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***Abstract*—The RPL routing protocol published in RFC 6550 was designed for efficient and reliable data collection in low-power and lossy networks. Specifically, it constructs a Destination Oriented Directed Acyclic Graph (DODAG) for data forwarding. However, due to the uneven deployment of sensor nodes in large areas, and the heterogeneous traffic patterns in the network, some sensor nodes may have much heavier workload in terms of packets forwarded than others. Such unbalanced workload distribution will result in these sensor nodes quickly exhausting their energy, and therefore shorten the overall network lifetime. In this paper, we propose a load balanced routing protocol based on the RPL protocol, named LB-RPL, to achieve balanced workload distribution in the network. Targeted at the low-power and lossy network environments, LB-RPL detects workload imbalance in a distributed and non-intrusive fashion. In addition, it optimizes the data forwarding path by jointly considering both workload distribution and link-layer communication qualities. We demonstrate the performance superiority of our LB-RPL protocol over original RPL through extensive simulations.**

***Index Terms*—Load balanced routing; workload detection; workload signaling; link quality adaptation; buffer capability utilization; low power and lossy networks**

I. INTRODUCTION

Low power and Lossy Networks (LLNs) have a wide spectrum of applications in areas such as automated environment monitoring, e.g., habitat monitoring [1] and building monitoring [2]. Since sensor nodes employed in the LLN typically have tight resource constraints and short radio communication ranges, data collection in LLNs is inherently challenging. First of all, due to the nature of the wireless communication media, communication condition varies dramatically depending on environment, such as traffic in urban areas. As a result, the data collection reliability can be affected. Moreover, as sensor nodes are deployed for monitoring purposes, the data traffic intensity may vary depending on the geographic distribution of physical phenomena. Therefore, without a proper communication workload balance mechanism, some of the sensor nodes may quickly exhaust their energy, causing the whole network to disconnect.

In order to achieve reliable and energy efficient data collection, the IETF ROLL working group has published RFC 6550, which is a routing mechanism called RPL specifically designed for LLNs. RPL selects the routing path by establishing a Destination Oriented Directed Acyclic Graph (DODAG). Depending on the specific application, different routing metrics can be adopted, such as expected transmission count (ETX). Routing path construction relying solely on a single pairwise transmission quality metric may not be able to capture the real communication scenario. For example, the pairwise metric may result in a single node with good transmission quality to each neighboring node being associated with a large number of children. In this case, the parent node can be severely congested and drop a large number of packets due to buffer limitation. Therefore, load balancing under the non-uniform node distribution as well as non-uniform traffic patterns becomes critical.

To mitigate the workload imbalance problem in LLNs, a routing protocol should have the following desirable features. (1) *Distributed*: Since it is impossible for any central server to obtain global information about energy consumption and communication status of each sensor node in a large-scale LLN, a distributed routing protocol is a must. (2) *Non-intrusive*: Using periodic information collection and control messages to obtain each node's information in an LLN incurs high communication overhead and may affect regular tasks, hence, a better strategy is to detect and signal workload imbalance in a non-intrusive way. (3) *Reliability*: In order to balance workload among sensor nodes, some data traffic may be relayed through a path with imperfect communication link quality. To maintain reliability, a routing protocol should jointly consider workload balancing and communication link quality.

The main objective in this paper is to design a routing protocol that is suitable for large-scale LLNs. To achieve this, we incorporate the load balance mechanism into the RPL routing protocol. Our contributions can be summarized as follows. First, we provide an analytical model to quantify the impact of resource limitations to the packet delivery reliability in LLNs. Second, we design an effective routing protocol based on RPL. Third, we analyze the proposed routing protocol, and conduct extensive simulations to validate the overall routing protocol performance.

The rest of the paper is organized as follows. Section II presents prior works on load balanced routing for LLNs. Section III provides background information and a brief description of the RPL protocol. Section IV describes our load balanced routing protocol in detail. Section V demonstrates the performance of the proposed LB-RPL protocol. Section VI concludes the paper.

II. RELATED WORK

There have been extensive studies on load balanced routing in a large-scale LLN environment. Depending on the routing structure, existing approaches can be classified into hierarchical or flat routing model. Hierarchical routing approaches [3]–[6] typically organize the network into clusters, where sensor nodes within one cluster can directly communicate with each other. Workload balance among sensor nodes usually focuses on either the arrangement of clusters [5] or the selection of cluster heads [3]. Because of the restriction of one-hop distance between nodes within a cluster, such a hierarchical approach may not be suitable for large-scale LLNs. On the contrary, flat routing model [7] typically requires packet transmission in a multi-hop fashion, and allows sensor nodes to make routing decisions by themselves. Although this approach is more suitable for large-scale LLNs, load balancing is more challenging due to the lack of global information. Routing algorithms proposed in [8]–[10] leverage the distributed, multi-hop feature of the flat routing model, and construct a logical tree structure to facilitate routing and load balancing. The establishment of the routing tree may rely on different metrics, e.g., [11], [12]. The tree structures may be dynamically changed according to the load distribution. To detect load imbalance, a threshold based approach is proposed in [10]. In this paper, we adopt the tree routing structure construction procedure by RPL protocol, and dynamically adjust routing paths according to workload distribution. Instead of relying on a predefined fixed threshold, we perform load imbalance detection in a distributed fashion.

Due to the lossy nature of wireless communications, multi-path based data collection approaches have been studied. To ensure reliability, data packets are forwarded through multiple paths towards the data collector [13]–[15]. In [13], a randomized forwarding mechanism is proposed to facilitate load balancing. However, simply spreading out workload among all neighbors may cause significant packet loss over low quality links. He *et al.* [14] proposed a multi-path geographic routing protocol, called SPEED. Although it achieves load balancing and reliability through multiple routing paths, the information of each node's geographic location may not be available for many application scenarios. Yan *et al.* [15] proposed a similar load balanced routing approach like our LB-RPL protocol. However, since they do not have a distributed load imbalance signaling mechanism, simply spreading the load among all parent nodes may not be effective. That is, for a parent node with more children, its workload will still be heavier than others. In LB-RPL, a sensor node with heavy workload can signal its status by delaying transmission of DIO packets. In this way, all the neighbors can get the signal, and fewer nodes will select it as next hop for packet forwarding. Therefore, its heavy workload can be alleviated.

III. PRELIMINARIES

A. System Architecture

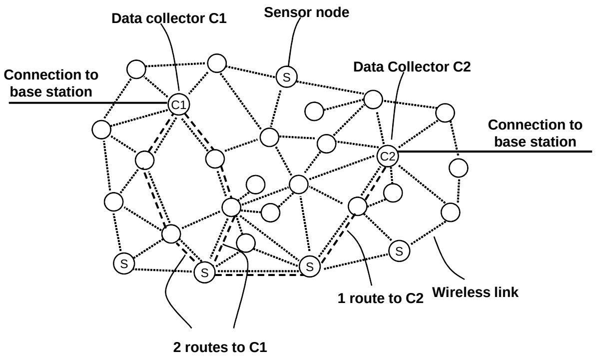


Fig. 1. An example deployment of a two-tier large-scale sensor networks for environment monitoring.

We consider a large-scale sensor network deployed in an outdoor environment. An example network is depicted in Figure 1. All sensor nodes in the deployed area are responsible for monitoring nearby physical phenomena, thus they are all data sources. Sensor nodes communicate with each other through wireless radios. To ensure coverage, sensor nodes are densely deployed so that each sensor node has a set of neighbors. To facilitate data collection, the whole network is organized in a two-tier hierarchical fashion, where several data collectors with richer resources than ordinary sensor nodes are deployed to collect data from sensor nodes in their proximity. Each data collector node is responsible for covering a sub-set of all deployed sensor nodes. Sensor nodes need to forward their data through single or multiple hops to one of the data collectors. Since the majority of the traffic direction is from sensor nodes to data collectors, we assume sensor nodes and the data collectors have the same wireless transmission range for analysis purposes.

Data traffic generated by all sensor nodes can be either regular or burst. Since our load balanced routing algorithm is intended to perform under various traffic situations, we do not make any assumption on the traffic pattern. We assume a fair channel allocation MAC protocol (e.g., 802.11 or 802.15.4) is used.

B. Overview of RPL protocol

As discussed in Section I, the RPL protocol relies on a Destination Oriented Directed Acyclic Graph (DODAG) for packet forwarding. The basic procedure for building such a DODAG is as follows. The root node (data collector) broadcasts a DAG Information Object (DIO) message, where RPLInstanceID, the DODAG identifier, a monotonically increased version number, Rank and other fields are included. The sensor nodes that are closest to the root will first hear this message, and decide if they want to join this DODAG. Once they decide to join, they compute their own rank values independently, and transmit the DIO message with their own rank values and the latest version and DODAG identifier to their neighbors. The same procedure

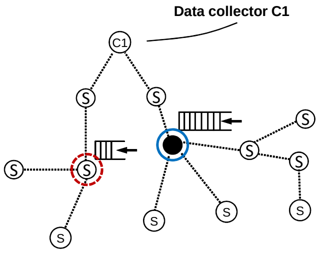


Fig. 2. A snapshot for unbalanced workload in sensor networks. Comparing two nodes that are two hops away from the collector, the dark solid node has more data packets to be forwarded than the other node.

continues until a node finds out that it has already received a copy of the message.

Since RPL is designed for lossy network environment, each node in the DODAG maintains a set of parent nodes for fault tolerance purposes. Among these parent nodes, one of them is selected as the preferred parent. The preferred parent will be used as the primary relay node for packet delivery. An example of a DODAG is depicted in Figure 2.

C. Problems with RPL protocol

RPL is designed for LLNs and performs routing in a distributed way. However, the critical load balance feature is missing in RPL. Without load balancing, the uneven data traffics, as well as the non-uniform distribution of sensor nodes in large-scale LLNs may result in significant load imbalance for those sensor nodes that have more neighbors than others. Therefore, the energy depletion of these sensor nodes is much faster than those with light workload. This will result in gaps and holes in the whole network and render the network disconnected.

In addition, the routing metrics recommended and popularly used with RPL protocol, e.g., expected transmission count (ETX) and packet delivery ratio, only focus on the pairwise communication quality between two nodes. Since wireless communication may be easily interfered by neighbor nodes' transmissions, even a perfect link between two nodes may not work well under heavy traffic conditions.

IV. LB-RPL: LOAD BALANCED ROUTING PROTOCOL

In this section, we first formulate the problem, and then propose a Load Balanced routing protocol based on RPL, called LB-RPL. The LB-RPL protocol focuses on addressing the buffer limitation caused packet loss and workload balancing.

A. Problem Formulation

To select a primary parent for packet forwarding, the most commonly used routing metrics in RPL typically belong to a specific network layer. For example, RSSI captures the physical layer signal quality for communication; ETX represents the aggregated link layer communication quality. However, for data collection in LLNs, not only the transmission qualities between a sender and a receiver should be considered, but also the channel contention and resource limitations at the receiver side should be considered. The notations used to formulate the problem are summarized in Table I.

TABLE I
NOTATION SUMMARY

Symbol	Definition
p_i^b	packet drop probability due to buffer limitation
λ	packet arrival rate
μ	service rate
q_r	buffer size at a sensor node
p_i^c	packet drop probability at node i due to channel condition
p_{ij}^c	packet drop probability from node i to node j due to channel condition
d_i^s	overall packet delivery probability
s_{ij}	number of packets forwarded from node i to node j
f_{ij}	forwarding probability from node i to node j
$\mathcal{S}$	one realization of workload distribution
T_i	timer value for node i
T_0	constant number to assist timer calculation

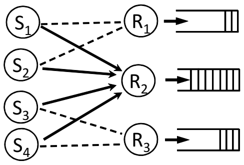


Fig. 3. A queuing model for relay node in packet forwarding process. Nodes S_1 to S_4 represent data sources while node R_1 to R_3 represent relay nodes. When all the data sources choose R_2 as next hop for data communication, packets may be lost due to the buffer limitation at R_2.

Consider the scenario where there are multiple sensor nodes transmitting packets to a single relay node, as depicted in Figure 3. Assume the aggregated number of packets generated by all source sensor nodes follows a Markov process. Due to the MAC layer contention, we assume the processing of the packets, i.e., forwarding of the packets, at the relay node is also a Markov process. Therefore, the system can be modeled as an M/M/1/K queue, where K denotes the buffer size at the relay node. According to the finite queue analysis in [16], when the number of packets arrived exceeds the buffer size, these packets are dropped. Packet drop probability is given by

$$p_i^b = \begin{cases} \frac{1}{q_r+1} & \rho = 1 \\ \frac{\rho^{q_r}(1-\rho)}{1-\rho^{(q_r+1)}} & \rho \neq 1 \end{cases}, \tag{1}$$

where $\rho = \frac{\lambda}{\mu}$, and λ is the packet arrival rate and μ is the service rate [16].

From this equation we observe that *the number of packet sources* plays a critical role in determine the ratio of the packet arrival and departure. In addition, when the ratio equals to one, the *buffer size at the relay node* also significantly affects the packet drop rate.

There are many channel condition metrics that can be used in routing. Here, we adopt the overall packet delivery ratio to quantify the communication quality. Denote the packet drop rate that is determined by channel condition as p_i^c. Combined with the buffer related packet loss, we can conclude that the probability for a packet to be successfully delivered from node i to j is

$$d_i^s = (1 - p_i^b) \times (1 - p_i^c). \tag{2}$$

RPL only uses preferred parent as next hop towards data collector. However, multiple nodes from the parent set can be used simultaneously. As a result, a sensor node need to decide which node or nodes may result in the maximum packet delivery ratio. The challenge here is that for sensor nodes in an area, there are multiple sensor nodes that make decisions in a distributed fashion; therefore, other sensor nodes' data traffic may significantly affect the packet delivery ratio at a particular relay node. Denote the set of packet load distribution using a distribution matrix

$$\mathcal{S} = \begin{bmatrix} s_{01} & \cdots & s_{0n} \\ \vdots & \ddots & \vdots \\ s_{n1} & \cdots & s_{nn} \end{bmatrix}, \tag{3}$$

where n is the total number of sensor nodes. The optimal workload distribution for the overall system is

$$\widehat{\mathcal{S}} = \arg\max_{\mathcal{S}_i} \sum_{i \in \mathcal{N}} d_i^s$$

According to this formulation, we can see that the packet forwarding workload tremendously impacts the overall packets delivery ratio, and potentially affects the network lifetime. However, selecting an optimal workload distribution is very challenging even when the global information is given. Therefore, we propose a distributed load balanced routing protocol to achieve a better performance.

B. LB-RPL Routing Protocol

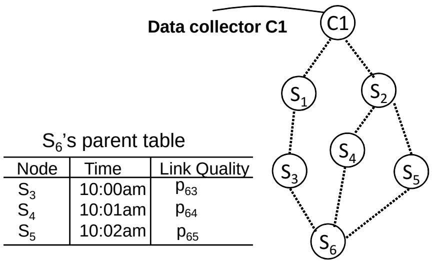
Our proposed LB-RPL protocol leverages the parent/children structure established by RPL protocol. However, instead of selecting a single parent node for a node as primary parent based on pairwise link condition indicators, LB-RPL takes into account the workload differences, and strives to spread out the data traffic among the parent nodes. The LB-RPL protocol modifies the DODAG construction procedure in RPL by incorporating the following two functionalities: (1) workload imbalance detection and signaling; (2) load balanced data forwarding. A summary of our LB-RPL protocol is listed in Algorithm 1 and 2.

1) Workload imbalance detection and signaling: Similar to RPL, the root of a DODAG sends out DIO message periodically, with a unique DODAG identifier and a version number. After a node receives this message, it will decide whether it wants to join this DODAG or not, and computes a rank value once it decides to join. The same approach for rank calculation used in RPL can be adopted here.

Different from RPL, in order to perform workload imbalance detection and signaling, the node will not transmit the new DIO with its rank immediately. Instead, *it will start a timer that is proportional to its workload in the previous period, and transmit the DIO message after the timer expires.* The same procedure continues at each increased level of the DODAG until the DIO message with the latest version number reaches the leaf nodes. Determining an appropriate timer value is critical for achieving load imbalance detection and signaling. According to our analysis in Section IV-A, the buffer storage limitation of a sensor node significantly affects the packet delivery rate. Thereafter, the *buffer utilization counter* is employed to quantify a node's workload. The buffer utilization counter can be calculated in two ways: (1) the average number of packets queued in the buffer within a certain time period; or (2) the total number of packets that have been pushed into the buffer. Selection between the two methods depend on specific application as well as the hardware used. We propose to use the following method to evaluate a timer value.

$$T_i = T_0 \times \text{Buffer Utilization Counter}. \tag{4}$$

After a node receives multiple copies of the same DIO message from different lower ranked nodes, it will form its parent set as described in RPL. Depending on the time these DIO messages are received from these parent nodes, the priority order of these parents are determined accordingly. An illustrative example of parent set at a sensor node is depicted in Figure 4.



S6's parent table

Node	Time	Link Quality
S_3	10:00am	p_{63}
S_4	10:01am	p_{64}
S_5	10:02am	p_{65}

Fig. 4. An illustrative example of packet forwarding at a sensor node. According to the order of received DIO message from different parent nodes, S_6 has a parent table as shown in the figure. S_6 selects the top two parents, i.e., S_3 and S_4, and send the fraction of $\frac{p_{63}}{p_{63}+p_{64}}$ packets to S_3. The rest of the packets are forwarded to S_4.

2) Load balanced data forwarding: Unlike RPL, where a single sensor node in the parent set is selected as preferred parent according to a single metric, in our LB-RPL, the top k parent nodes are all considered as a potential next hop for data forwarding. The probability of node i to forward data packet to a particular parent node j is calculated as

$$f_{ij} = \frac{(1 - p_{ij}^c)}{\sum_{j=1}^{k}(1 - p_{ij}^c)}. \tag{5}$$

As a result, the data packets generated by the current sensor node is distributed among k parent nodes proportionally according to their pairwise link qualities. Moreover, when one of the parent nodes suffers from heavy workload from current data collection period, it will add more delay in DIO message transmission in next round. A long delay can result in a parent node with heavy workload out of top k list in its children's parent table. As a result, this node will not be used as next hop by many children for data forwarding, and workload imbalance can be alleviated.

Algorithm 1 Sensor Node Initialization Procedure

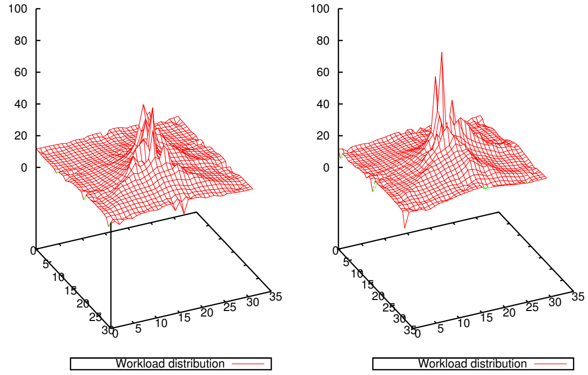
```
Initialize parent set and buffer utilization counter
Update the latest received version number
Insert the DIO message source into parent set according to the message arrival time
Calculate its own rank value
Set timer value $T_i$ according to Equation 4
Generate a DIO message with its own rank number and the latest version number
When timer $T_i$ expires, broadcast a DIO packet with current rank and version number
```

Algorithm 2 LB-RPL: Load Balanced RPL Routing Protocol

```
A sensor node listens to the radio channel
Once a message $M$ arrives, check the type of the message
if $M$ is a DIO message then
    if New version of DIO then
        Invoke Sensor Node Initialization Procedure
    else
        if Current DIO version then
            if Rank value carried in the message is less than current node's rank then
                Insert the DIO message source to parent set according to message arrival time
            end if
        else
            Discard this message
        end if
    end if
else
    if $M$ is a DAO message then
        Process it according to RPL
    else
        if $M$ a is data message then
            if the data message comes from a child of current node then
                Increase workload counter
            end if
            Forward this message by choosing the first two parent nodes from parent table, and selecting one as next hop with probability Equation 5
        end if
    end if
end if
```

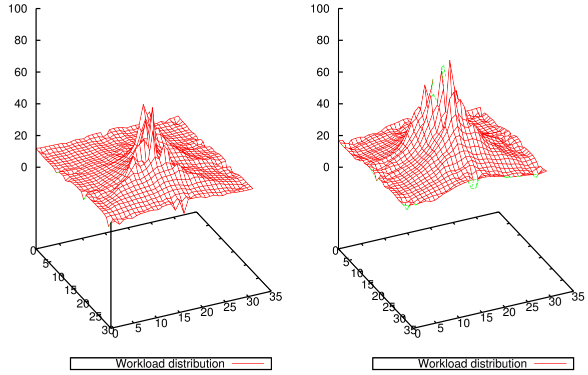
V. PERFORMANCE EVALUATION

We evaluated the performance of our LB-RPL protocol via simulations using NS2 [17]. In the simulation, a total number of 1000 sensor nodes are randomly deployed in a 320 by 320 field, where the average distance between two nodes is about 10 meters. Due to the randomly generated topology, we first prune out any network that is disconnected. To focus on the load balance performance, we placed only one data collector in the middle of the field during the simulations. However, our LB-RPL protocol is capable of accommodating the scenario of multiple data collectors. We conduct multiple simulation runs to get the average performance statistics. To better reflect the low power and lossy features of the targeted networks, we adopt IEEE 802.15.4 as the physical and MAC layer of our simulation.



(a) LB-RPL protocol (b) RPL protocol

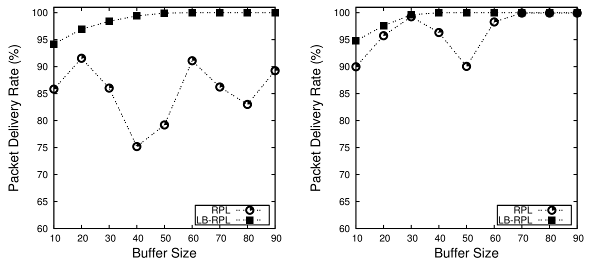
Fig. 5. The 3D mesh of a snapshot of the workload distribution for the network: each node has a buffer size of 40.



(a) LB-RPL protocol (b) RPL protocol

Fig. 6. The 3D mesh of a snapshot of the workload distribution for the network: each node has a buffer size of 50.

We conducted simulations using a data generation rate of 1 packet per 5 minutes scenario. To investigate the load distribution in the simulated network, we plot the workload, i.e., the total number of forwarded packets, of each sensor node using mesh graphs, shown in Figure 5 and Figure 6. Figure 5 has a smaller buffer size and hence depicts higher peak workload. From these figures we observe that, because the data collector is placed at the center of the network, sensor nodes that are closer to the data collector always have heavier workload than those edge nodes. This is exhibited by the prominent center portion of these mesh figures. However, the nodes with the heaviest workload using LB-RPL have much smaller numbers of forwarded packets than that of the nodes using RPL. This indicates that LB-RPL successfully spreads out the workload among these nodes around the data collector. In addition, nodes at about the same distance from the data collector have similar workload when using LB-RPL, shown in Figure 5(a) and Figure 6(a). Whereas, when using RPL, those nodes at the same distance from the data collector may have significantly different workload, depicted in Figure 5(b) and Figure 6(b). This demonstrates that the LB-RPL protocol helps balance the packet forwarding workload among sensor nodes at similar levels (similar distance from the data collector).



(a) 2 packets per 5 minutes (b) 1 packets per 5 minutes

Fig. 7. Packet delivery ratio for different packet generation rate.

TABLE II
PACKET LOSS DUE TO BUFFER LIMITATION

Buffer Size	RPL	LB-RPL
10	4149	1797
20	2470	928
30	3665	475
40	5545	177
50	4012	23
60	1698	0
70	2325	0
80	2699	0
90	1697	0

TABLE III
AVERAGE PACKET DELIVERY DELAY

Buffer Size	RPL	LB-RPL
10	0.2528	0.0844
20	0.8022	0.0783
30	1.6208	0.0783
40	5.4900	0.0783
50	5.5361	0.0783
60	3.1235	0.0783
70	3.9740	0.0783
80	5.1730	0.0783
90	3.5005	0.0783

Besides LB-RPL's performance for load balancing, we also investigate the overall packet delivery reliability, i.e., packet delivery ratio and delay. For this set of simulations, we vary the packet generation rate at sensor nodes. Figure 7 depicts the packet delivery ratio of the simulated sensor network under different buffer size settings. In accordance with our previous analysis, when the buffer size at each node is small, many packets are dropped due to buffer limitation, resulting in low packet delivery ratio. This conclusion is also supported by the number of packet losses versus buffer size listed in Table II. By increasing buffer size, LB-RPL achieves 100% packet delivery ratio, which is much better than the performance of RPL under the same configuration. This is because in RPL, some sensor nodes are so heavily congested that even increasing the buffer size cannot alleviate the congestion caused by load imbalance.

Table III lists the average packet delivery delay under different buffer size configurations. From this table we can observe that LB-RPL exhibits a much short delay than the RPL protocol. This is because by balancing the workload among sensor nodes LB-RPL essentially helps reduce congestion. As a result, packets will not be queued in some sensor nodes for a long time.

VI. CONCLUSION

In this paper, we propose a load balanced routing protocol based on the RPL protocol to achieve balanced workload distribution among nodes in large scale low power and lossy networks. A distributed and non-intrusive technique is provided to realize automatic workload imbalance signaling and detection. Workload distribution and communication condition are jointly considered to select optimal data forwarding paths for maximizing packet delivery rate. Simulation results show that the proposed load balanced routing protocol performs much better than RPL protocol in terms of balanced workload distribution, packet delivery rate, and end-to-end packet delay.

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