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A Comparative Performance Evaluation of A load-balancing Algorithm using Contiki: “RPL vs QU-RPL”

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ABSTRACT

The RPL (Routing Protocol for Low-Power and Lossy Networks) has emerged within constrained networks as the de-facto IPv6 routing standard, which entangles many concepts that make it a complex, albeit a rather flexible protocol. However, load balancing has been underemphasized, making it an essential and practical issue of RPL, given the resource-constrained nature of a low-powered and lossy network (LLN). In this paper, we aim at determining whether a suggested load-balancing schemenamed QU-RPL (Queue utilization based RPL)can be considered as a viable solution to the significant load-balancing problem in the standardised RPL under some specific conditions. Hence, our results show that QU-RPL does not provide significant improvements over RPL under the simulated environment, and there is still a further need for the development of a more efficient load-balancing mechanism.

Key words: Internet-of-Things, Load Balancing, Low-power and Lossy Networks, Routing, RPL, QU-RPL

1. INTRODUCTION

The concept of the Internet of Things is increasingly determining the development of communication networks in the present as well as in the future. Consequently, the Low Power and Lossy Networks (LLNs) notion is the most influential application of the IoT [1], [2].

The latter is a variation of wireless sensor networks in which many integrated systems (or "things") are highly resource-constrained in terms of their information processing capacities as they are mostly battery-powered and have restricted memory storage, and their interconnecting connections are volatile resulting in elevated packet loss rates or rapid power depletion within such systems.Thus, to support the vision of IoT with thousands of highly-constrained devices interconnected via multi-hop mesh networks, such devices must be accessed separately via a singular Internet Protocol

(IP) address. As a result, IPv6 has therefore been the recognised protocol, established since the preceding era [3], and typically used for IoT applications over legacy IPv4 addressing [4].

Driven by the above-mentioned requirements of LLNs, the IPv6 LLN Routing Protocol (RPL) was standardised back in 2012 by the IETF to eventually accommodate a wide range of LLN concepts such as precision farming, smart cities and smart transportation systems, which require the use of a considerable quantity of sensor nodes [8]. However, it has been notedthat RPL lacks an efficient routing primitive that ensures a fair distribution of traffic among nodes while minimising overhead. The absence of such mechanism may prevent the distribution of traffic among multiple nodes, potentially increasing data loss caused by the node packet buffer overflow or leading to a faster depletion of the energy of overloaded nodes which in turn may result in service disruption [1], [9]. For this reason, load-balancing is an essential and practical RPL issue that, given the circumstances, has been somewhat underemphasised.One of the benefits of integrating the IP with WSN is providing mobility management protocols to enhance the telecommunication systems [10], [11], [12].Another works are implemented to increase the users’ satisfactory when they are using the critical applications in the world of IoT in terms of fault tolerance of IoT networks and security [13], [14]. Although of the great enhanced that are made by the researchers, we will only focus in this research on the RPL evaluation to enhance the packet routing in the IoT networks.

Furthermore, a plethora of studies have evaluated RPL and its suitability from various aspects, and have concisely reported several pitfalls challenges that RPL is confronted with even today after so many years from its standardisation, which need to be addressed [15], [16].Some of the prominent limitations that fall under the umbrella of RPL are related to load-balancing.Therefore, some authors focus solely on suggesting solutions to load balance a RPL network [17], [18], [19]. For instance, the study in [20]hypothesises that using Queue-Utilisation for load-balancing is a feasible solution that can guarantee the building of a balanced RPL topology. Carrying out their experiments under a real testbed with a deterministic topology of a few nodes, they show that their proposed solution significantly outperforms RPL in terms of (mention the metrics that they used).In this paper, we evaluated the proposed solution compared to de-facto RPL under both uniform and random node distribution with a relativelyhigh number of nodes through the means of Cooja simulations.

The remainder of this paper is organised as follows. Section II introduces a brief overview of the RPL routing protocol and its proposed extension. The problem statement of this paper, which addresses the issue of load balancing in RPL is presented in section III. The proposed evaluation methodology is described in Section IV. Consequently, details of the comparative performance analysis can be seen in Section V. Lastly, Section VI concludes the paper and discusses its future direction.

2. RPL AND QU-RPL OVERVIEW

RPL is a distance-vector and a source-routing protocol utilised in LLNs that allows IPv6 addressing and packets to be transferred over IEEE 802.15.4 networks [8]. Its purpose is to support networks which are comprised of myriads of nodes, where a large proportion of them are very much resource-onstrained. The fundamental topological structure used in RPL is a Destination Oriented Directed Acyclic Graph (DODAG), where every node of the network is directly connected to another; thus, exemplifying a serviceable routing solution for LLNs. It mainly builds up collection-based networks based on a neighbour discovery process, where nodes periodically send data to a central collection point. Additionally, RPL was designed to be exceedingly adaptable to multivarious network conditions and to provide alternative routes, whenever the default routes are inaccessible.

Thus, to create and maintain a DODAG, the root node multicasts to all RPL nodes within its range a type of control message called the DODAG Information Object (DIO) carrying the routing information needed to build the DODAG such as the rank, a relative distance of a node to the DODAG root. Once the neighbouring nodes have received such a message, they will calculate their own rank towards the root and then select the root as their next hop, and, lastly, will continue to forward the packet to their neighbouring nodes. In a similar fashion, the receiving nodes will select their next-hop towards the root based on the information in the received DIO. Ultimately, this process will continue until the last node has joined the DODAG.

Furthermore, RPL is designed with numerous robust features such as having a suppression mechanism for exiguous delays when transmitting data and rapid topology reconfiguration (while ensuring it is loop-free), which are considered to be the self-healing techniques of the protocol. However, the load imbalance is considered as a significant weakness. More specifically, whenever RPL is used in large scale low-power and lossy networks, some nodes will suffer from congestion, and this problem severely degrades network performance.Consequently, load balancing within DODAGs is an essential area of research and aims to address problems such as the formation of herds and bottlenecks of nodes that are closest to the sink.Thus, the primary objective inachieving the balance is by declining the number of children of the overloaded bottleneck nodes.

As a result, within the context of filling the missing load-balancing gap, the proposed QU-RPL considers congestion of traffic when selecting a parent via a queue-utilisation (QU) factor for each node [20].In the case of congestion, the node will select the parent by considering only the queue utilisation factor. Chiefly, each of the nodes produces a group of parent candidates from its neighbouring nodes and selects the best alternative parent node much like in the de-facto RPL but with a more sophisticated routing metric, which emphasises on the QU factor.Briefly, in its original implementation, each node can relay its QU information to its neighbour nodes by employing changes to the format of RPL's control messages or by modifying the objective functions with the purpose of adding a new metric container (as originally done by the creators of QU-RPL). In addition, the extension can also be implemented by altering the objective function so that the rank value can be redefined and the QU factor included in it.

3. PROBLEM STATEMENT

Generally, as noted in the preceding section, RPL has been devised solely for LLNs and has several distinctive features as to optimise its topology, however, it considers no techniques for efficiently balancing traffic loads within its specification.

Furthermore, it has been noted that, although the protocol has been planned to be employed within low rate traffic scenarios, it also necessitates for the suitability of coping with high-rate transmissions. In essence, however, RPL cannot deal with it in an efficient manner, thus the network is faced with multiple issues such as high rate of packet loss, energy depletion, and load imbalance. The latter becomes even more burdensome due to nodes near a sink having to relay very high-rate traffic, although each node of the DODAG generates low-rate data. Thus, load balancing among nodesis an essential area of research and aims to address problems such as the formation of herds and bottlenecks of nodes that are closest to the sink.

Another concern with RPL is when a new node attempts to attach itself to an already formed network,as shown in Figur 1. If the rank value declared by DIO messages is low, meaning it is closer to the sink, it can quickly draw many other nodes to itself, which at that point are other parents' children, resulting in the "Thundering Herd Phenomenon" or simply the "Herding Effect" [8]. This sudden alteration would significantly result in network instability, most notably within large-scale networks with dense traffic. Moreover, if the overloaded node is a bottleneck node, it has a more harmful effect, which, ultimately, may congest the network.It is worth noting that within the RPL specification, an efficient parent switching mechanism has also not been articulated.

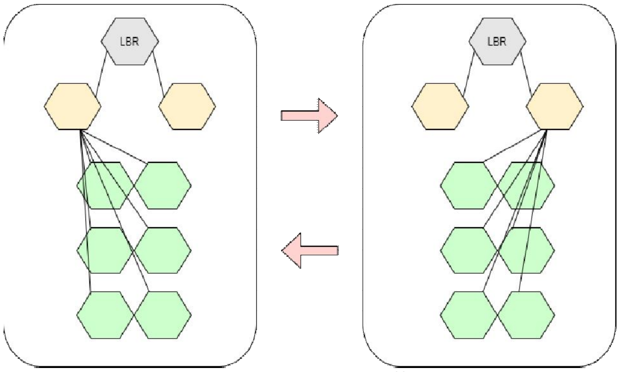


Figure 1: "Herding" effect

Additionally, QU-RPL aims to provide stability so as to prevent frequent and sudden parent switching, and to avoid the previously illustrated "herding" effect by probabilisticallyselecting the parent with the smallest QU leading to a more balanced load within the network. Thus, when deciding on whether to switch the current parent to a better alternative, QU-RPL takes into consideration both the conditions of stability and the congestion of traffic and therefore thwarts constant parent switching [20]. As noted, the suggested QU-RPL claims to be an improvement of RPL in terms of load-balancing by preventing frequent parent switching for the purpose of providing stability within large-scale LLNs. It considers traffic congestion when selecting a parent via a queue utilisation (QU) factor for each node. However, had there been other approaches, which acknowledged their evidence or even challenged the originality of their claim, their findings might have been more persuasive.Ultimately, the main aim of the paper is to investigate whether the discussed RPL extension would be able to tackle the lack of an efficient load-distribution technique within the standardised protocol. The experimental results will back up or disprove the assertion for their data and opinions about the reliability of the suggested enhancement by comparing the performance of RPL and QU-RPL under different scenarios in terms of power consumption, load-distribution, packet delivery ratio and latency.

4. EVALUATION ENVIRONMENT

The objective of this comparative study is to reveal the characteristics of QU-RPL and its load-balancing capabilities in different scenarios. Firstly, some modification of code was required in order to be able to implement the suggested load balancing algorithm and replicate most of its features. After that, the experiments are carried out under certain conditions within a simulated network environment.

It has been asserted that each LLN network is always application-specific because of the environments in which the sensors are deployed vary from condition to condition. Therefore, thorough testing is required to understand the conditions under which sensor nodes are deployed to estimate the interaction accurately between one another. However, it is a rather time-consuming task to develop and debug applications for such networks. Thus, by providing actual device and network modelling functions, "Cooja", a Contiki networking simulator, simplifies this procedure. [21]. Cooja, hence, is considered a relevant tool for conducting comparative studies and is compatible with the requisites of the present research as a result of which the behaviour of real nodes is accurately emulated as the simulator incorporates the actual code implemented on said nodes. Additionally, simulations offer an ideal model, which try to simulate protocols in order to understand their behaviours. Different topologies and settings can be experimented with and analyse the proposed algorithm in a controlled and repeatable environment. Thus, both versions of RPL would be assessed thoroughly through a variety of determinants such as energy consumption, latency and packet delivery ratio with respect to load balancing. In accordance with many similar conducted comparative studies, in order to arrive at an informed conclusion on the performance of the proposed extension of the RPL, a benchmark must be developed and used to compare and evaluate the extension. As pointed out in the previous paragraph, the Cooja simulator allows for more granularity in terms of the user being able to control most parameters for conducting an evaluation. The following table depicts a summary of theparameters configured for the evaluation environment for running the comparative evaluation of the proposed load-balancing implementation. Additionally, to be able to get more accurate results and because of the time required for each scenario, the results are averaged over three repetitions of each scenario with different random seeds so as to verify the consistency of the aggregated data.

5. PERFORMANCE EVALUATION

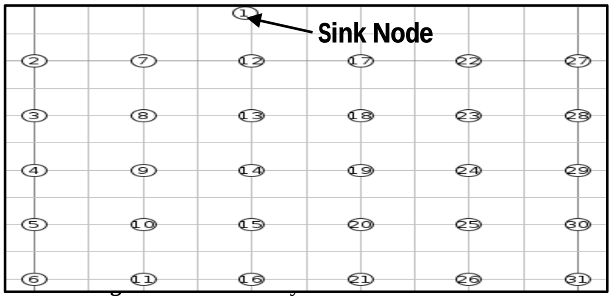
Following the methodology described in the preceding section, the RPL and QU-RPL were simulated and compared to shed light on the performance of both through a series of tests under certain conditions and while varying the rate of traffic in each experiment. Finally, with the help of comprehensible charts, the rationale for the impact of our QU-RPL replica and the potentially affected metrics involved will be discussed.

Table 1: Configurations of the evaluation environment

Simulation Parameters	
Parameters	**Values**
Operating System	Contiki 3.0
Simulation Tool	Cooja Simulator
Emulated Mote Type	Tmote Sky
Leaf Nodes Count	30/50
Root (Sink) Nodes Count	1
Routing Protocol(s)	ContikiRPL/QU-RPL
Simulation Duration	1200000ms (20m)
Radio Environment	Unit Disk Graph Medium (UDGM) with distance loss
Transmission range	30 m
Interference range	35 m
Mote Start Delay	1000 ms (Default value)
Data rate	1/2/10 seconds per packet
Objective Function	MRHOF
Random Seed	Autogenerated
Positioning of nodes	Uniformly / Randomly

A. 30-Node Scenario (Uniformly Distributed)

The following sub-sections emphasis on the performance of the proposed implementation by taking into account several performance metrics that were analysed and discussed for a 30-node configuration in which the nodes were distributed uniformly as depicted in Figure 2.



- **Average Packet Delivery Ratio(PDR)**

PDR is the ratio of packet delivered correctly at the DODAG root over the number of total packets sent by all nodes. As a criterion, the packet delivery ratio (PDR) is used to calculate how many of the transmitted packets of each client node reach the sink node. In addition, PDR, in particular, justifies a network's reliability in the context of the Internet of Things. In Figure 3, the PDRof the two implementations is depicted. Intuitively, the figure shows that the higher the data rate, the less PDR, which can be attributed easily to the congestion incurred in the network under increased traffic load. The figure shows also that QU-RPL have the same PDR of that of RPL under light traffic. When increasing the packet rate from 6 pps to 30 pps, QU-RPL performs better. However, under heavy traffic of 60 pps, QU-RPL again introduces no significant enhancement over RPL This give the impression that the load balancing employed by QU-RPL is able load-balance the traffic only under light or moderate traffic. However, the load balancingintroduced under light traffic did not translate to better PDR as there is no problem here with the congestion. In addition, the improved PDR under moderate traffic shows that QU-RPL load-balancing is working here.

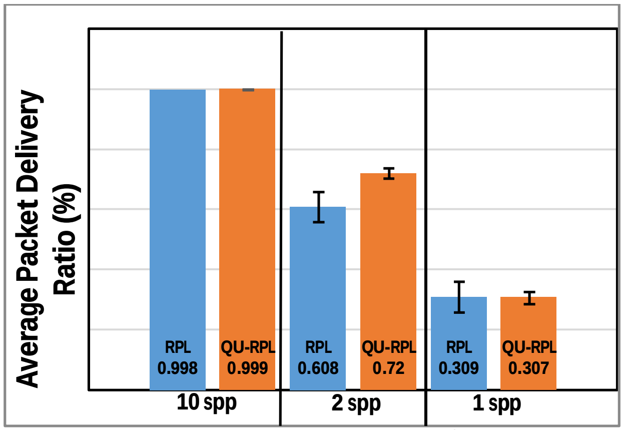


Figure 3: Average Packet Delivery Ratio(30 Uniformly Distributed Nodes)

- **Average Power Consumption**

Power consumption is the average energy consumed by the whole network during operation. Essentially, high-energy consumption can reduce device functionality in the context of IoT (and particularly in LLNs); therefore, it is one of the primary determinants used in the development of efficient protocols and certain mechanisms for such networks. Subsequently, it is advisable to have a network where nodes do not consume too much energy but still provide stable and consistent service. Figure 4 shows the energy consumption profiles of both RPL and QU-RPL under different traffic rates. The figure illustrates that both protocols show comparable energy consumption profiles under the three cases. However, In the case of moderate traffic QU-RPL has achieved the same power consumption of that of RPL under a higher packet delivery as mentioned earlier.

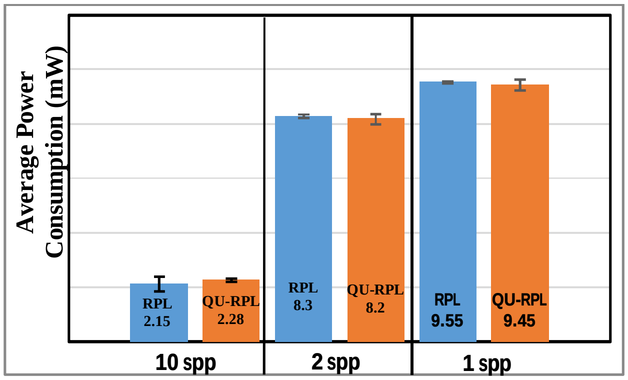


Figure 4: Average Power Consumption (30 Uniformly Distributed Nodes)

- **Average Latency**

The end-to-end latency is primarily used to describe the total period from the moment a source node produces a packet to the point where it is received by the root node. Numerous determinants could have an impact on the latency such as distance between the nodes, the quality of the links and the overall network workload. However, as it can be observed in Figure 4, both implementations have experienced a rather similar end-to-end latency which give the impression that the load-balancing mechanism introduced by QU-RPL has no noticeable impact on the latency in the network under simulated conditions.

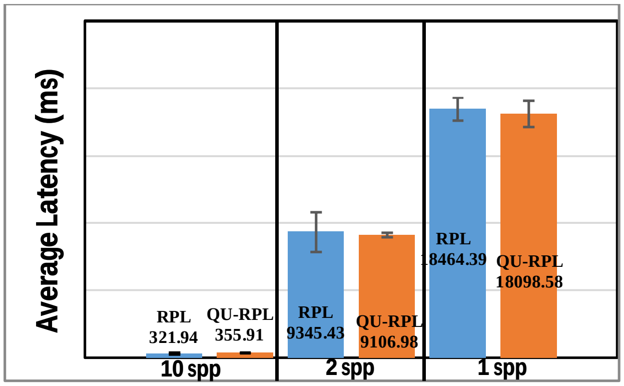


Figure 4: Average Latency(30 Uniformly Distributed Nodes)

B. 50-Node Scenario (Randomly Distributed)

Likewise, this sub-sections evaluates both RPL and QU-RPL within a 50-node network, in which the nodes, however, have been randomly distributed in order to put the replica of QU-RPL to the test to detect its efficiency in a larger and denser network.

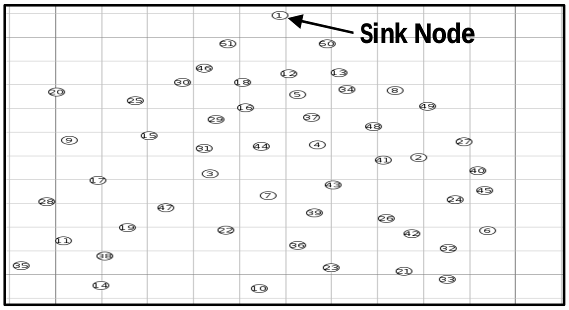


Figure 6:30 Uniformly Distributed Nodes

- **Average Power Consumption and PDR**

  As depicted in Figure 7 and Figure 8, bothprotocols again show comparable power consumption profiles under the 50-node scenario while at the same time showing comparable PDR rates which again gives the impression that the load-balancing employed by QU-RPL may have a only a minor impact on the reliability of the network under this scenario.

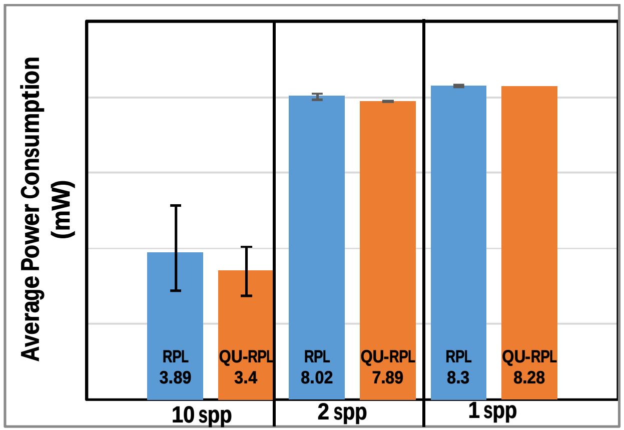


Figure 7: Average Power Consumption(50 Randomly Distributed Nodes)

- **Average Latency**

It goes without saying that it is evident from the experimental data that due to a packet passing through numerous intermediate nodes to reach its destination, as the node density has increased, it has resulted in the excessively increased latency compared to the previously described experiment (the above-described 30-node scenario). Ultimately, RPL and QU-RPL still demonstrate a rather similar latency performance as the node density increases (as seen in Figure 8).

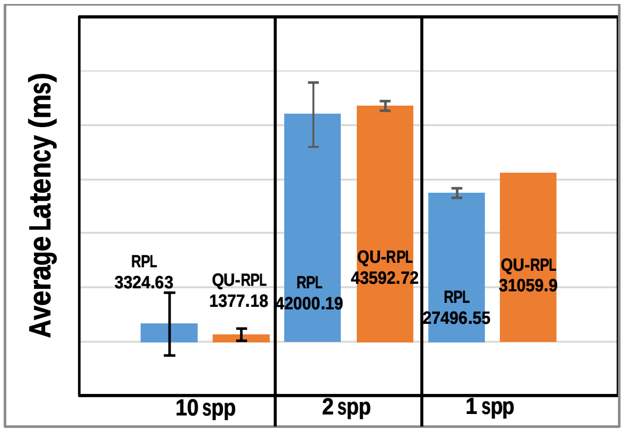


Figure 8: Average Latency(50 Randomly Distributed Nodes).

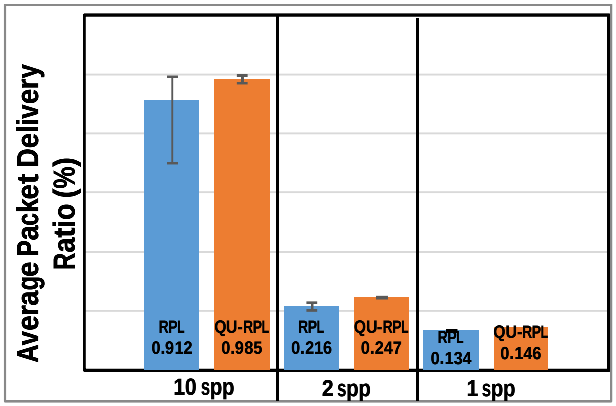


Figure 9: Average Packet Delivery Ratio(50 Randomly Distributed Nodes)

However, considering what has been discussed about the results for the average PDR in Figure 9, it can also be observed and hinted at the assumption that QU-RPL scales slightly better within a more extensive set-up than RPL despite QU-RPL's slightly larger latency. Nevertheless, the latter still implies that in order to justify it, further experiments should be carried out.

6. CONCLUSION

In this paper, we have conducted an evaluation study that investigates the efficiency of a recent load-balancing mechanism extension of the standard RPL, referred to as QU-RPL under two different scenarios. The mechanism was then implemented and compared to the RPL standard in terms of power consumption, packet delivery ratio and latency by means of Cooja and Contiki simulations and under uniform and random deployments. Furthermore, it should be restated that the authors of QU-RPL claim that their work "greatly alleviates the packet loss problem at queues, thereby achieving significant improvement in end-to-end packet delivery performance". However, contradictory to expectations, the data collected after comparing the results corroborate the verdict of this study that, under certain simulated conditions (i.e. uniform and random node distribution and varying the traffic rate), In the majority of scenarios, QU-RPL showed no significant improvement in terms of power consumption, PDR and latency when compared to the de-facto RPL. While the results may not be enough to reject the hypothesis that QU-RPL is a viable load-balancing extension, it does support a trend that later researchers may wish to explore, perhaps by refining the experiment. Alternatively, this paper can be extended to study other load-balancing models by implementing such models on real hardware and not rely solely on simulation or emulation tools to maximise the justification when conducting such evaluation studies. Regardless, the experimental results from this paper ought to highlight further the rationale that IETF's RPL needs extensive work to be improved upon, in order to mitigate its lack of efficient load balancing mechanisms.

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