after which each sink in all areas can transmit these data to a root.

5.2.2. Packet delivery ratio

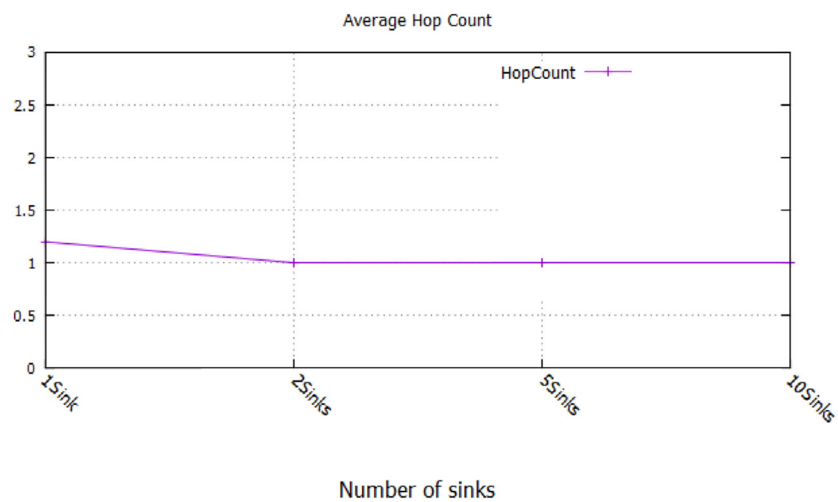
In Fig. 8, we increased the number of sinks while we kept the same value of the senders (30 nodes) to measure the packet loss ratio. Simulation results show that the PDR increases as the number of sink nodes increases. Thus, the RPL performance is worst when we use a lower number of sink nodes. This conclusion is justified by the low value of PDR that the nodes provide. In contrast, for a high number of sink nodes, the senders try to send data to the nearest sink, which leads to few lost packets. This can be explained by the fact that sinks collect data from leaf nodes. For this, we calculate the PDR from the sink (number 1) that collects data from the maximum number of nodes. This can have another impact on the network, i.e., the redundancy of the sent packets, particularly if the nodes are situated at the same distance away from multiple sinks.

5.2.3. Control Traffic Overhead

Fig. 9 illustrates the Control Traffic Overhead of nodes. As presented in the figure, the high values of sink nodes provide low traffic overhead. Furthermore, the number of transmitted packets decreases with the increase of sink nodes. In the case of multiple sinks, the network is more stable than the case of one single sink because nodes transmit data to the nearest sink. This choice of sink



a) ETX variation vs Number of sinks



b) *Hop Count vs Network size*

Fig. 7. Comparison of Hop Count and ETX metrics in network with the increase of sink nodes.

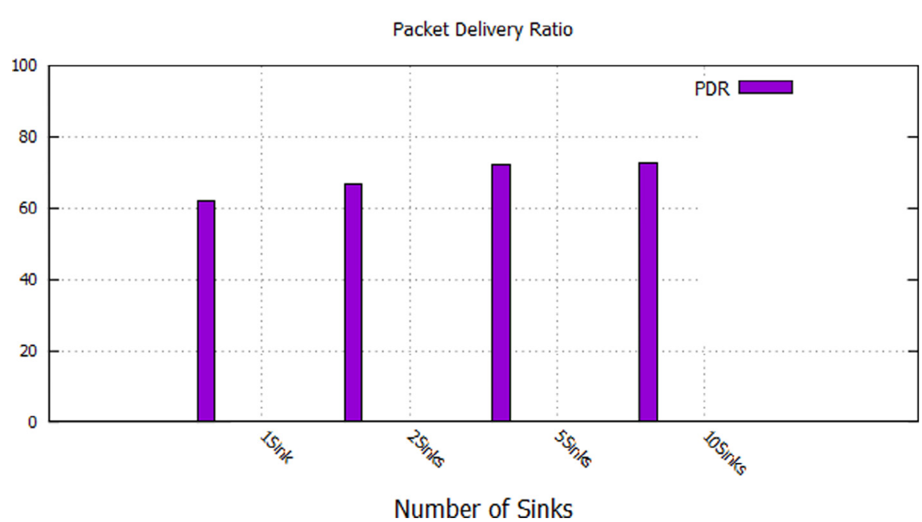


Fig. 8. Comparison of the Packet Delivery Ratio with the increase of sink nodes.

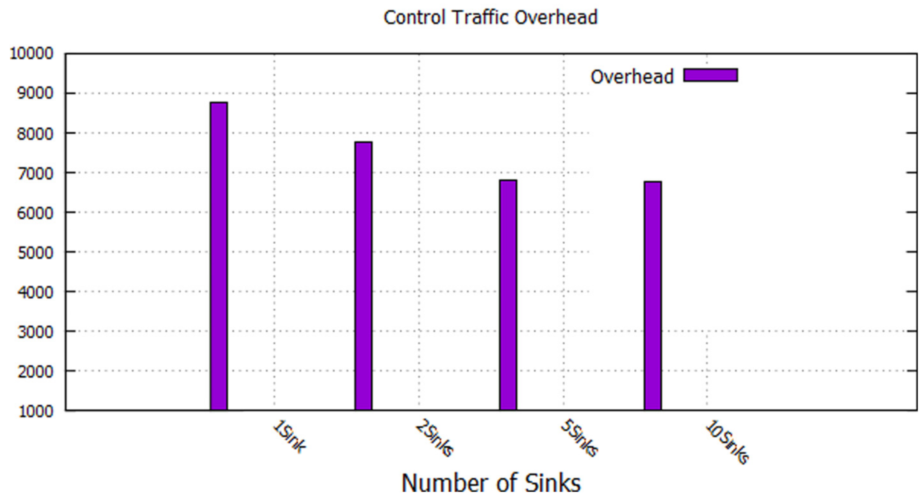


Fig. 9. Comparison of Control Traffic Overhead with the increase of sink nodes.

node based on its rank allows reducing redundancy and retransmission by senders. More sinks allow the senders to be comfortable to send data to one sink or two according to their needs, therefore, the overhead is reduced. Additionally, nodes do not need to send more packets to check the availability of the network because there is less congestion and collision between packets. This is because sender nodes send data to the nearest sink. In this case, nodes consume fewer resources, as shown in Figs. 9 and 10.

5.2.4. Energy consumption

As explained above, the increase of sink nodes allows consuming fewer resources. We have measured the energy consumption in such case to prove this conclusion as illustrated in Fig. 10. This increase of sink nodes from 1 to 10 reduces the energy by −55.86% (see Fig. 10). Sink nodes do not consume much energy because they work as collectors of data from senders and do not need to retransmit packets to check the network availability or to find neighbors. The sink nodes transmit the first message to all nodes to be presented as a sink. After this message, sink nodes act as a server such that all sender nodes try to send to them their collected data. These actions justify the fact that the energy consumption is lower in this condition. Moreover, while the increase of the number of sink nodes reduce the energy consumption, it is not only related to the presence of sink nodes, but also on how the senders react in the presence of multiple sinks. The choice of the nearest sink according to its rank is due to how sender nodes calculate the best path to the root. When the sink node broadcasts the DIO messages, sender nodes in the same transmission range of the sink receive the DIO messages. Afterward, nodes based on the OF decide to join the DODAG. The sink node broadcast more frequently the DIO messages when the network is not stable or in the case of a new node join the network. Reducing control messages allow reducing energy consumption. Moreover, reducing the number of retransmission of expected transmission count (ETX) has an impact on reducing the energy consumption.

5.3. Performance assessment of RPL under mobility

Obviously, the routing protocol consumes more resources in the mobile case than in the static one. However, the main idea in this scenario is to show how RPL behaves in this type of repartition of mobility. The test has been performed by considering both group and entity models. In the current work, we have considered two important parameters to study the behavior of RPL: the number of nodes and the mobility models. In all figures, the simulations focus on analyzing the performance of RPL, considering the Control

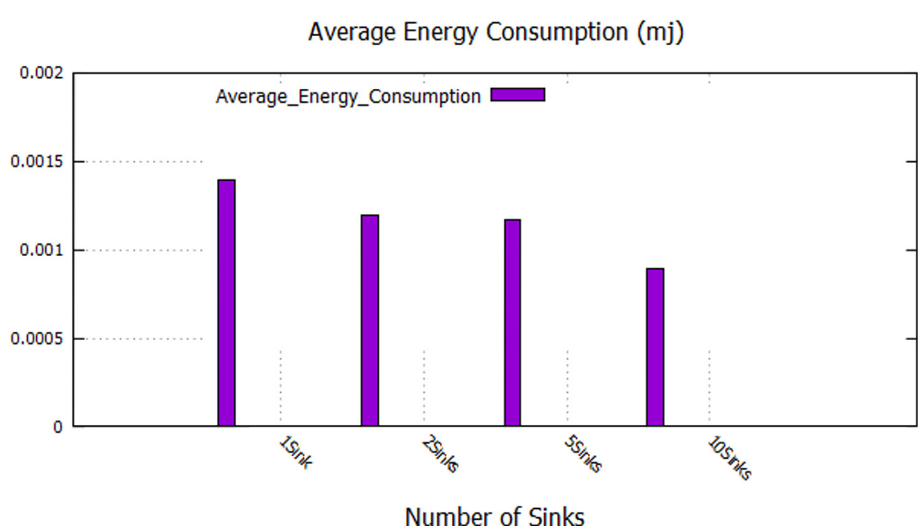


Fig. 10. Comparison of the Energy Consumption with the increase of sink nodes.

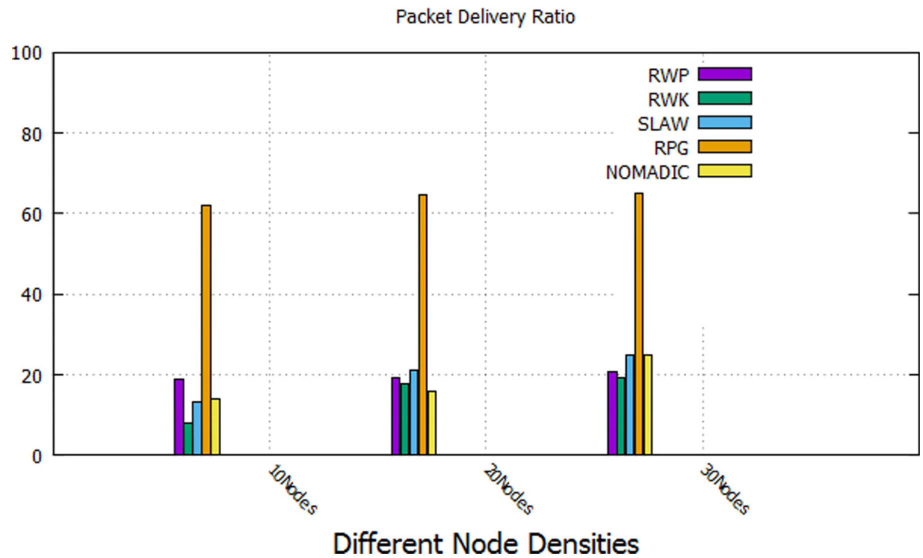


Fig. 11. Comparison of the Packet Delivery Ratio for different densities of networks using group and entity models.

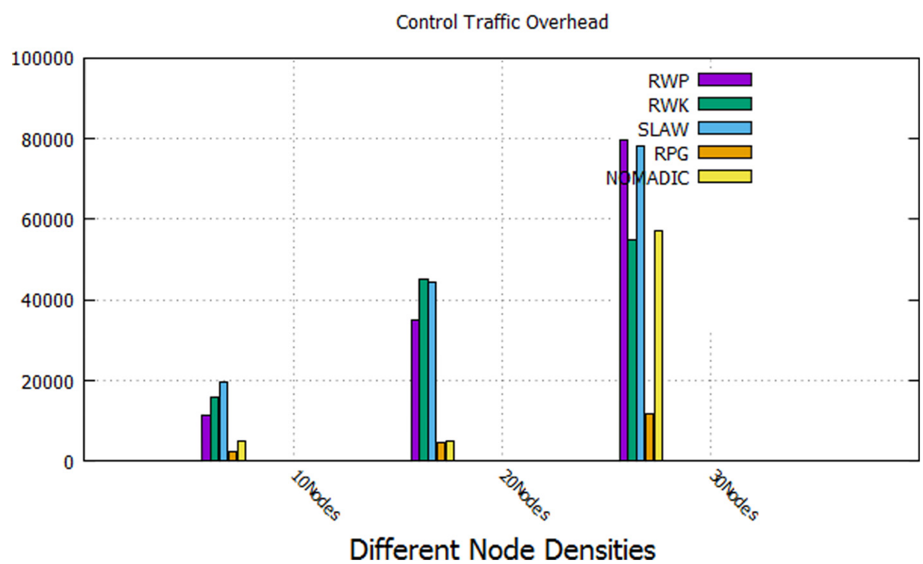


Fig. 12. Comparison of the Control Traffic Overhead for different densities of networks, applying group and entity mobility models.

Traffic Overhead, the PDR, and the energy consumption. The results are compared between five mobility models divided into two classes: group mobility models and entity mobility models. For the group mobility models, we have to choose the RPG and Nomadic models, whereas, for the entity model, we have to choose the RWK, RWP, and SLAW models. The topology used in all simulations is "one-to-many", which contains one sink node, with the rest being sender nodes.

5.3.1. Packet delivery ratio

Fig. 11 shows the PDR value. Note that the PDR value describes the quality of the protocol performances. It allows for illustrating the level of delivery data to the destination. The group mobility models provide a higher value of PDR than the entity models. This can be justified by the number of received packets and sent packets that it provides. With reference to the structure of group models, nodes can receive the maximum of data in regards to the distance between each other. In contrast, with entity models, each node in the network move according to its own parameters and then the movement of nodes can allow it to lose its data.

This explains the low value of PDR with the entity models. These results increase when the network becomes denser.

5.3.2. Control Traffic Overhead

Fig. 12 shows the Control Traffic Overhead of nodes. As presented in the figure, the entity models provide a higher value of traffic overhead than the group models. Additionally, the scalability of the network also impacts the traffic. The increase in the number of nodes also increases the traffic, which can be justified by the fact that nodes transmit more data when they move and also when their numbers increase. Moreover, nodes transmit more data to join a destination, which becomes more difficult when they move.

5.3.3. Energy consumption

Similar to Fig. 12, in Fig. 13, RPL provides better performances with the entity models in terms of energy consumption than with

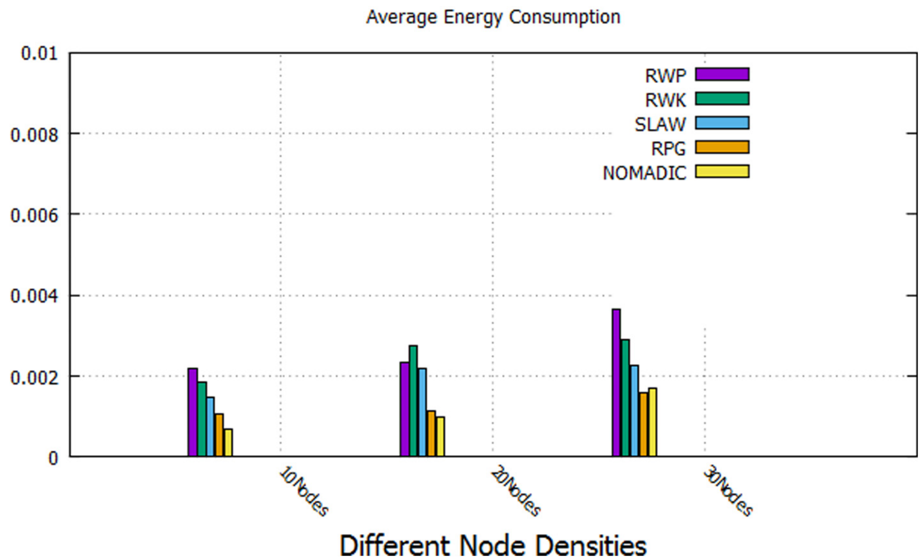


Fig. 13. Comparison of the Energy Consumption of different densities of networks, using group and entity mobility models.

the group models. In the group models, the nodes need to decide the best path toward the destination according to the group. This decision is based on the calculation of the route from all nodes inside the group, with the best one being chosen. In contrast, in the entity models, the nodes can communicate with each other independently; then, each one can reach a decision without any group decision. Briefly, RPL in a group mobility model can consume more resources than in an entity one. Moreover, this consumption of energy becomes more serious when the network is dense.

6. Conclusion

In this work, we have evaluated the performances of RPL in different scenarios. As with most routing protocols, RPL has some shortcomings in terms of topology changes and mobility conditions. The majority of recent studies did not consider all scenarios and all metrics for a comprehensive evaluation of RPL behaviour. In our work, we suggested a new study of RPL in both static and mobile case using different mobility models. We compared the performance of RPL in three scenarios that cover the most important metrics. We varied the number of nodes, the number of sink nodes and the mobility models. To evaluate the suggested scenarios, we chose five important metrics: number of hops, ETX, PDR, Control Traffic Overhead and Energy Consumption. The results showed that HC, ETX, Control traffic overhead and Energy consumption increase when the network becomes denser, whereas the PDR decreases. In the second scenario, where the number of the sinks is greater, we noticed an improvement of RPL performances. Our results showed a decrease of HC, EX, Control traffic overhead and Energy consumption in these conditions. The energy consumption is reduced up to 55.86%. Moreover, the PDR also increased, which indicates more stability of the network and fewer lost packets in comparison with the network using a single sink. Finally, we used RPL in different mobility models that belong to two different mobility categories: group-based mobility and entity-based mobility. The results showed that RPL acts better in terms of Control Traffic overhead and energy consumption when it is used with entity models, whereas with group models, it provides better PDR than with the entity-based models.

In our future work, we will design a new objective function that uses a combination of a set of metrics. These metrics will be used as the criteria for selecting the best path to the destination based on fuzzy logical method.

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