PERFORMANCE EVALUATION OF RPL OBJECTIVE FUNCTIONS WITH CoAP IN LOW POWER AND LOSSY NETWORKS

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ABSTRACT
Low Power and Lossy Networks defines a network structure which consists of contrained devices. Low Power and Lossy Networks (LLNs) are highly challenging networks as they are extremely resource constrained in terms of processing power, memory and energy, such as battery. LLNs are intrinsically deployed in harsh environments and commonly show unstable low bandwidth, high packet loss and link failures. It is expected that LLNs will bring new innovative applications into our lives. On the other hand, it is not possible to use standardized internet protocols because LLN devices are weak in terms of memory and processing power. As a result, IETF formed 6LoWPAN WG and ROLL WG to bridge LLNs with the Internet. ROLL WG standardized RPL for the routing needs of LLNs. RPL leverages different Objective Functions (OFs) to construct RPL topology. Further, IETF standardized CoAP application layer protocol for the data exchange needs of LLN nodes. Also, because there are restricted devices in LLN networks, heavy protocols such as TCP cannot be used. Mechanisms such as congestion control implemented by TCP are operated with applications such as CoAP in the application layer in networks consisting of restricted devices. How RPL OFs will perform when CoAP is used at application layer is not broadly investigated area. Like so, in this work, we evaluated different OFs of RPL where LLN nodes run CoAP for data exchange. MRHOF and OF0, the two most commonly used Objective Functions in RPL, were considered in the evaluations in this study. Our results indicate that Minimum Rank with Hysteresis Objective Function (MRHOF) demonstrate better results than Objective Function Zero (OF0).

Index Terms: RPL, CoAP, Low Power and Lossy Networks, OF0, MRHOF

I. Introduction

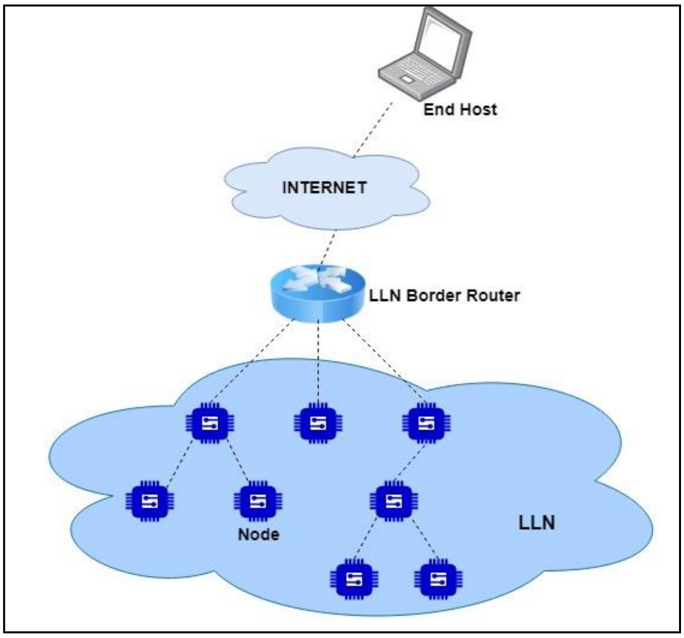
Low Power and Lossy Networks (LLNs) are composed of a large number of low power wireless nodes along with one or more gateway nodes [1]. The low power nodes are wirelessly interconnected with each other and identified by constrained resources such as energy, processing, memory and bandwidth. The gateway nodes connect the LLN into another network such as the Internet. Such an example LLN network is presented at Figure 1. As wireless nodes possess limited power and run in lossy harsh environments, LLNs usually exhibit unstable low data rate, packet losses and momentary link failures.
LLNs pioneer many applications, including healthcare, energy metering on the smart grid, smart webs, smart houses, smart cities and intelligent transportation [2], [3]. As the cost of LLNs becomes cheaper, faster, better and more intelligent, people will rely on these applications to make superior choices. These applications will have a significant impact on many aspects of our lives such as how we live, work, travel, health care and learn.

The absence of IP-based network architecture prevented LLNs from interoperating with the Internet. Thus, Internet Engineering Task Force (IETF) chartered the 6LoWPAN (The IPv6 in Low Power Wireless Personal Area Networks) and ROLL (The Routing over Low-Power and Lossy Links) Working Groups (WGs) to standardize at distinct layers of the Internet protocol stack with the target of connecting LLNs to the Internet. 6LoWPAN is a milestone protocol that link the LLNs with IP world. It provides a new dimension for an intact interoperability with the Internet.

There have been several work for defining an adequate routing protocol for 6LoWPAN-compliant LLNs such as Dymolow [4], Hydro [5] and Hilow [6]. However, none of these proposals gained considerable attention in the area where growing demand was required for a standard solution [7]. To fill this gap, IETF ROLL WG has proposed a routing protocol, named as RPL. The ROLL WG of IETF specifically designed IPv6 Routing Protocol for Low Power and Lossy Networks (RPL) compliant with the 6LoWPAN protocol for LLNs [3], [8], [9]. To construct the RPL topology, RPL uses the Objective Functions (OFs) that leverage routing metrics to calculate the best path of nodes.

Fig. 1: Low Power and Lossy Network

The entire topology construction is exceptionally dependent on the used OF by the LLN. The network performance is directly affected by the means of route selection. The best route is selected according to metrics and constraints of OFs. Thus, the notion of OF presents a great flexibility for enabling QoS-aware routing that supports various application requirements. Hence, each application can choose a different OF. OF defines how RPL leverage metrics into rank used to select and optimize routes. The IETF is standardized two different OF, namely Objective Function Zero (OF0) [10] and Minimum Rank with Hysteresis Objective function (MRHOF) [11]. The design of competent OFs is still an open research area [12].



The Constraint Application Protocol (CoAP) was designed by IETF for application layer communication considering energy, computation, memory and limited communication capacity of LLN nodes [13]. The CoAP is a specialized web transfer protocol for constrained physical LLN nodes. CoAP has a protocol primitive that is similar to client-server model of HTTP (Hyper Text Transfer Protocol). It is expected that billions tiny LLN nodes will be running CoAP protocol in the near future [14]. Thus, in this work, we investigated how RPL OFs, namely OF0 and MRHOF, achieve when CoAP is operated as application layer protocol. Obtained results presents that CoAP clients perform better when RPL MRHOF is preferred as an RPL OF.

II. Related Work

We categorized the related work into Performance Evaluation of CoAP, Performance Evaluation of RPL, Performance Evaluation of RPL OFs and CoAP-based Performance Evaluation of RPL OFs. We provide the related work details in this section.

A. Performance Evaluation of CoAP

A low-power CoAP implementation is evaluated in a testbed experiments for two duty cycling mechanisms [15]. The performance of CoAP is also compared to HTTP [16]–[18] and MQTT [19].

B. Performance Evaluation of RPL

Fig. 2: Network Topology

The performance of the RPL is carried on a testbed environment in terms of power consumption, packet loss and packet delay [8]. RPL performance is evaluated in network scalability, multiple sink and mobility models configurations [20]. Evaluation and analyzing the performance of the RPL are proceeded in other work [21]–[24].

C. Performance Evaluation of RPL OFs

Performance of RPL OFs, namely OF0 and MHROF, are evaluated on Cooja simulator [25]–[27]. MRHOF and OF-EC objective functions along with different trickle timers are used for performance evaluation of RPL [28]. Evaluating and analyzing the performance of RPL OFs are investigated in other work [29]–[33].

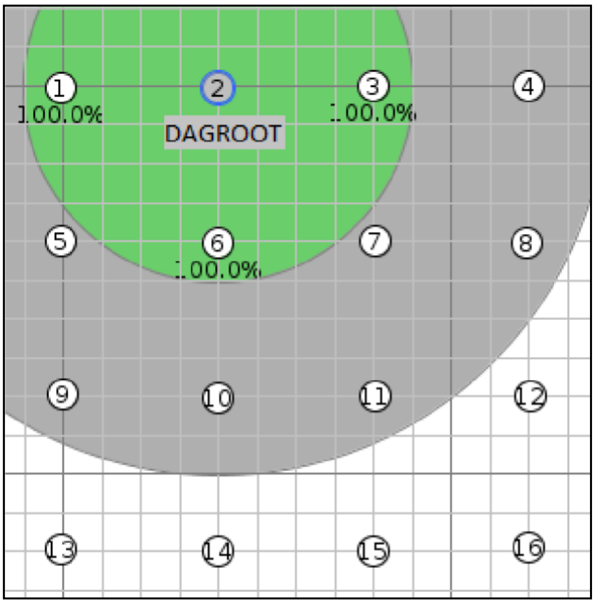
D. CoAP-based Performance Evaluation of RPL OFs

The performance evaluation of CoAP using RPL OF0 and MRHOF along with LPL is conducted in a testbed environment where nodes run TinyOS [34]. It is observed that MRHOF of RPL performs better than OF0. In this study, we also examined performance of RPL OF0 and MRHOF when CoAP is used at application where nodes run ContikiOS.

III. Simulation Environment

As physical testbeds are expensive and not easy to access, evaluations of objective MRHOF and OF0 have been conducted in simulation environment. For these simulations, Cooja Network Tool [35] has been chosen. This simulation tool supports multiple nodes and operating systems. Within the selected operating system that is ContikiOS, it is possible to select an OF for RPL routing.

For simulations, different network sizes have been considered. For this purpose, simulations have been ran for networks with 5, 10 and 15 CoAP clients. Network topology is given in Figure 2. Also, to get more analytic results, all simulations have been repeated for link layer PDR values 100 and 90. Each of the created simulation scenarios has been run 5 times. All scenarios with variable values are given in Table I. During experiments, each client sends 100 CoAP requests, and Success Rate, Average Packet Time, Maximum Delay Between Packets and Total Time performance metrics are calculated based on CoAP responses.



A. Performance Metrics

1) Success Rate: Success Rate indicates percentage of successfully received CoAP responses. In other words, this metric represents application layer PDR.

2) Average Packet Time: Average Packet Time means average of total elapsed time of successfully received CoAP response. Elapsed time begins when CoAP request is sent and ends when CoAP response is received. One thing to consider about this performance metric is only successful CoAP request-response couples are calculated. Failed requests are ignored for this performance metric.

3) Maximum Delay Between Packets: This metric illustrates the maximum time elapsed between two successfully received CoAP responses. This metric can be utilized by real-time applications.

4) Total Time: Total Time is the total elapsed time to receive 100 CoAP responses.

Scenario	Objective Function	Node Count	PDR
1	MRHOF	5	100
2	MRHOF	5	90
3	MRHOF	10	100
4	MRHOF	10	90
5	MRHOF	15	100
6	MRHOF	15	90
7	OF0	5	100
8	OF0	5	90
9	OF0	10	100
10	OF0	10	90
11	OF0	15	100
12	OF0	15	90

TABLE I: Simulation Scenarios

IV. Performance Evaluation

To figure out the performance difference of two different objective functions, multiple simulations have been ran. As an outcome of these simulations, results graphs have been produced with different performance metrics. Figure 3 shows all results graphs. These graphs were analyzed according to their performance metrics.

A. Success Rate

Figure 3a shows the Success Rate values for different objective functions, different PDR values and different node counts. As can be seen in this graph, for small networks which consist of only 5 nodes, there's no significant difference between objective functions. However, the increase in the number of nodes makes the difference between objective functions more visible. According to the data in the graph, in cases where the number of nodes is 10, MRHOF objective function shows a better success rate than OF0 objective function. According to these results, the reduction of PDR value from 100 to 90 did not affect MRHOF objective function much, but this did not occur in OF0 objective function. As the network environment becomes more crowded (increasing the number of nodes to 15), these differences become more pronounced. It is clear that the MRHOF objective function is better than the OF0 objective function if an assessment should be made according to the success rate metric. Again, it can be said that MRHOF objective function can better tolerate the changes in PDR value.

B. Average Packet Time

Average packet time values for objective functions MRHOF and OF0 are given in Figure 3b. Performance difference between these objective functions is not easy to distinguish for smaller networks with only 5 nodes. Even in small networks, effect of decreasement of PDR value is visible in graph. Lower PDR value lead up to increased packet delivery time. For more crowded networks which contains 10 or 15 nodes, performance difference of objective function MRHOF and objective function OF0 becomes clearer in terms of average packet time. For networks with 10 or 15 nodes, average packet time is lower when objective function OF0 is chosen. However, there's a point to keep in mind while evaluating these results.

As previously mentioned, observations show that objective function MRHOF is superior to objective function OF0 in terms of success rate. However, in terms of average packet time, objective function OF0 looks better than objective function MRHOF. This is due to calculation way of average packet time. While calculating average packet time, only successful packets are considered while failed packets are ignored. This situation should be keep in mind while analysing average packet time values. This case is also observable with result graph with lower PDR value in network with 15 nodes.

C. Maximum Delay Between Packets

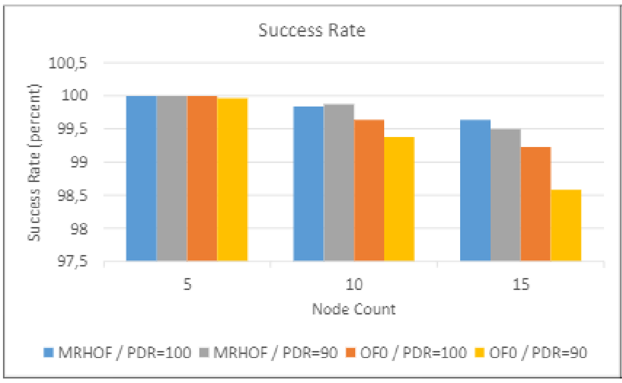
Comparison of objective function MRHOF and objective function OF0 in terms of maximum delay between packets is given in Figure 3c. This graph shows the value of maximum wait time between two sequential, successful packets. This results shows the difference between two objective function even in small networks with 5 nodes. As the network grows larger, this difference increases. For all network sizes, objective function MRHOF gives lower values than objective function OF0 in terms of maximum delay between packets. Another thing to point out is, objective function MRHOF is more resistant to changes in PDR value for maximum delay between packets values.

D. Total Time

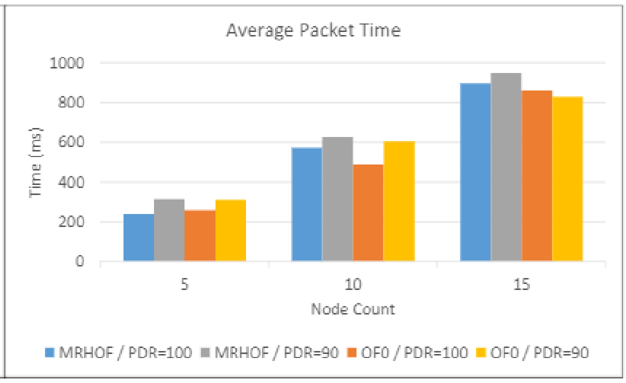
The total time taken to transmit (successful or failed) 100 packets is given in Figure 3d. This value also can be used while calculating average throughput. Crowded networks, packet delivery failures or re-transmissions can increase this value. While evaluating this metric, graphs shows significant difference between objective functions and PDR values. As a matter of course, higher total time values are expected for lower PDR values. Once again, difference between objective function MRHOF and OF0 is not very significant for smaller networks. But in general, objective function MRHOF keeps its superiority against objective function OF0. In numerical terms, total time values of objective function OF0 increased by approximately 55% compared to objective function MRHOF for a network with 15 nodes and PDR value is set to 100.

V. Conclusion

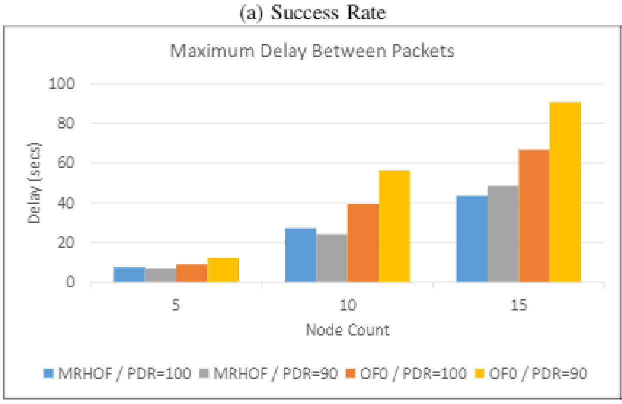
Performance Evaluation of CoAP over various RPL Objective Functions is not a widely explored area. In this work, we analyzed the performance of RPL OF0 and MRHOF. We used CoAP clients and different PDRs at physical layer. The reason is that CoAP is currently a de facto standard in LLNs, and as CoAP has default congestion control mechanism, physical layer PDR does influence the performance. As far as we know, there is no previous research on performance evaluation of RPL OFs when ContikiOS, CoAP and various PDR values are used for analysis. We also get the same overall results presented in [34] where RPL MHROF is more suitable than RPL OF0 when CoAP operates at application layer.



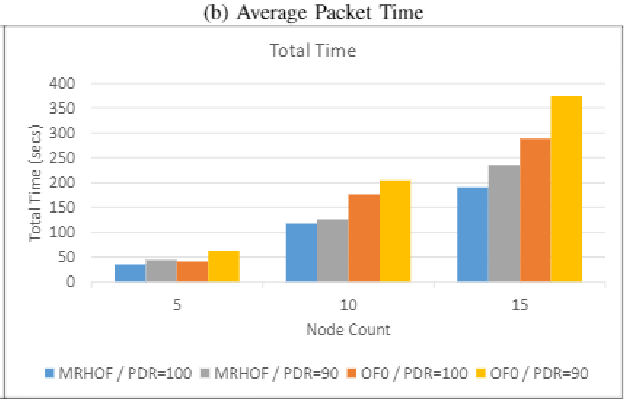
(a) Success Rate



(b) Average Packet Time



(c) Maximum Delay Between Two Successful Packets



(d) Total Time

Fig. 3: Results Graphs with Different Objective Functions for Different Performance Metrics

ACKNOWLEDGMENT

This work was supported by SIREN project funded by the Scientific and Technological Research Council of Turkey (TUBITAK) under Grant No 116E025.

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