TAOF: Traffic Aware Objective Function for RPL-based Networks

Chenyang Ji*, Remous-Aris Koutsiamanis†, Nicolas Montavont†, Periklis Chatzimisios*,
Diego Dujovne‡ and Georgios Z. Papadopoulos†

* CSSN Research Lab, Alexander TEI of Thessaloniki, jichenyang920@gmail.com, peris@it.teithe.gr
†IMT Atlantique, IRISA, UBL, France, firstname.lastname@imt-atlantique.fr
‡Escuela de Informática y Telecomunicaciones, Universidad Diego Portales, Chile, diego.dujovne@mail.udp.cl

***Abstract*—Within the context of the Internet of Things (IoT), the distance-vector IPv6 Routing Protocol for Low-power and Lossy Networks (RPL) is one of the most popular choices for the network routing layer. Within RPL, distance calculation is abstracted by the Objective Function (OF) and two OF implementations have been standardized, namely OF0 and MRHOF. However, these OFs build network topologies where bottleneck nodes may suffer from excessive unbalanced traffic load. The load distribution problem is a major issue for existing OFs defined in RPL because it decreases network performance and the network's lifetime. In this paper, we propose a new OF called the Traffic Aware Objective Function (TAOF), which balances the traffic load that each node processes in order to ensure node lifetime maximization. To implement this OF, we altered the DIO message format, introduced a new RPL metric, named Traffic Rate, and used a new parent selection algorithm. Simulation experiments have been conducted to examine the performance of our proposal. The results show that TAOF achieves enhanced performance in terms of Packet Delivery Ratio (PDR) and that it builds more stable networks with fewer parent changes.**

***Index Terms*—Internet of Things; Low-power and Lossy Networks; LLNs; RPL; Load Balancing; Objective Function.**

I. INTRODUCTION

The Internet of Things (IoT) is a new application field for the Internet, putting smart objects into a network and enabling data retrieval and distant monitoring/actuation. Smart objects are devices with a specific function (e.g., data collection) and usually they have limited resources in terms of energy, computational power, and memory [1]. Examples of smart objects are sensors, actuators and other items embedded in electronics. The IoT has become very popular recently because of the tremendous number of smart objects connected to the Internet due to the ongoing digital revolution. IoT applications cover a wide range of use cases, each of them with different network performance requirements. Well-known examples of IoT applications are smart cities and wearable devices.

The networks that consist of smart objects are usually Low-power and Lossy Networks (LLNs), meaning that the link between devices in the same network are unstable [2], [3]. From the use cases published during 2009 and 2010, the routing requirements are described in [4]. Fulfilling to these requirements, the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) was submitted as a Request For Comments (RFC) in the Routing over Low-power and Lossy networks (RoLL) Working Group (WG) to the Internet Engineering Task Force (IETF) [5]. RPL is the main candidate to act as the standard routing protocol in IPv6-based LLNs [6], such as Wireless Sensor Networks (WSNs) [7].

RPL builds a network topology called a Destination Oriented Directed Acyclic Graph (DODAG). The Objective Function (OF) in RPL guides the construction of a DODAG, according to a set of rules and the rank computation method in RPL using specific metrics. So far, two OFs have been standardized in RPL, the Objective Function Zero (OF0) [18] and the Minimum Rank with Hysteresis Objective Function (MRHOF) [19].

A major problem with the existing OFs is the load distribution problem. In this paper, we propose a solution called the Traffic Aware Objective Function (TAOF). TAOF defines a new parent selection algorithm using a new metric called ”Traffic rate”. This new metric measures and reports the traffic load each node processes.

The organization of the paper is the following. We first briefly describe RPL and the related load balancing problem in Section II. Section III provides a literature review of existing proposed solutions for this problem. Section IV thoroughly describes the TAOF proposal, whereas in Section V we evaluate its performance. Finally, Section VI discusses the derived conclusions and proposals for future extensions of our work.

II. BACKGROUND

In order to satisfy routing optimization objectives such as minimizing energy or latency, RPL was designed by the ROLL WG with the objective to meet the requirements from LLNs [6]. It separates packet processing and forwarding in order to be useful in a wide range of LLN applications. RPL is a proactive distance vector protocol, meaning that every device in the network maintains table(s) representing a partial view of the topology and RPL uses these routing tables to determine the best path based on distance (e.g., number of routers a packet has to pass).

RPL builds a DODAG topology in which each link is oriented in such a way that no cycles are formed between

978-1-5386-7272-3/18/$31.00 ©2018 IEEE

nodes and that all the links are contained in paths oriented towards or away from the root node.

RPL uses an OF to guide the construction of the DODAG, in other words, the criteria that will be used to build the best path towards the root. Each node compares its neighbors and selects one of them, the one that is closer to the root in comparison to itself, as its parent according to the criteria defined by the OF. The information used to decide the best parent is included in RPL control messages. There are three different types of control messages:

- The DODAG Information Object (DIO) advertises the routing metrics and constrains of a node.
- The Destination Advertisement Object (DAO) constructs and maintains downward routes.
- The DODAG Information Solicitation (DIS) solicits a DIO from other RPL nodes.

A control message can carry different options to allow the extension of the functionality offered. The option necessary for parent selection is the DAG metric container, which is used to report metrics or constraints along the DODAG.

The devices utilized in a LLN are usually battery operated and, thus, it is required for RPL to be energy efficient, while the constructed network should provide a certain level of stability. In order to maximize network life-time, RPL needs to balance the load assigned to each node to ensure that energy usage is spread among nodes.

The problem of existing OFs is that they rely on a single metric or a combination of two metrics for parent selection. This degrades the performance of the DODAG because it is not possible to take into consideration all the properties of a good link with only one or two metrics, while in some cases, the requirements may be antagonistic to each other. For example, using the Expected Transmission count (ETX) as a single routing metric may lead to high latency in routing messages since nodes tend to select the same node as the preferred parent leading to queue overflow. The existing OFs build networks where the load is mostly assigned to some nodes that carry a “favored” metric value and these nodes might have to process a traffic load more than their capabilities. This is known as the load distribution or load balancing problem.

This problem greatly affects network performance and it becomes worse when the overloaded node is the bottleneck node (nodes close to the DODAG root) or the only parent candidate. When a node becomes overloaded it forwards and receives more packets than other nodes. Because the highest power consumption period for a LLN device is when packets are received and forwarded, the overloaded node consumes more energy and its battery will drain faster than other nodes. When an overloaded node leaves the network due to battery depletion, the load will be assigned to its neighbors which leads with high probability to the creation of another overload node. Another consequence of an overloaded node is that the more packets a node forwards in a certain time period the more packets will be waiting in the queue to be forwarded. Thus, an overloaded node is more prone to packet loss from buffer overflow and tends to forward packets with increased delay due to the queuing process.

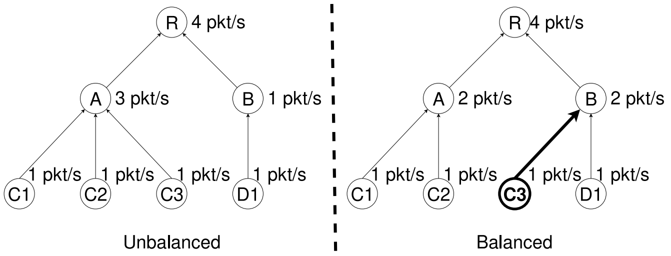


Fig. 1. Load distribution problem.

An example describing this problem is shown in Figure 1 where node A is the overloaded node since it forwards 3 pkt/s whereas the other nodes forward only 1 pkt/s. This happens because node A is the preferred node to be selected as parent by the other nodes. The optimal load balancing would be to build a network as in Figure 2 where both nodes A and B forward 2 pkt/s.

III. RELATED WORK

In this Section, we present a synthesis of previous research work on the RPL load distribution problem.

A. Literature Review

After thorough study of the related literature, we have classified the different proposals into four categories according to the parent selection mechanism proposed in each:

1) Using a combination of existing metrics for parent selection. An example for this category is the fuzzy logic OF [8].
2) Adjusting the overloaded node after the network has been formed by the original RPL. An example for this category is MD RPL [9].
3) Multi-path routing in which nodes select more than one parent to deliver the data packets to the DODAG root. Examples for this category are HECRPL [10] and CA RPL [11].
4) Using a custom-designed metric for parent selection. Examples for this category are PC-RPL [12], QU-RPL [13], ALABAMO [14], IRPL [15], Improved RPL [16] and LB-OF [17].

B. Standardization Efforts

As previously stated, the OF guides the construction of a DODAG by controlling how nodes select the best parent.

There are two standardized OFs, the Objective OF0 [18] and MRHOF [19]. More specifically,

- OF0 was designed as the default OF for RPL. It selects the path to the nearest grounded root, creating a DODAG that can fulfill the application’s requirements.
- MRHOF selects the parent with minimum path cost and in order to avoid oscillation, this OF adds hysteresis. The hysteresis makes the parent change conditional on the

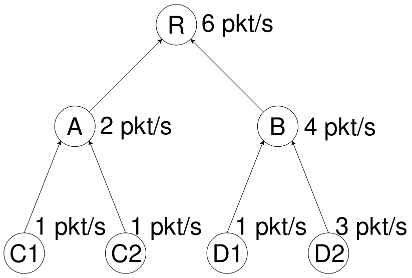


Fig. 2. The unbalanced scenario when employing LB-OF.

difference of path costs of original parent and alternative parent being higher than an specific threshold.

Although OF0 and MRHOF are the two standardized and most popular OFs, they do not overcome the problem of load distribution. In order to solve this problem, there are a set of proposals in the literature, as described in Section III-A. The most efficient work among the proposed solutions is LB-OF [17], which aims to achieve load balancing by adjusting the number of direct children for each node. Since the child number is difficult to obtain in non-storing mode, LB-OF proposes an amended DIO format and a mechanism to process the amended DIO. Moreover, LB-OF proposes a new RPL metric to be used for parent selection.

However, the main drawback of LB-OF is that the number of children cannot indicate the traffic load each node forwards, because each node may forward different traffic flow sizes, as described in Figure 2.

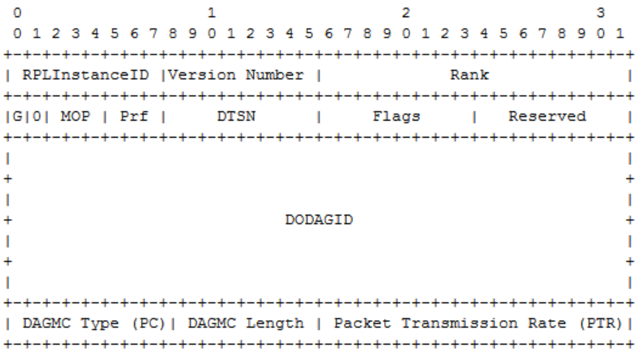
Thus, there is a need for a metric to quantify network traffic in order to detect an overloaded node. The difference between a normal and an overloaded node is that the number of forwarded packets is higher in the second case. The number of packets sent from a node during a certain period can indicate the amount of current traffic load, thus, overloaded nodes can be detected. To overcome such unbalanced traffic loads in the network, this work proposes TAOF.

IV. PROPOSED SOLUTION

In our proposal, TAOF leverages the load assigned to each node using a new RPL metric named Packet Transmission Rate (PTR) that represents the number of packets each node forwarded during a certain time period. This metric can directly indicate the load in a per-node basis.

To do so, we amended the DIO format and inject the packet transmission rate into the DAG Metric Container option as illustrated in Figure 3. Note that we do not introduce any additional traffic overhead. We simply extend the existing DIO structure.

In order to record the number of data packets forwarded by each node in a certain time period, each node contains a buffer that records the timestamps for each data packet forwarded. The required size of the buffer depends on the device's memory capacity. When a node generates a DIO message, it first scans the buffer to get the number of data packets forwarded by comparing the timestamps with the current time. This number is later added to the DIO message in the DAG metric container.



```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| RPLInstanceID |Version Number |             Rank              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|G|0| MOP | Prf |     DTSN      |     Flags     |   Reserved    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                            DODAGID                            +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| DAGMC Type (PC)| DAGMC Length | Packet Transmission Rate (PTR)|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Fig. 3. TAOF DIO format.

Each node should identify from their neighbor set which nodes are acceptable to be selected as a preferred parent. For this purpose, the ETX metric is employed to filter out parent candidates with low link quality, based on a predefined threshold. This ETX threshold should be different depending on application requirements.

After the elimination of parent candidates using ETX, the node gets a parent candidate set without any low quality links. From the parent candidate set, the node obtains the transmission rate for each neighbor from the DIOs and compares their values between them. Finally, the node will choose the parent candidate with the least packet transmission rate value. The metric value of alternative parent will be compared to the transmission rate of original parent. The difference between these two values will be compared to the parent change threshold to decide if the procedure of parent change should take place, implementing a hysteresis functionality. If the difference is less than the threshold, it means that nodes send similar numbers of data packets so there is no need to change parent. If the difference is greater than the threshold, then the parent change will take place because the node is overloaded and has to process much more traffic than other nodes. The factors that affect the value of the threshold vary, e.g., the buffer size of a node, the time period used, the frequency a node sends data packets, etc. The configuration of the threshold differs among scenarios and should be selected for each use-case.

V. PERFORMANCE EVALUATION

In order to evaluate TAOF, we conducted simulations using the COOJA simulator over Contiki OS. We simulated the topology over various link qualities ranging from 70% to 100%. Finally, we compared our proposed TAOF schemes against the state-of-the-art LB-OF and MRHOF objective function, by employing the same simulation parameters. The configuration parameters are shown in Table I. The considered topologies in the simulations are illustrated in Figure 4.

TABLE I
SIMULATION SETUP

Simulator	**Value**
Operating System	Contiki OS
Simulator	COOJA
Motes	COOJA
Topology	**Value**
Topology	Multi-hop, see Figure 4
Number of nodes	12 (including the sink)
Number of sources	1 source
Node spacing	10 m (in average)
Simulation	**Value**
Duration	1100 $seconds$
Retransmissions	2
Payload size	17 $bytes$
Routing model	RPL [5]
Objective Function	MRHOF, LB OF, TAOF
MAC model	TSCH [7]
TSCH	**Value**
EB period	3.42 sec
LB period	30 sec
Slotframe length	101
Timeslot length	15 ms
Hardware	**Value**
Antenna model	CC2420
Radio propagation	2.4 GHz
Transmission power	0 dBm
Radio model	Directed Graph Radio Medium (DGRM)

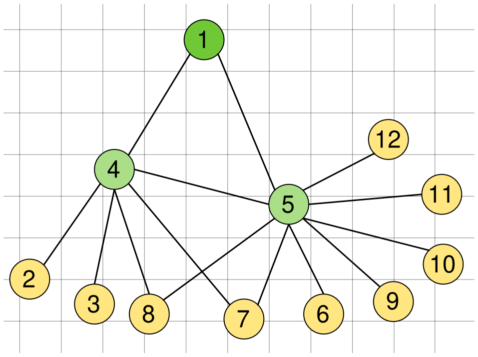


Fig. 4. Simulated topology.

As it can be observed in Figure 5, both LB-OF and TAOF significantly improve the network reliability. Indeed, such results show that load balancing algorithms are necessary for RPLRPL-based networks. The standardized proposal MRHOF does not provide any intelligent on distributing the traffic. Furthermore, we can observe that our proposed scheme TAOF outperforms MRHOF and LB-OF, in terms of PDR, for all considered scenarios.

Figure 6 illustrates the number of transmitted DIO messages for various values of link quality. The number of transmitted DIO messages leverages the stability of a topology since fewer DIOs mean fewer changes. As it is shown in the figure, TAOF sends fewer DIOs and the difference between MRHOF and TAOF becomes relevant; for 90% link quality, TAOF sends almost 50% fewer DIOs. Thus, the network achieves better stability because when nodes send fewer DIOs the parent does not change. In other words, the topology is balanced and nodes are not overloaded.

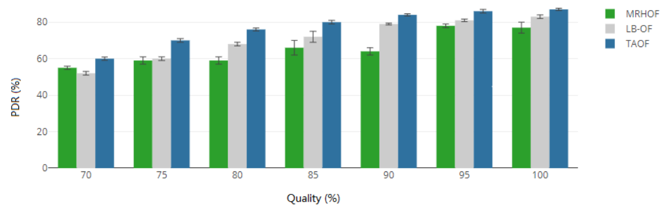


Fig. 5. PDR performance per link quality.

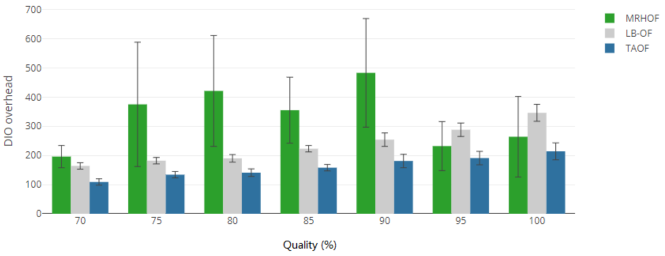


Fig. 6. Number of DIO control packets sent in the network per link quality.

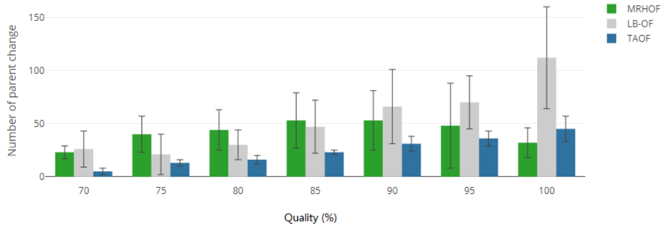


Fig. 7. Number of parent changes over various link qualities.

Figure 7 illustrates the number of parent changes for various link quality values. The number of parent changes is the criterion to determine the stability of a network because each change causes extra overhead to the network and the nodes during the procedure of parent change are not able to process traffic flow so the load would be transferred to other nodes for an interval. As Figure 7 shows, TAOF achieves the least number of parent changes.

Likewise, another criterion indicating network stability is the number of transmitted DIO messages by critical nodes.

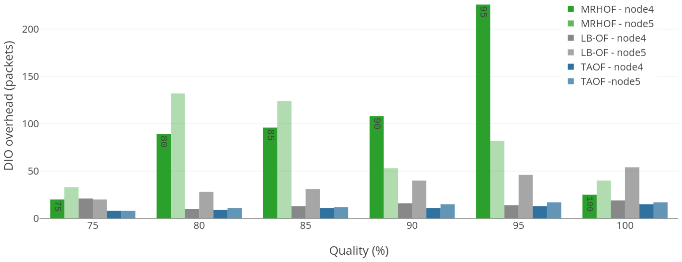


Fig. 8. Number of DIO control packets sent for the “critial” nodes 4 and 5.

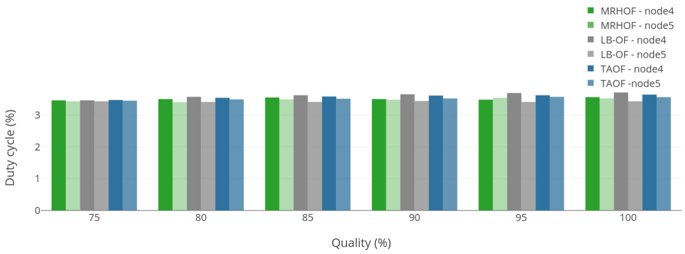


Fig. 9. Energy consumption for nodes 4 and 5.

Figure 8 depicts the number of transmitted DIO messages for two critical nodes in the topology, nodes 4 and 5. These nodes are described as critical nodes because they are the only ones that the senders can use as relay nodes to reach the root node. As shown in Figure 8, TAOF achieves the smallest number of transmitted DIO messages, meaning that the converged network tends to be more stable.

What we actually want to achieve with our proposal is to guarantee load balancing for the critical nodes and, thus, to maximize the lifetime of the network. For this reason, we studied the energy consumption of critical nodes, in particular nodes 4 and 5 (Figure 9). Although the average energy consumption is equivalent to the alternatives, and in several cases the energy consumption of node 5 exceeds the other two choices, the difference in energy consumption between nodes 4 and 5 is the least among the three choices. This means that the network tends to have a longer lifetime because every node shares approximately the same traffic amount, so there will be no premature energy exhaustion in any of the nodes.

VI. CONCLUSIONS

The IoT is a promising field with numerous applications but with critical design constraints. This work addresses the issue of creating routing topologies that promote energy efficiency and network reliability by considering traffic load balancing.

The basis of this work is RPL, the most popular routing protocol for LLNs. More specifically, in our work, we modified the parent selection mechanism, since this is the most relevant issue in RPL that affects network performance. The design of our proposal is motivated by the need to avoid creating an unbalanced network, in terms of traffic load, which in turn leads to premature energy exhaustion of overloaded nodes. The proposed solution is to avoid choosing overloaded nodes during the parent selection process and detach children from the overloaded node. As part of the solution, we also introduced a new metric, named packet transmission rate and a new parent selection algorithm, without imposing additional control traffic overhead.

The simulation results, comparing TAOF against MRHOF and LB-OF, show that TAOF achieves higher reliability than other choices under the same network conditions. Moreover, it achieves better PDR while sending fewer DIO messages, which indicates that TAOF builds more stable networks and this is corroborated by the comparison of the number of parent changes under different link quality values.

The future steps of our work include extending the metric information and parent selection process to handle networks consisting of heterogeneous nodes.

REFERENCES

[1] K. Kritsis, G. Z. Papadopoulos, A. Gallais, P. Chatzimisios and F. Theoleyre, "A Tutorial on Performance Evaluation and Validation Methodology for Low-Power and Lossy Networks", *IEEE Communications Survey & Tutorials*, vol 20, pp. 1799-1825, 2018.

[2] Georgios Z. Papadopoulos, Antoine Gallais, Guillaume Schreiner, Emery Jou and Thomas Noel, "Thorough IoT testbed Characterization: from Proof-of-concept to Repeatable Experimentations", *Elsevier Computer Networks*, vol 119, pp. 86-101, 2017.

[3] Georgios Z. Papadopoulos, Antoine Gallais, Guillaume Schreiner and Thomas Noel, "Importance of Repeatable Setups for Reproducible Experimental Results in IoT", *Proceedings of the 13th ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN)*, 2016.

[4] E. K. Pister, E. P. Thubert, S. Dwars and T. Phinney, "Industrial Routing Requirements in Low-Power and Lossy Networks", *Internet Engineering Task Force (IETF)*, Fremont, CA, USA, RFC 5673, Oct. 2009.

[5] T. Winter, P. Thubert, A. Brandt, J. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, JP. Vasseur and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", *Internet Engineering Task Force (IETF)*, RFC 6550, 2012.

[6] H. Kim, J. Ko, D. E. Culler, J. Paek, "Challenging the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL): A Survey", *IEEE Communications Survey & Tutorials*, Vol 19, 2017.

[7] "802.15.4-2011 - IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)", IEEE Computer Society, Sep. 2011.

[8] O. Gaddour, A. Kouba, N. Baccour, M. Abid, "OF-FL: QoS-Aware Fuzzy Logic Objective Function for the RPL Routing Protocol", *12th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, 2014.

[9] M. Mamdouh, K. Elsayed, A. Khattab, "RPL Load Balancing via Minimum Degree Spanning Tree", *9th IEEE International Workshop on Selected Topics in Mobile and Wireless Computing*, 2016.

[10] M. Zhao, P. H. J. Chong, H. C. B. Chan, "An energy-efficient and cluster-parent based RPL with power-level refinement for low-power and lossy networks", *Computer Communications*, vol 104, pp. 17-33, 2017

[11] W. Tang, X. Ma, J. Huang, J. Wei, "Toward Improved RPL: A Congestion Avoidance Multipath Routing Protocol with Time Factor for Wireless Sensor Networks", *Journal of Sensors*, vol 2016.

[12] H. S. Kim, S. Bahk, J. Paek, D. E. Culler, "Do Not Lose Bandwidth: Adaptive Transmission Power and Multihop Topology Control", *13th International Conference on Distributed Computing in Sensor Systems*, 2017.

[13] H. S. Kim, H. Kim, J. Paek, S. Bahk, "Load Balancing Under Heavy Traffic in RPL Routing Protocol for Low Power and Lossy Networks", *IEEE Trans. on Mobile Computing*, vol. 16, no. 4, pp. 964-979, 2017.

[14] T. B. Oliveira, P. H. Gomes, D. G. Gomes, B. Krishnamachari, "ALABAMO: A LoAd BAlancing MOdel for RPL", *Brazilian Symposium on Computer Networks and Distributed Systems (SBRC)*, 2016.

[15] W. Zhang, G. Han, Y. Feng, J. Lloret, "IRPL: An energy efficient routing protocol for wireless sensor networks", *Journal of Systems Architecture*, vol 75, pp. 35-49, 2017.

[16] Z. Wang, L. Zhang, Z. Zheng, J. Wang, "An Optimized RPL Protocol for wireless Sensor Networks", *IEEE 22nd International Conference on Parallel and Distributed Systems*, 2016.

[17] M. Qasem, A. Al-Dubai, I. Romdhani, B. Ghaleb, W. Gharibi, "A New Efficient Objective Function for Routing in Internet of Things Paradigm", *IEEE Conference on Standards for Communications and Networking (CSCN)*, 2016.

[18] P. Thubert, "Objective function zero for the routing protocol for low-power and lossy networks (RPL)", *Internet Engineering Task Force (IETF)*, Fremont, CA, USA, RFC 6552, Mar. 2012.

[19] O. Gnawali and P. Levis, "The minimum rank with hysteresis objective function", *Internet Engineering Task Force (IETF)*, Fremont, CA, USA, RFC 6719, Sep. 2012.