Evaluating and Analyzing the Performance of RPL in Contiki

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ABSTRACT

To meet the development of Internet of Things (IoT), IETF has proposed IPv6 standards working under stringent low-power and low-cost constraints. However, the behavior and performance of the proposed standards have not been fully understood, especially the RPL routing protocol lying at the heart the protocol stack. In this work, we make an in-depth study on a popular implementation of the RPL (routing protocol for low power and lossy network) to provide insights and guidelines for the adoption of these standards. Specifically, we use the Contiki operating system and COOJA simulator to evaluate the behavior of the ContikiRPL implementation. We analyze the performance for different networking settings. Different from previous studies, our work is the first effort spanning across the whole life cycle of wireless sensor networks, including both the network construction process and the functioning stage. The metrics evaluated include signaling overhead, latency, energy consumption and so on, which are vital to the overall performance of a wireless sensor network. Furthermore, based on our observations, we provide a few suggestions for RPL implemented WSN. This study can also serve as a basis for future enhancement on the proposed standards.

Categories and Subject Descriptors

C.2.4 [**Computer-Communication Networks**]: Distributed Systems – *network operating systems;* D.4.4 [**Operating Systems**]: Communications Management – *network communication*

General Terms

Performance

Keywords

WSN, RPL protocol, Contiki

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INTRODUCTION

With the development of the next generation Internet of Things (IoT), short range wireless networking are embracing Internet technologies. As a result, the communication between wireless sensor networks (WSNs) and Internet becomes a hot research area. However, it is well known that the Internet architecture is ill-suited for WSNs because of their stringent constraints on resources, power consumption, and quality of communication channels. To address the needs and problems, IETF has developed IP-based protocols for low-power and lossy networks through the 6LoWPAN and RoLL working groups, which provide us a feasibility of using IPv6 in WSNs [1-2].

In this set of protocols, 6Lowpan enables the reachability of the wireless sensor platform to the global IP network, and the routing protocol RPL serves as the de-facto routing standard for IPv6 enabled WSN [4]. Both of these standards are designed with the constraints on reliability, energy efficiency, and scalability in mind [3]. In particular, the design of the RPL protocol is a challenging problem. Constrained by scare resources, low data rates, low power consumption and lossy links, the classic routing algorithms such as AODV, OSPF, OLSR, do not meet the requirements of WSN applications.

Despite the careful design of the RPL protocol, there is a strong need for an evaluation of the RPL protocol with implementations close to the real-world. However, previous evaluations of the performance are limited to one or two aspects of the RPL protocol in common WSNs scenarios[2,6-10], and they fall short of providing a global comprehension of the problem. In this work, we conduct evaluation experiments on a variety of scalable scenarios, and take the whole life cycle (both the network construction process and the working stage) of the WSN into account. The metrics covered in our study include latency of radio duty cycle and packet forwarding, overhead of signaling, as well as power consumption. Based on these results, we make analysis and provide guidelines for real-world implementation of IPv6 enabled WSNs based on the IETF standards.

The remainder of this paper is organized as follows. We present an overview and background of RPL protocol in Section 2. In Section 3, the evaluation environment and methodology are provided. We give the results obtained from our experiments and analyze the reasons in Section 4. Finally, we draw conclusions in Section 5.

OVERVIEW AND BACKGROUND OF RPL PROTOCOL

The IETF RoLL working group designed the routing protocol for low power and lossy network (RPL)[11]. The RPL protocol emerges as the de-facto IPv6 routing standard for WSN. It is a tree-oriented routing protocol to form a Destination-Oriented Directed Acyclic Graph (DODAG) with some defined metrics and an objective function to guide the selection of the best path to the root node. The RPL implementation in the Contiki operating system takes the Expected Transmission Count (EXT) metric as default[12].

RPL provides a mechanism to disseminate information over the dynamically formed network topology by a set of ICMPv6 control messages, such as DIO, DAO, DIS. The DIO message contains information about the rank, the objective function, the node id and so on. It defines and maintains upward routes. The DAO message advertises prefix reach-ability towards the client nodes of a DODAG to enable downward traffic. The DIS message is used to proactively solicit the DODAG related information from neighboring nodes. The key role in RPL is the root node which acts as a bridge between the local wireless sensor network and the Internet. Information captured by sensors is delivered to the root node.

Figure 1 shows a simple example of DODAG building process. Among the three client nodes, node 3 is beyond the radio range of the root node. The root node starts building a network topology by broadcasting a DIO control message with its rank and id to client nodes. In this case, client node 1 and node 2 are within the radio range of the root, and they respond with DAO messages to the root for joining the DODAG. Client node 3, which cannot hear from the root node, starts to send DIS message proactively to solicit DIO from neighbor nodes after waiting for a period of time. Suppose client node 2 receives this DIS message, it will then forward the DIO message received earlier to client node 3. Upon receiving this DIO message, client node 3 sends back a DAO message to client node 2, which will be forwarded to the root node. In this way, client node 3 joins the DODAG, completing the construction process.

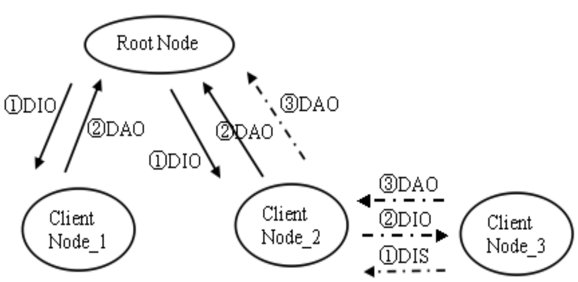

Figure 1. DODAG construction process.

EVALUATION ENVIRONMENT AND METHODOLOGY

In this section, we present the evaluation environment and methodology used for experimentation. Contiki operating system and its simulator COOJA are selected for studying the RPL protocol [13-14]. Contiki is an open source, multi-tasking operating system designed for WSN, and its release 2.7 provides ContikiRPL, designed to connect Contiki's IPv6 stack with underlying MAC and Radio Duty Cycling protocols[15]. COOJA is a flexible simulator designed for simulating networks of sensors running the Contiki operating system[14]. Our objective is to analyze the performance of RPL in WSN, at both the network construction stage and functioning stage. To this end, we take a typical wireless sensor network spanning over a 100m x 100m area. We take sky mote node as experiment node type. The physical layer and medium access control layer protocol are based on the classic IEEE 802.15.4 PYH and MAC standards. The IEEE 802.15.4 MAC is enhanced using ContikiMAC, which is an asynchronous, sender-initiated radio duty cycling protocol [16]. The 6LoWPAN has been used as an IPv6 header compressor at the network layer[8,17]. As indicated earlier, the routing protocol is RPL. The UDP protocol has been used as the transport layer protocol. Based on our understanding of the RPL protocol, we identify a set of important metrics for our evaluation, which are defined as follows:

Latency of message delivery. This is the time spent on the transmission of a message between a pair of nodes, either directly, or via a DODAG path. The overall time can be decomposed into the radio duty cycle (the time to bring up the node for working), and the actual packet transmission time. Clearly, this is a fundamental factor affecting the performance of the WSN. For simplicity, we just refer to this term as latency in subsequent parts if no confusion arising.

Signaling overhead. In addition to data transmission, control messages are exchanged to ensure that the WSN is constructed efficiently and functions correctly. These control messages are referred to as signaling overhead.

Convergence time. This is a measure on how fast a group of wireless sensor nodes construct a network topology and reach the functioning stage of a WSN for data transmission.

Table 1. Configuration of Contiki and COOJA

Settings	**Values**
Radio Mediums Model	Unit Disk Graph Medium (UDGM): Distance Loss
Ranges of Nodes	Rx and Tx: 50m , Interference: 100m
PYH and MAC Layer	IEEE 802.15.4
Duty Cycle	ContikiMAC
Mote Type	Tmote Sky
Transport Layer	UDP
Network Layer	uIPv6 , 6LoWPAN
Objective Function	ETX

Factors affecting these metrics include network topology, the numbers of sink and client nodes, the density of deployed nodes, hops of nodes and so on. Table 1 summarizes the configuration of Contiki OS and COOJA simulation. In next section, we will present the results and analysis.

PERFORMANCE EVALUATION

In this section, we study the performance of RPL routing protocol in Contiki operating system. We first focus on the network construction stage, and then we pay attention to the performance of the functioning stage .

Analysis of network construction

RPL is a tree-oriented protocol, and the RPL-based network construction stage is to build a DODAG based on a neighbor discovery process. The main operation is to build downward and upward paths between the root node and client nodes. Figure 2 shows a WSN topology (1 sink node and 20 client nodes) constructed by COOJA, and arrows in the figure indicate the packet transmission direction. Be aware that this is a dynamic process, and the final topology might be different from the one presented in Figure 2.

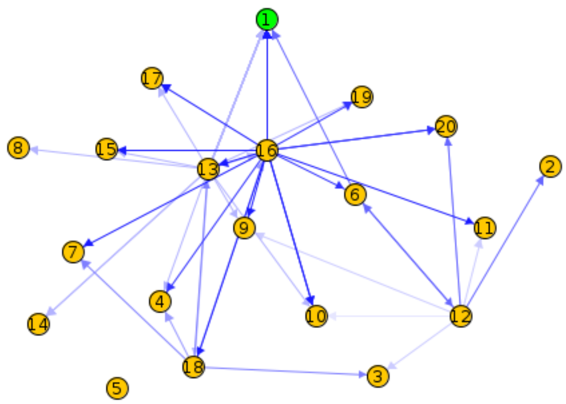

Figure 2. The topology of WSN.

The analysis of signaling overhead

From the background section, we get an idea that the control messages transmitted for DODAG construction may flood the network, and the construction stage may take a long time. To validate this assumption and to provide guidelines for potential optimization of this process, we perform a quantitative analysis on this signaling overhead. Figure 3 shows the statistics on control messages and data messages in terms of transmitted network packets sent by WSN nodes. Clearly, control messages dominate most of the construction procedure, whereas UDP and radio data messages are negligible compared to control messages. The reason leading to this result is that in the RPL implemented network, the DODAG root node starts building network topology by broadcasting RPL control messages to all nodes in its radio range, and a large number of messages responding this broadcast are generated and forwarded to the root node. On the other hand, UDP messages are sent as a confirmation only upon the establishment of a link path to the DODAG root node. The radio message is the IEEE 802.15.4 type message along with UDP message, due to the UDP message transmission via IEEE 802.15.4 frame data. From Figure 3, we can see that it takes nearly 60 seconds for the control messages to disappear, which indicates the completion of the network construction stage. Note that the spikes of control messages after 80 seconds are caused by new nodes joining the WSN.

From above analysis, we can see that the main overhead of the WSN construction stage is RPL signaling. Another conclusion is that RPL is sensitive to nodes changes (indicated by the spikes of blue lines after 80 seconds). To get more insights, we break the control messages into three groups, namely the DIO, DAO, and DIS messages. This breakdown is presented in Figure 4. It is clear that DAO messages take the lead, followed by DIO messages, whereas DIS messages are quite insignificant.

Firstly, the scarce of DIS messages can be easy to understand, as in most cases, only client nodes beyond the radio range of the root node need to generate DIS messages asking for DIO messages from neighbor nodes. For DIO and DAO messages, as mentioned in Section 2, the DAO messages are used to maintain downward traffic from the root node to the client nodes. And the DIO messages are for upward traffic. The DAO messages have to be forwarded up to the root node from all client nodes which are willing to join or already in the DODAG. The DIO messages are broadcast only at one hop distance from one node to its parent. Thus the overhead of DAO transmission is much higher than DIO transmission.

To study the scalability of RPL with respect to the scale of the network, we evaluate the increase on the number of control messages (in terms of network packets) with the increase on the number of WSN nodes. Figure 5 shows that the RPL protocol has a reasonably good scalability, in which the number of control messages tend to increase at a lower speed than the number of WSN nodes, especially when the scale of WSN becomes large.

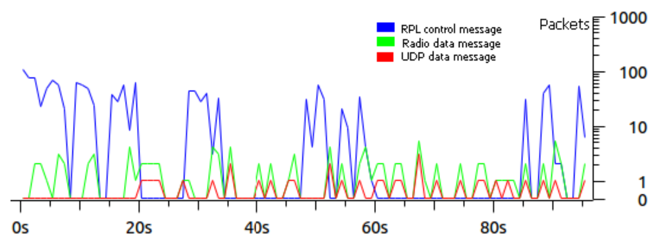

Figure 3. Control messages and data messages.

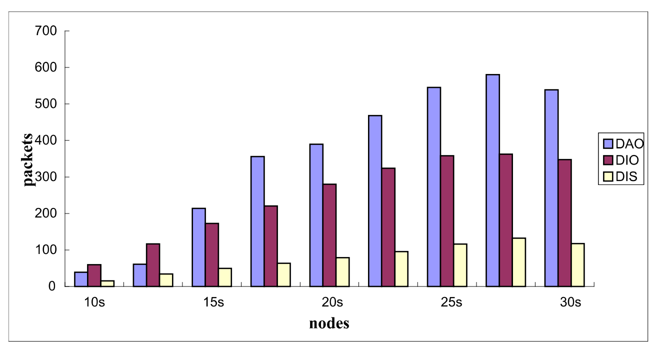

Figure 4. Breakdown of RPL control messages.

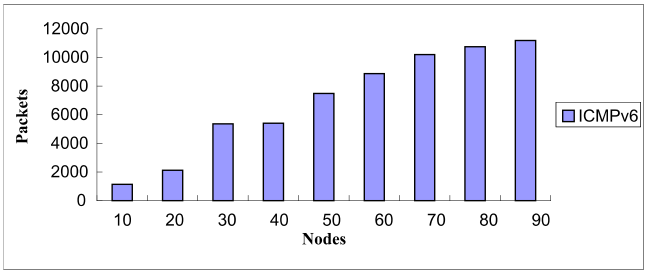

Figure 5. The increase speed of ICMPv6 messages.

The analysis of latency and convergence time

In this section, we study the latency and convergence time of the RPL network. As introduced earlier, latency is the time interval between a state message sent by one mote and received by another one. A number of factors have an impact on the latency and convergence time, including the time spent on packet processing (6LoWPAN, ContikiMAC protocol, Radio model which are underlying modules of Contiki)[18], radio duty cycle, network density, the number of DODAGs etc, and we evaluate their impact accordingly.

ContikiMAC provides an asynchronous, sender initiated radio duty cycle mechanism [16-17]. The feature of radio duty cycle is that, a packet is sent repeatedly until it gets an acknowledgment from the receiver. The receiver periodically wakes up to listen on packet transmissions from neighbors. Once there is a packet transmission started, the receiver keeps its radio on until the transmission completes. A potential concern of this mechanism is the delay and power consumption, as the the sender keeps sending packets repeatedly until the receiver wakes up and responds to the sender. On the other hand, if we want to save power of the sender and shorten the time of packet transmission by letting the receiver wake up frequently, we may end up wasting power consumption at the receiver side when it needlessly wakes up without data to receive. To help make a reasonable trade-off, it is important to study the relationship between the latency and the load of packet transmission in the WSN. Figure 6 presents results on this relationship. We can see that the latency for transmitting a single packet does not increase with the overall load of packets. The reason is that, with less packets, the nodes often go to radio-off state for saving energy, and it will take extra timing overhead switching back to radio-on state for packet transmission. Whereas with higher load of packets, the timing overhead on node competing for each packet is alleviated by less node state switching time.

Figure 7 evaluates the impact of network density and hop distance on the convergence time, it is clear that the convergence time increases linearly with each of these two factors. We also observe the impact of increasing the number of root nodes given the same set of nodes in the WSN. In this case, we see a clear drop of time with the increase of root nodes. This is intuitive as more root nodes means more choices and less contentions of client nodes on selecting an optimal path during network construction. What is interesting lies in the fact that the impact of the number of root nodes are very significant. This provides us with a guidance of using more root nodes as an effective method when facing performance problems.

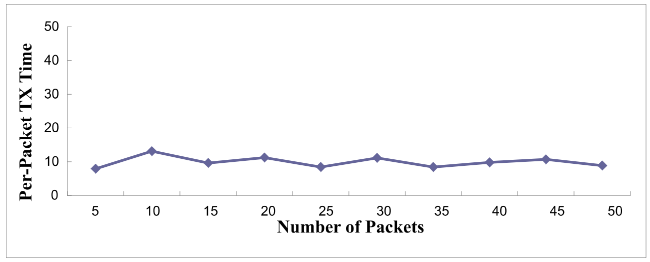

Figure 6. Relationship between latency and packets.

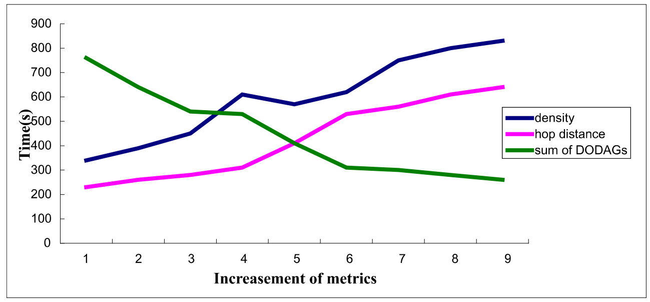

Figure 7. Factors affecting the convergence time.

The analysis of power consumption

Power consumption is the first order constraints of WSN, and it is indispensable to evaluate the power consumption of a WSN running RPL. We conduct this evaluation work in two aspects. Firstly, we evaluate the power consumption of the whole network to get an overall picture on power. Then we study the power consumption of individual nodes to get more insights. The difference of power consumptions between client nodes and sink nodes is also evaluated and analyzed.

Earlier research suggests that radio transceiver is the major source of power consumption in a WSN node. For example, the power consumption by the radio is three orders of magnitude larger than that of the CPU for the Tmote Sky platform [19]. Because of this, we focus on radio transmission to measure the power consumption. As mentioned above, ContikiMAC is the default radio duty cycle protocol in the Contiki operating system. And the majority of energy is spent on idle listening, repeated packet sending and reception. Therefore, we can use the time of radio on as an equivalent metric of power consumption instead of using absolute power consumption in joules.

Figure 8 reports the overall usage of radio in the network. It can be seen that the radio keeps on most of time, thus the power consumption is significant during this period. This suggests that a protocol revision that reduces the time of active radio would make an effective reduction on power consumption in this period. Figure 9 presents the difference between sink nodes and client nodes on power consumption. An observation is that the sink nodes spends the vast majority of power on receiving packets from client nodes rather than sending packets actively. As for the client node, it spends power on forwarding packets more than packets reception. This coincides with our observation on the breakdown of RPL control messages in Figure 4. They together suggest that the potential direction on improving the RPL protocol might be on how the client nodes should respond to the root node, and how they should interact with nearby peer nodes in the network. If the amount of DAO messages can be brought down, both convergence time and power consumption can be effectively reduced.

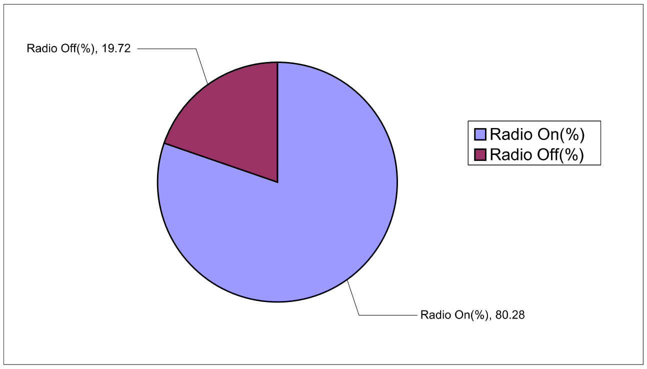

Figure 8. The radio usage in the network.

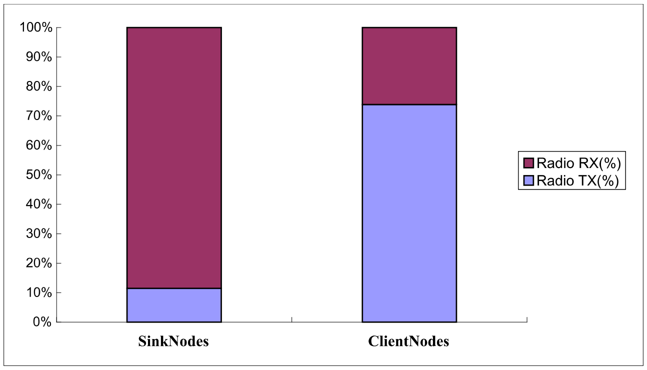

Figure 9. The radio usage of each node.

The analysis of functioning stage

In this section, we pay attention to the performance of the network during the functioning stage, in which the network topology has been constructed, and data packets are being transmitted among WSN nodes as well as across the WSN boundary. In this period, we are concerned with the scenario when a node joins in or leaves the network, as this is the most relevant situation to RPL protocol during this stage. In addition, we also pay attention to the energy consumption on peer to peer packet delivery.

For nodes joining the DODAG, the latency and robustness depend on their number of neighbors. The new node sends packets to all of its neighbors, and then calculates path cost based on the predefined objective function to choose a preferred parent. On the one hand, more neighbors means more energy consumption and more time overhead. Figure 10 presents the impact of neighbors on node joining. We can observe that the number of neighbors has a significant impact on node-join time.

For nodes leaving the DODAG, there are several situations to consider. In one situation, The root node initiates the rebuild of the DODAG for path cost reduction or link robustness improvement. In this case, the individual nodes just recalculate the specified metrics to update the objective function, and some of them may get excluded from their current DODAG if their objective functions give unfavorable results. Another possible situation is that a node does not continue to work for its own reasons. The effect on the overall DODAG depends on its position and role in the network. If it is just a leaf node in the network, the impact may be ignored. But if it takes an important role in the network, such as a relay node in the middle of a link path, it may have a significant impact on the network topology. The cost for rebuilding network topology depends on the number of its child nodes. As we can see from Figure 11, the rebuild time increases almost linearly with the number of child nodes.

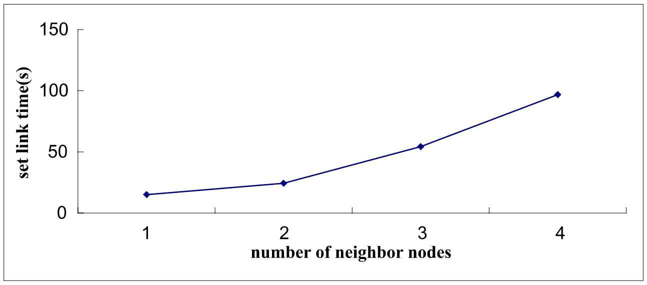

Figure 10. The impact of neighbors on node joining.

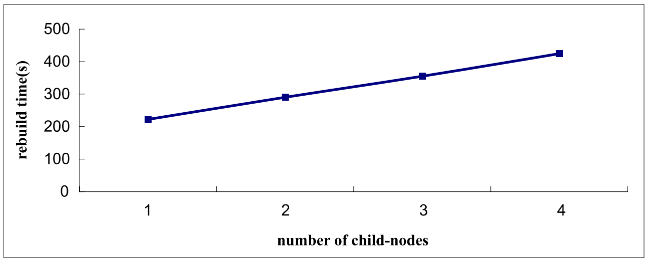

Figure 11. The impact of child-nodes on rebuild time.

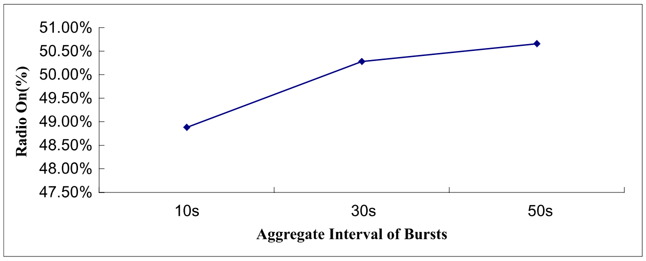

Figure 12. The impact of packet transmission pattern on energy consumption.

For peer to peer data packets transmission, we study the impact of transmission pattern on energy consumption. Normally, the transmission of a non-trivial amount of data is not accomplished in a single burst. Instead, the data transmission consists of a number of bursts interleaved by time intervals. Since there might be a large number of interleavings, to simplify the evaluation work, we only study the impact of the aggregate time interval between bursts on energy consumption.

The result is presented in Figure 12. From the result, we could see that although shorter sending intervals lead to less energy consumption, the difference is not so significant. There is only about 3% increase on energy consumption (in terms of the ratio of radio-on time) when the aggregate interval increases from 10s to 50s, a 5-time increase. Thus, in real implement, if we need to transmit non-trivial number of packets, we can get some saving on energy by transmitting the data as soon as possible, but the saving is not very significant, the major gain is transmission time. However, it should be noted that the experiment conducted is a simplified one to the reality, in that we only study the aggregate time interval between data bursts. For more realistic experimentation, we should take the number of individual intervals and their lengths into consideration. We leave this as a future work.

CONCLUSIONS

In this paper, we evaluate and analyze the performance of the IETF RPL routing protocol using COOJA simulator under Contiki operating system. It is the first effort covering the whole life cycle of RPL enabled WSN. We analyze the performance of network construction process by measuring several important metrics, and then we investigate the performance and possible situations during the functioning stage of the WSN. The results indicate that RPL is a pretty robust protocol for WSN. But there are still several aspects to be improved, like signaling overhead, latency and so on. In addition, our work provides guidelines for the design of future Internet of Things with IPv6 networking enabled.

ACKNOWLEDGMENTS

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