Performance evaluation of RPL on a mobile scenario with different ContikiMAC Radio Duty Cycles

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***Abstract*—IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) is the only standardized routing protocol for Low Power and Lossy Networks. Therefore, RPL is the routing protocol chosen for most Internet of Things (IoT) applications. However, the RPL protocol has some open issues when the scenario includes mobile nodes. Since many IoT applications include mobility, this is an important problem to address. Node mobility does not permit the network to stabilize and because of this keep exchanging control messages. Mobility increases the packet loss because mobile nodes may leave the coverage area before transmitting the data. This problems also increase the power consumption. Another important factor affects the RPL performance. To save nodes energy, the data link layer implements a radio duty cycle. These duty cycles turn the radio off when it is not used. One common and used radio duty cycle protocol is the ContikiMAC. Changes in the frequency of the duty cycle modifies the RPL performance. This work shows how the change of radio duty cycle of ContikiMAC on a hybrid scenario, composed by fixed and mobile nodes, interferes on RPL performance. Results show that the nodes mobility degrade the metrics tested. The choice of radio duty cycle is very important to the network performance. The results show that the RPL performance is strictly dependent of the duty cycle.**

I. Introduction

In the last few years the number of devices connected to the Internet increased and for the next years, the industry expects this growth to be exponential. The expectation is that 20 to 50 billion devices will be connected to the Internet by 2020 [1]. All these connected devices corroborate to the Internet of Things development. One important observation about the IoT is that many networks will be composed of sensor and actuators, that will be used to monitor environments, people and animals. These devices, commonly know as motes, are hardware constrained. Networks formed by these devices are known as Low Power and Lossy Networks(LLN). Thus, to the perfect operation and interoperability of all these devices new network protocols need to be developed.

One of this new protocols is the RPL routing protocol. This protocol was specifically developed to the LLN's constrains. RPL [2] is prepared to use the IPv6 address, and more specific the 6LowPAN (IPv6 over Low power Wireless Personal Area Networks). Routes in RPL are formed using metrics that allow the networks to keep alive for longer periods. One route can be avoided by the nodes if one node in this route has a low battery, for example. But the RPL performance depends of the data link layer protocol too. To save nodes energy, the link layer protocol implements a radio duty cycle. This duty cycle turns the radio off when node does not perform any transmission/reception or process any information.

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RPL standardization does not specify anything about the mobile nodes, however, many IoT applications will be used by mobile nodes. Some works study the mobility problem, like [3] and [4]. Other works try to solve the mobility problem, [5], proposing some changes or mechanisms to RPL. ContikiMAC problems and possible solutions are presented by other works, such as [6] and [7]. However, until this moment, there is not any study that analyzes the interactions between nodes mobility and ContikiMAC. This work shows how the changes in ContikiMAC duty cycle impacts on a hybrid network, formed by mobile and fixed nodes. The scenario is composed by fixed nodes (FN) and mobile nodes (MN) with their movements defined by the random waypoint mobility model. The work will be focused on the energy consumption, but other metrics will also be analyzed, as packet loss and latency.

This work is organized as follows. Section II presents the RPL protocol and the mobility problem. Section III presents the problems associated with the ContikiMAC. In Section IV test scenarios and node configurations are shown. Section V is dedicated to the results analysis and Section VI presents the conclusions and future work.

II. RPL Overview

RPL is a distance vector protocol, based on directed acyclic graphs and oriented to destination [2]. RPL protocol was developed to attend the requirements of Low Power and Lossy Networks, LLNs. These requirements are the low power of the devices and low computational capabilities, like their tiny memory for instance. RPL needs to be efficient when controlling the routes because the nodes can be inaccessible for long periods of time. RPL is destination oriented, so the topology of the networks based on this protocol has a root node that acts as a sink. This sink node is the destination of the messages of the other nodes in the network. The topological structure of RPL is called DODAG, Destination-Oriented Directed Acyclic Graph. The presence of a sink node and the DODAG organization makes RPL a hierarchical protocol.

RPL uses Objective Functions (OF) to define metrics and how this metrics will be used to create the routes. There are two standardized OFs. A simple one is called OF0, that does not use metrics, only gives a route to the incoming node to connect to the sink. And the other is the Minimum Rank Hysteresis Objective Function (MRHOF). This OF uses one metric, like energy, to define a threshold. Nodes use this threshold to decide if it changes the current parent node to another one with better metrics.

To construct a new DODAG, sink node sends to their neighbors a DIO (DODAG Information Object) message. This message contains information about the OF in use and a rank number. Rank is a number calculated by the nodes and represents the distance of this node to the sink. Sink node has the lowest rank in the network. Nodes receive this DIO and calculate their ranks, build and send a new DIO message. Based on this received DIO, nodes choose their preferred parent, a node that will receive the messages. When all nodes send and receive a DIO and chose a preferred parent they start to send a DAO (Destination Advertisement Object) message to the sink. DAO message is used to set up the downwards routes, so the sink node can send messages to the nodes. A new incoming node in a formed DODAG needs to send a DIS (DOGAG Information Solicitation) to the other nodes requesting a DIO. After this node receives this DIO it calculates the rank and sends a DIO to the neighbors and the DODAG is updated.

To maintain the routes nodes send periodic DIO messages. The time between this DIOs increases when there is no changes in the network. This mechanism is called trickle timer [8]. The timer is set to the initial value every time the RPL register an event on the network.

RPL standardization does not specify anything about node mobility. However, many IoT applications will use mobile nodes, like animal monitoring. Many problems appeared when RPL is used by MN. The packet loss of the MNs may be higher than FNs, because the MNs lose connectivity with their preferred parent. Packet delivery ratio of FNs decreases when there are MNs in the network because a fixed node can choose a MN as preferred parent and this MN left the coverage area. Control messages could have the same problem, but the effect is the DODAG presents instabilities. Because of the mobility the time between control messages are very short, in other words, trickle timer always identifies an event and reset it to the default value. The increase of control messages also increases the power consumption of the nodes. Depending on the position where MN is, it could generate loops in the network, caused by a wrong and outdated rank. MNs could stay out of the network for a long time because of the trickle timer.

The works presented in [3] and [4] analyze the behavior of RPL in a mobile scenario, using some mobility models. Only [4] presents the energy consumption metric. Other works present some solution to the RPL performance, but these solutions are restricted to a specific scenario. Two works study RPL in VANET scenarios and made some changes in the protocol. In [9] is proposed to change the sending time of the control messages, and in [10] is used geographical information as OF metrics. The work presented in [5] proposed a mechanism called Smart-HOP to manage nodes hand-off. In [11] is proposed the use of an intermediate layer to support the nodes mobility. Other works as [12], [13] and [14] present other changes to the RPL in mobile scenarios.

Only [14] presents the nodes power consumption, and [6] presents some MAC issues for RPL. Thus it is necessary to perform an analysis of the protocol with different MAC configurations in mobile scenarios.

III. ContikiMAC Overview

ContikiMAC is a Radio Duty Cycle protocol (RDC), presented in [15]. The RDC is part of the Medium Access Control sub-layer. ContikiMAC is used together with the Carrier Sense Multiple Access (CSMA) in Contiki Operating System [16]. The duty cycle mechanism uses periodical nodes wake-ups to listen for a packet transmission of neighbors. When a packet is detected, node turns radio on to receive this packet. After receiving the packet, the node sends an acknowledgment to the transmitter. A sender node sends its packets during the wake up period until it receives an acknowledgment. The ContikiMAC implements a mechanism of fast sleep. In this mechanism nodes detect the packet destination and if this packet is not destined to it the node can sleep. Other mechanism implemented by ContikiMAC is a phase-lock. Based on a scenario where nodes have a stable and periodic wake-up interval, the sender could send its packet in the exact moment the receiver will be awake. Nodes learn the wake up period of their neighbors based on the acknowledge messages.

Some works analyze and make some proposals to improve the RDCs protocols. In [6], the authors compare various RDCs protocols, but they did not consider to change the frequency of ContikiMAC. This work used a scenario only with fixed nodes. They show, as expected, the RDCs protocols may improve the RPL performance. In [7] is proposed a modification in ContikiMAC that makes the frequency of RDC adaptive. This work shows the benefits of changing the RDC frequency based on the power consumption of nodes. But the authors do not test the mechanisms proposed in mobile scenarios, neither present the performance of ContikiMAC with different frequencies.

IV. Simulation Setup

For the simulation tests was used the COOJA simulator with SkyMotes nodes. COOJA is a simulator integrated to the Contiki Operatingl System [16]. The network simulated was composed by 21 fixed nodes, randomly distributed in a square with 200 meters side. One of the fixed nodes is the sink node. First of all, one scenario without mobile nodes is simulated to have a parameter to compare the influence of mobile nodes on the network. After this, mobiles nodes are inserted in the network. The mobility model is the Random Way Point model, which was generated using the BonnMotion software [17]. The number of MNs are incremented by five for each simulation scenario, until 20 MNs. All MN move with the same speed, but the scenarios were tested with two different speeds, 1 and 2 m/s. Two duty cycles was also used, 8 and 32 Hz.

Figure 1 shows the topology used in the test in presence of five mobile nodes (21 to 25).

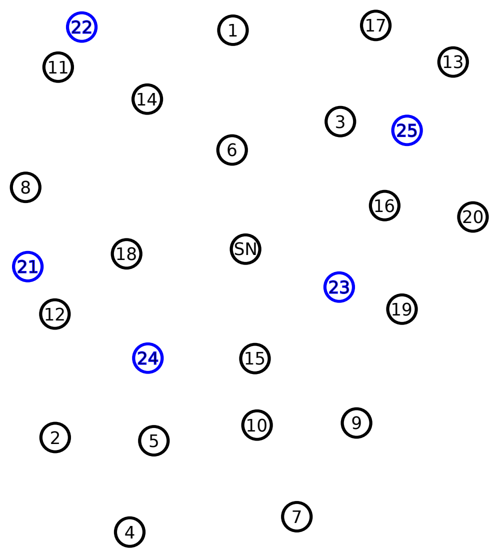

Fig. 1. Test topology with five MNs

Nodes transmit one data packet to the sink every 30 seconds. All nodes are configured to use ETX (Expected Transmission Count) as metric to calculate the routes. Scenarios were tested for thirty minutes and repeated thirty times. In this work four metrics are studied, ETX, packet delivery ratio (PDR), latency and power consumption. The results have a confidence interval of ninety-five percent.

V. Performance Evaluation

This section will be divided by the metrics used to analyze the RPL. Results presented here are the average values of each metric. All metrics will be shown in two graphs types. The first one shows the results grouped by node type: fixed or mobile. To keep graphs more readable will be presented only the results of scenarios without MNs and the scenarios with 10 and 20 MNs. Scenarios with 5 and 15 MNs present intermediated values. The second graph shows the results of mobile nodes grouped and the results of FNs grouped by hops to the sink node. To analyze this second graph just one scenario is presented. The chosen scenario is the one with 20 MNs with 2 m/s speed. The other scenarios had the same behavior, with only changes in the amplitude of values.

A. Latency

Figure 2 presents the latency of data packets sent by fixed and mobile nodes. As expected, the scenario without MNs achieved better results than with MNs. This occurs because the presence of MNs in the network may represent more hops to the data to reach the sink node. The increase of MNs in the network increases the latency. This can be seen in the difference between the scenarios with 10 and 20 MNs. It is possible to note that the node speed had low impact in the performance.

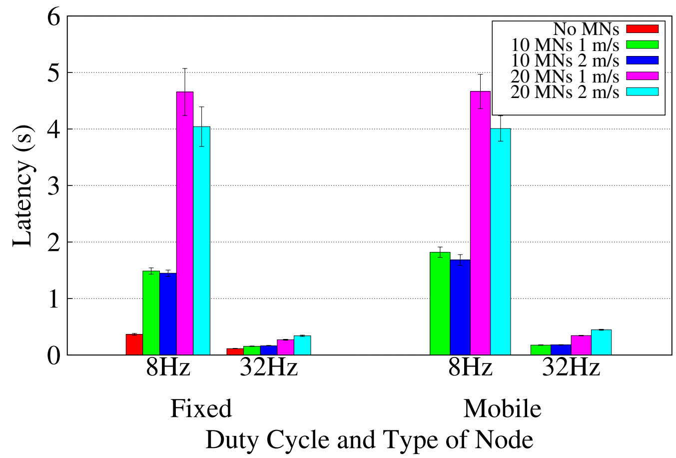

Fig. 2. Latency for fixed and Mobile Nodes

Figure 3 shows a scenario with 20 MN with 2 m/s speed. This figure is more illustrative to understand the RDC interaction with RPL. With an RDC of 8 Hz nodes have a higher latency than when 32Hz is used. This can be seen in Figures 2 and 3 and it happens because nodes wake up more times with a RDC of 32 Hz. So, nodes keep the packets for a shorter period until send it to the next hop. The more hops a node is from the sink, the higher the latency.

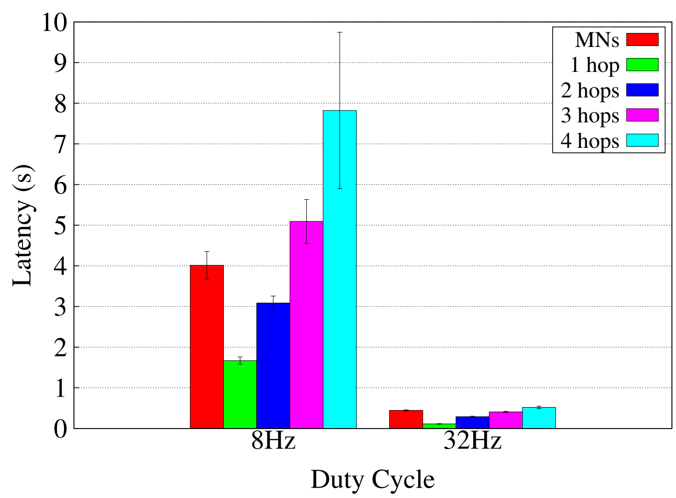

Fig. 3. Latency for one specific scenario

B. Expected Transmission Count

In Figure 4 is possible to see the interference of mobile nodes in the network. With more MNs the ETX increases because there are more hops between the source and sink node. Speed changes have different effects for the two RDCs. With 8 Hz the increase in speed reduces the ETX. In contrast, with 32 Hz the increase in speed increases the ETX too. As described for the latency, when nodes use a 32Hz RDC the interactions between fixed and mobile nodes happens more often. But, with a higher speed, MNs leave the coverage area of their parents quickly.

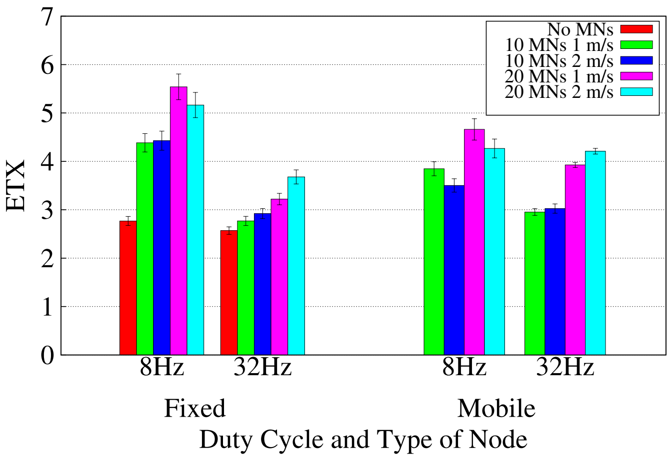

Fig. 4. ETX for fixed and Mobile Nodes

In Figure 5 is shown the ETX by hops to the FNs and by grouped MNs. The hops used is based on hops for a network without MNs. So, for a 8Hz RDC, the interaction between MNs and FNs causes an increase in the ETX, especially for the FNs with more hops. When FNs are closer to the sink, the influence of MNs is lower because of the MRHOF. Nodes closer to the sink hardly receive a new rank information that is better than the actual. For a 32Hz RDC, the influence of the MNs is lower than for 8Hz. Since for 32 HZ all nodes are more frequently awake, the probability of a packet being forwarded also increases, thus decreasing the ETX.

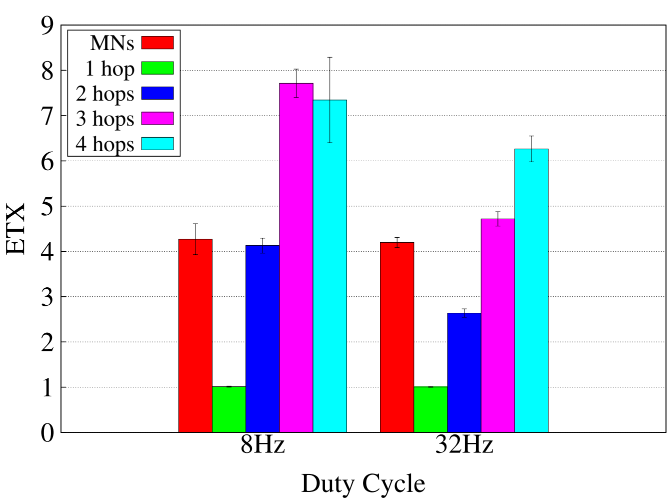

Fig. 5. ETX for one specific scenario

C. Packet Delivery Ratio

Figure 6 shows the results of PDR. The presence of mobile nodes makes PDR of FNs lower. This is caused by the selection of MNs as preferred parents. And this behavior is aggravated with the increase of MNs in the network. When nodes use a 32Hz RDC, the PDR increases because nodes stay awake more time and can use a MN as parent while these nodes are in the coverage area. Is possible to note that, in general, a higher speed decreases the PDR.

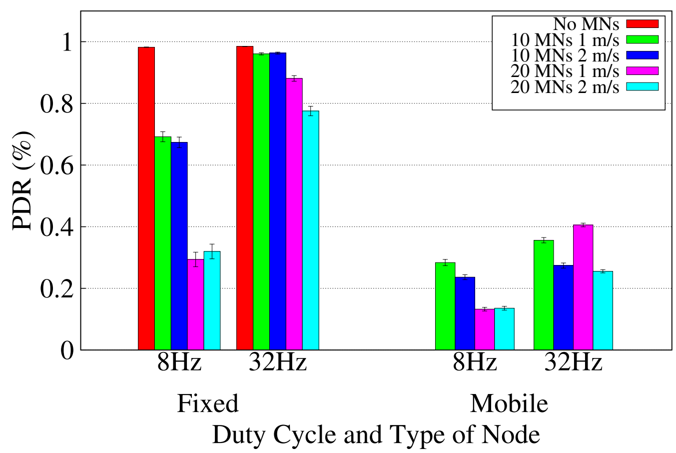

Fig. 6. PDR for fixed and Mobile Nodes

Figure 7 shows the results of a specific scenario. Using a 8 Hz RDC, fixed nodes more distant from the sink and mobile nodes present a poor performance. For the FNs, the distance represent more hops to the sink. And if a MN was selected as a router to this packet, is possible that this MNs is not on the coverage area, so the packet will not be forwarded. Some of the nodes will not have their packet received by the sink. When nodes uses 32Hz, the PDR presents better values. FNs have a poor performance, but the majority of packets will be delivered. For the MNs, the problem persists. Almost 80% of packets will be lost, so the applications could not work very well.

D. Energy Consumption

Figure 8 shows the results of energy consumption. The first important observation is that without the MNs, the energy consumption with 8 Hz is lower than using 32 Hz. This happens because the network stabilized, in other words, the use of trickle timer decreases the number of control messages in the network. Moreover, because of the low data traffic, nodes do not need to hear the channel for data frequently. So, the use of a low RDC is more energy efficient.

This situation changes when MNs are inserted in the network. MNs do not permit the tickle timer to get long time intervals for control messages. MNs causes many events in the network, and these events reset the trickle timer. One FN that chose an MN as preferred parent and uses an RDC of 8 Hz stay awake longer waiting for an acknowledgment of the

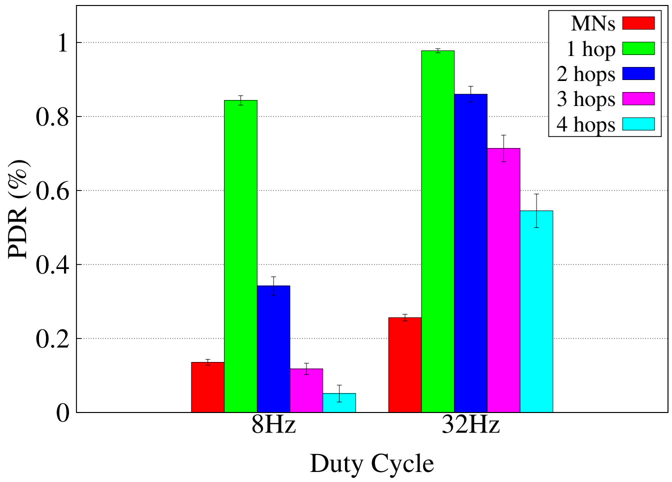

Fig. 7. PDR for one specific scenario

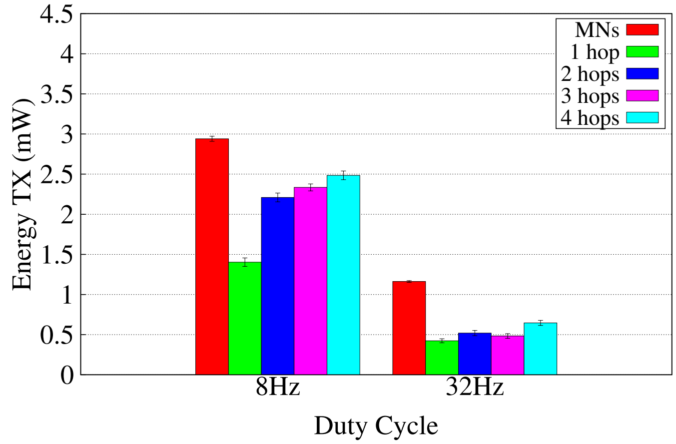

Fig. 9. TX Energy Consumption

parent. But is possible that the parent is not in the coverage area anymore.

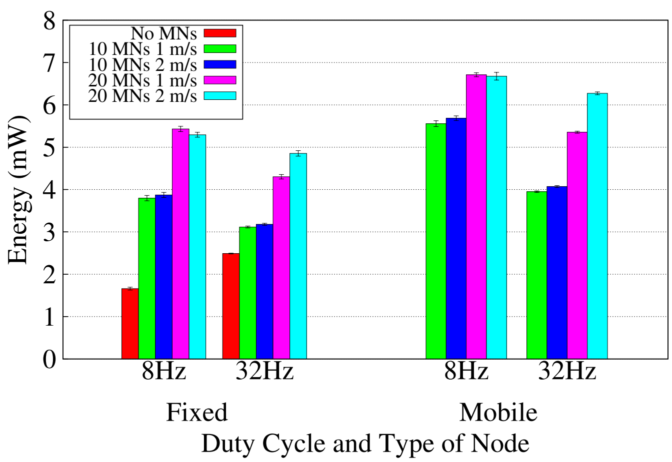

Fig. 8. Fixed nodes energy consumption

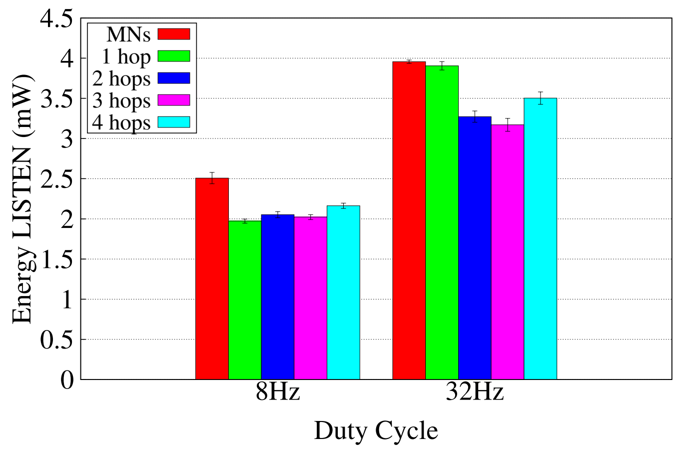

Fig. 10. LISTEN Energy Consumption

In Contiki the energy consumption is calculated by the sum of the four nodes activities. Energy consumed in processing is defined in CPU activity. LPM is the energy consumption when nodes are not processing or even receiving/transmitting data. TX and LISTEN are used to calculate the energy to transmit and listen to the channel, respectively. Figure 9 and 10 show the energy consumption for TX and LISTEN activities for the specific scenario. It is possible to see that the TX and LISTEN activities are the highest energy consumers.

Using a 32 Hz RDC nodes stay awake more time, so the energy used in TX is lower than when using 8 Hz. The LISTEN activity behavior is opposite, since the energy consumption is higher when nodes use 32 HZ RDC. One problem to use 32 Hz is that the energy consumption of the sink node neighbor is higher than the other nodes. If this node has a high energy consumption their lifetime will decrease. And, depending on the topology, one part of the nodes could be isolated from the rest of the network.

VI. Conclusion

This work presented a performance evaluation of RPL protocol on mobility scenario with different radio duty cycles. The results showed that RPL have its performance degraded when MNs are present on the network. The performance depends also on the chosen RDC. Most of the metrics show a 32 Hz RDC is better than 8Hz. But the use of 32 Hz generate high energy consumption for the neighbors of the sink node. If this node is turned off the network will fail to function properly, for some routes would not be reestablished. With a duty cycle of 8 Hz in a mobile scenario, some nodes will never have their packets delivered. This means that some applications will be not reliable. The confidence interval corroborate to show that the use of 8Hz duty cycle has a higher influence on the network than 32 Hz.

RPL is the routing protocol chosen for the IoT applications, but it needs to be thoroughly tested for mobile scenarios and different mobility models with variable radio duty cycles. One important analysis for the future is the number of control messages exchanged by nodes caused by mobility and RDC. For future work improvements to the RPL in mobile scenarios considering the RDC may be proposed.

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