Alayed, W., Mackenzie, L. and Pezaros, D. (2018) Evaluation of RPL's Single Metric Objective Functions. In: 10th IEEE International Conference on Internet of Things (iThings-2017), Exeter, England, UK, 21-23 June 2017, pp. 619-624. ISBN 9781538630662 (doi:10.1109/iThings-GreenCom-CPSCom-SmartData.2017.98)

Evaluation of RPL's Single Metric Objective Functions

Walaa Alayed*†, Lewis Mackenzie* and Dimitrios Pezaros*
*School of Computing Science
University of Glasgow, Glasgow, UK
Email: w.alayed.1@research.gla.ac.uk, lewis.mackenzie@glasgow.ac.uk; dimitrios.pezaros@glasgow.ac.uk
†Princess Nourah bint Abdulrahman University, Riyadh, KSA
Email: wmalayed@pnu.edu.sa

***Abstract*—In this paper, we evaluate the performance of RPL (IPv6 Routing Protocol for Low Power and Lossy Networks) based on the Objective Function being used to construct the Destination Oriented Directed Acyclic Graph (DODAG). Using the Cooja simulator, we compared Objective Function Zero (OF0) with the Minimum Rank with Hysteresis Objective Function (MRHOF) in terms of average power consumption, packet loss ratio, and average end-to-end latency. Our study shows that RPL performs better in terms of packet loss ratio and average end-to-end latency when MRHOF is used as an objective function. However, the average power consumption is noticeably higher compared to OF0.**

***Index Terms*—LLN, IPV6 Routing, RPL, Objective Function, OF0, MRHOF, Routing Metric.**

I. INTRODUCTION

Wireless Sensor Networks (WSN) where hundreds or thousands of ad-hoc devices are connected together [1], play an important role in the implementation of the Internet of Things (IoT). However, for IoT to become a reality, WSNs must be able to work seamlessly with the Internet Protocol (IP) to make devices addressable and reachable from any location. Trying to run existing Internet technologies and protocols on devices that are designed for low cost and low power consumption can be quite challenging due to limited power, memory, and processing resources [2].

Early research in WSNs was based on a view that new challenges need new solutions; hence, at that time, TCP/IP was considered inappropriate [3]. However, to achieve Internet connectivity on WSNs, the TCP/IP suite must be used either through a gateway, bridge or router, or directly on a node level. Yet, years of research focusing on transport and routing protocols for WSNs took the position that IP was not ideal due to the limited node resources and the large header overhead [3].

However, it has now become clear that using IP to connect WSNs on a node level is beneficial. First, compatibility with other devices and networks assures connectivity regardless of the protocols used at the lower layers. Second, application development is simplified because existing development tools for commissioning, managing and debugging can be used or adapted [4].

Typically, WSN nodes communicate at a data rate of 250 kbps or less on IEEE 802.15.4 networks. Therefore, protocol overhead must be kept to a minimum by transmitting only needed information. Broadcasts, too, must be minimised if not avoided altogether in such networks [3]. Some overhead is inevitable in IPv6 where header size alone is 40 bytes because destination and source addresses occupy 128 bits each. The Internet Engineering Task Force (IETF) 6LoWPAN-working group has been working to integrate IPv6 into such networks by focusing on the IPv6 address-ability and routing.

The 6LoWPAN [5], [6] adaption layer was introduced to overcome the limitation of running IPv6, which requires a 1280 bytes Maximum Transmission Unit (MTU) over more restrictive 127 bytes MTU in the IEEE 802.15.4 environment. It works above the MAC layer and enables full IPv6 functionality over low-power wireless personal networks (LoWPAN) (i.e., IEEE 802.15.4) providing header compression to reduce the IP header to only a few bytes by avoiding information redundancy [7]. A header compression mechanism such as 6LoWPAN can be used to solve this problem.

The rest of the paper is organised as follows. Section II gives an overview of RPL protocol and its main terminologies. In section III a brief overview of existing Objective Functions is given. Our simulation work and results are shown in section IV. Finally, the paper is concluded in section V.

II. PROTOCOL OVERVIEW

The IPv6 Routing Protocol for Low Power and Lossy Networks (RPL) RFC 6550 [8] was designed by the Internet Engineering Task Force (IETF) ROLL working group specifically for Low power and Lossy Networks (LLN) and is compatible with the 6LoWPAN protocol. It is a proactive distance vector tree based routing protocol that relies on sending periodic control messages.

RPL is based on a directed acyclic graph (DAG) topology concept that is a tree-like structure, except that in DAGs, a node can have multiple parents whereas in trees that is not the case. All traffic is routed to a single node known as the DODAG root to form what is called a Destination Oriented Directed Acyclic Graph (DODAG) where no cycles are present [8].

There are three types of nodes within the DODAG as shown in Figure 1: first, the *DODAG root* is considered as a sink and a gateway to other networks, and also has the ability to

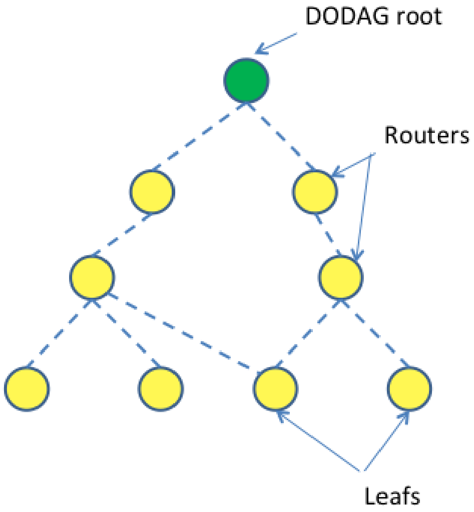

Fig. 1. RPL Destination Oriented Directed Acyclic Graph (DODAG)

construct a DAG; second, the *routers* which collect, generate and forward traffic but do not have the ability to construct a DAG; and third, the *leafs* or end nodes which only have the ability to join an existing DAG and generate data traffic but are unable to forward traffic on behalf of other nodes.

RPL supports three traffic patterns:

1) **Multi-Point to Point (MP2P)** is the most common traffic pattern in WSNs. It is a form of data collection or upward route where data are sent from multiple nodes towards DODAG root.
2) **Point to Multi-Point (P2MP)**, pattern where traffic is sent in a downward route from the DODAG root towards multiple nodes.
3) **Point-to-Point (P2P)**, pattern where traffic is forwarded between two nodes.

During the DODAG construction, each node selects a set of parents on its path towards the DODAG root where one or more are considered preferred parents. A preferred parent is selected based on an Objective Function (OF) that defines routing metrics or constraints that are translated into ranks used to construct the DODAG. This determines the node desirability to be a next hop on the route towards the DODAG root. In other words, a node's rank is a node's position relative to other nodes with respect to the DODAG root. The rank increases as the node moves away from the root and vice versa. The rank is then used to avoid and detect loops.

The RPL specification defines three types of control messages.

1) **A DODAG Information Object (DIO)** carries information that allows nodes to discover a RPL Instance and its configuration parameters, select a DODAG parent set and maintain the DODAG.
2) **A Destination Advertisement Object (DAO)** enables the support of downward routes which is optional in RPL by propagating destination information upwards within the DODAG. Optionally, upon explicit request or error, the DAO message can be acknowledged (DAO-ACK) from the destination back to the DAO's sender.
3) **A DODAG Information Solicitation (DIS)** enables nodes to request a DIO message from a reachable neighbour.

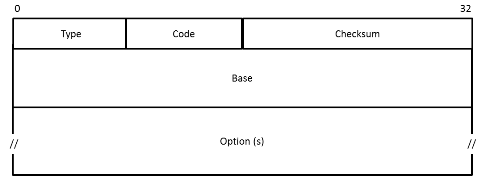

Fig. 2. RPL control message

All RPL control messages use ICMPv6 information messages with a type number of 155. Figure 2 illustrates the general RPL control message format.

A DODAG is constructed by configuring some nodes to be DODAG roots. Nodes advertise their presence by sending link-local multicast DIO messages to all RPL nodes. Nodes also listen for DIO messages and based on the rank of their neighbours they decide to join DODAG. Each node that decides to join will provide a routing table with entries having one or more DODAG parents as the next hop default route, as well as having other routes.

To maintain the DODAG, nodes generate a DIO message periodically based on a Trickle timer. The Trickle timer algorithm adapts the sending rate of DIO messages within DODAG. If the network is stable, sending DIO messages at a high rate is considered a waste of resources. Therefore, the Trickle algorithm in such a case will adapt the sending rate to send DIO messages less often by doubling the sending interval. On the other hand, if the topology is inconsistent, based on the trickle algorithm, the DIO messages send rate must be higher and so the sending interval is reset.

III. LITERATURE REVIEW

A. RPL evaluation

A performance evaluation of RPL compared to AODV and DYMO was done in [9]. The results show that RPL outperforms AODV and DYMO when it comes to average delay and network establishment. However, according to the study, RPL has higher routing overhead compared to the other two protocols.

In [10], the authors simulated an RPL model in Cooja to evaluate the performance of the routing protocol. They built a WSN in 600m x 600m space with one DAG root and a number of identical Tmote Sky nodes. They tested the protocol in both regular and random topologies. They also considered two locations for the DAG root, first at the border and then in the middle of the DODAG. They discussed the impact of: the number of nodes on the average power consumption, average hop distance, convergence time, and routing table size; the Objective Function on the average number of hops and average

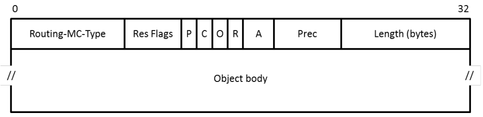

Fig. 3. Routing metric/constraint object generic format [12]

node energy; the number of DAGs on the convergence time, average node energy, and average hop count; the number of control packets on DAG roots, routers and leafs; Finally, the network size and density on the packet loss ratio.

They concluded that placing the DAG root in the middle of the DODAG would result in decreasing the hop distance and hence the convergence time. They noted that increasing the number of DAG roots forming multiple DODAGs will improve the overall network performance. Finally, regarding packet loss, their simulations show that sparse networks are exposed to high packet loss due to nodes not having alternative parents for immediate repair.

B. Objective Functions in RPL

RPL is a constraint-based routing protocol where nodes or links are either included or excluded based on certain criteria [11]. Whereas metrics are quantitative values that help find the preferred path. A routing metric or constraint can be either additive or multiplicative.

According to [12], RPL defines 8 routing metrics and constraints which are associated with either nodes or links as follows. The first three apply to nodes.

- *Node State and Attribute* (NSA) is used to provide information on node characteristics.
- *Node Energy* (NE) is used to provide information related to node energy.
- *Hop Count* (HP) is used to report the number of traversed nodes along the path.

The remaining metrics/constraints apply to links.

- *Throughput* is a result of trading power consumption for bit rate. Therefore, nodes report the range of throughput that their links can handle.
- *Latency* is used to report the link's latency.
- *Link Reliability* which can be measured by either or both of the following:
  - *The Link Quality Level* (LQL) is used to quantify the link reliability using a discrete value from 0 to 7.
  - The *Expected Transmission Count* (ETX) is the number of transmissions a node expects to make to a destination in order to successfully deliver a packet.
  - *Link Colour* (LC) is a 10-bit link constraint used to specify links for certain traffic types.

These metrics/constraints are carried in the DIO message optional field by using the DAG Metric Object Container object as shown in Figure 3. The flags are setup to indicate if the object is a metric or a constraint, whether it is additive or not, and if it is local or global.

As mentioned earlier, RPL uses external algorithms for certain functions. For instance, an Objective Function (OF) is used to calculate routing metrics to assign nodes' ranks that play an important role in the DODAG construction. The potential parents for a node are the nodes with the minimum rank from the node's set of parents. By default, RPL uses OF0 [13] as an OF where ranks assignment is based on the hop count metric. Another OF is (ETXOF) which is based on the ETX required to successfully transmit and acknowledge a packet on the link [14]. Comparing both objective functions, the authors in [10] observed that OF0 allows for lower power consumption and lower hop distance compared to ETXOF.

The Minimum Rank with Hysteresis Objective Function (MRHOF) [15] is an OF which also was implemented with a single route metric that can be either link ETX, node remaining energy or delay link metric. MRHOF selects routes that minimise a metric, while using *hysteresis* to reduce churn in response to small metric changes. Hysteresis works as follows: when a new minimum cost path is found, a switch to that path occurs only if it is better than the current path by at least a given threshold. Path cost is computed by adding components, so only additive routing metrics can be supported.

Previous objective functions did not support QoS. For this reason, an Objective Function based on Fuzzy Logic (OF-FL) is proposed in [11]. It specifies a holistic routing metric that effectively combines individual metrics to allow combinations between metrics that are different in nature. It takes into account 4 routing metrics: end-to-end delay, hop count, ETX link quality, and node energy.

In [16], the authors tested both OF0 and the Link Quality Level Objective Function(LLQ OF). LLQ OF is based on the link quality metric, indicated by Received Signal Strength Indicator (RSSI) depending on the distance between communicating nodes. They concluded that OFs determine the network stability as well as the average number of hop count and child nodes connected to each router, characterising the RPL overall structure. Hence using OF0, which tries to minimise the hop count in a battery-powered network can lead to fast energy drain at the nodes closest to the root.

In [17], the authors proposed formulas to quantify primary routing metrics. Furthermore, they investigated combining primary metrics in a lexical or additive manner. A lexical composite routing metric leads to strict performance metric prioritisation, which can be used to ensure application requirements while other performance aspects can be optimised to a certain extent. On the other hand, an additive composite routing metric offers a flexible way of combing metrics based on the metric weight pair.

IV. THE SIMULATION SCENARIO

First, we built a network model using Cooja [18] as a simulation tool assuming it will be installed in a home or an office area of approximately 150x150 m^2. The network is constructed using wireless sensor Tmote Sky nodes. The number of nodes will vary from a small to a medium size network. We started with a small network that is made of

TABLE I
RPL OBJECTIVE FUNCTIONS

OF0	Single metric	By default RPL uses OF0 [13] as an OF where the potential parents for a node are the nodes with the minimum rank from the nodes' parent set based on hop count.
MRHOF	Single metric	The Minimum Rank with Hysteresis Objective Function (MRHOF) [15] is an OF which was also implemented with a single route metric that can be either link ETX, node remaining energy or delay link metric.
LLQ OF	Single metric	LLQ OF [16] is based on the link quality metric, indicated by Received Signal Strength Indicator (RSSI) depending on the distance between communicating nodes.
OF-FL	Multi metric	Objective Function based on Fuzzy Logic (OF-FL) [11] specifies a holistic routing metric that effectively combines individual metrics to allow combination between metrics that are different in nature. It takes into account 4 routing metrics, which are: End-to-End delay, Hop count, ETX link quality and Node energy.

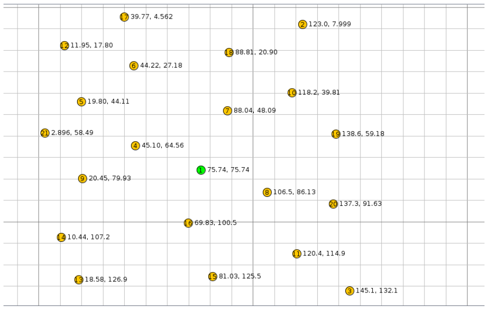

Fig. 4. Simulation Setup 21 nodes

11 randomly positioned nodes, where the DODAG root is positioned almost in the centre. We gradually increase the network size by adding 5 extra random positioned nodes till we reached a medium size network with 46 nodes. Figure 4 shows the simulation setup for 21 nodes. The nodes in this case are assumed to be static wireless sensor motes with $50m$ transmission range and generate packets randomly in an average interval of 1 $packet/min$. We ran the simulation for one hour of simulation time, details are shown in Table II. Over this network setup, for different objective functions, the performance of the RPL protocol is tested in terms of average power consumption, packet loss ratio, and average end-to-end latency.

A. DODAG construction

Figure 5 shows the impact that objective functions have on the DODAG construction. In a special case where the DODAG is constructed of 21 nodes physically positioned as shown in Figure 4, each objective function generates a different graph. Figure 5.(a) shows the DODAG construction when MRHOF-ETX is used and Figure 5.(b) when OF0 is used.

TABLE II
SIMULATION SETUP

Network area	150x150 m^2
Wireless Sensors type	Tmote Sky
Number of nodes	11 → 46 incrementing 5 nodes in each scenario
Transmission range	50 m
Interference range	100 m
Radio environment	Undirected Graph Radio Medium (UGRM)
Wireless	IEEE 802.15.4
Medium Access Control (MAC)	CSMA with 4 Maximum transmissions
Packet size	128 bytes
Number of DAGs	1
Objective Function	MRHOF-ETX, OF0
Transmission rate	Randomly on average 1 packet/min
Simulation time	1 hour

B. Performance Metrics

The performance metrics we measure are as follows:

- **Average power consumption** is the ratio of the total power consumed by each node to the number of nodes.
- **Packet loss ratio** is the ratio of the total lost packets from all nodes to the total number of sent packets. A packet is considered lost if it fails to reach its destination
- **Average end-to-end latency** is the ratio of the total packet end-to-end latency to the number of received packets. The packet end-to-end latency is defined as the time from when a node sends the packet till it reaches its destination.

C. Results

Compared to previous studies, here we are trying to evaluate the network-wide performance rather than focusing on the individual node level. To make sure the results are reliable, we run the simulation 30 times and results are extracted based on an average of these runs; error bars are calculated by using the Standard Error of the Mean (SEM).

1) Average Power consumption: In Figure 6, when the network is quite small, (11 nodes) the average power consumption is almost identical for both Objective Functions, however, as the number of nodes increases it is noted that MRHOF-ETX is consuming considerably more power on average compared to OF0. As MRHOF-ETX average power consumption continues to increase, OF0 reaches a steady average power consumption level of around 70 mW at 26 nodes and onwards. The high level of average power consumption in MRHOF-ETX is due to the extra calculations and comparisons required by the MRH algorithm so that more processing is being carried out at each node.

2) Packet Loss Ratio (PLR): Figure 7 shows almost a linear PLR increase as the number of nodes in the DODAG increases. The PLR is slightly higher in OF0 compared to

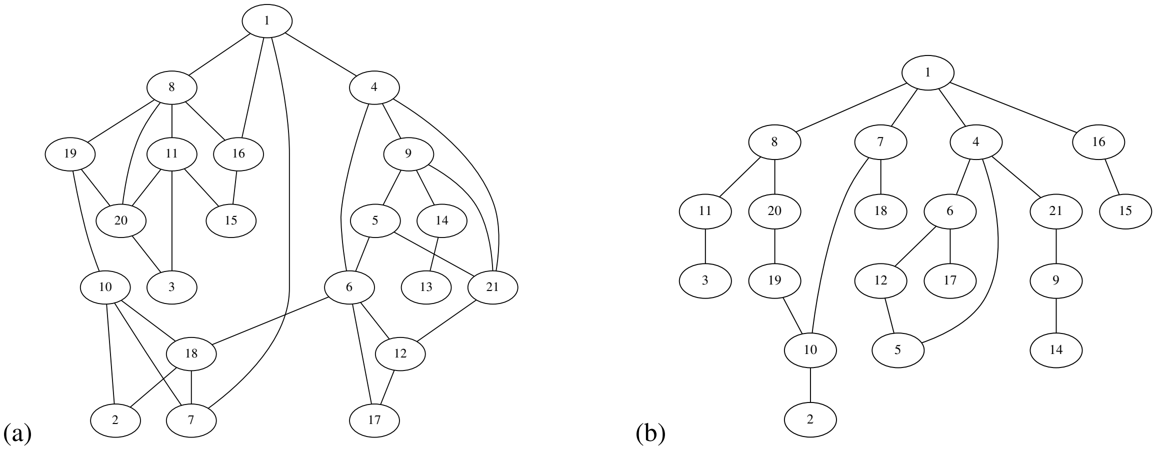

Fig. 5. RPL DODAG construction for different objective functions (a) MRHOF-ETX, (b) OF0

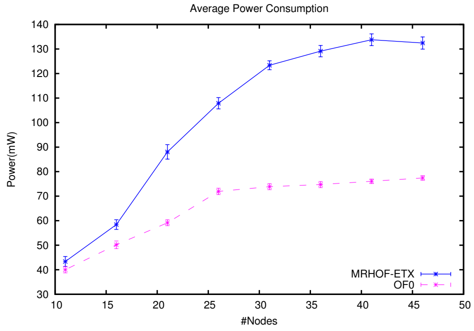

Fig. 6. Average power consumption

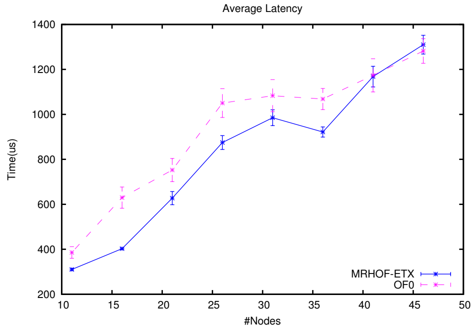

Fig. 8. Average end-to-end latency

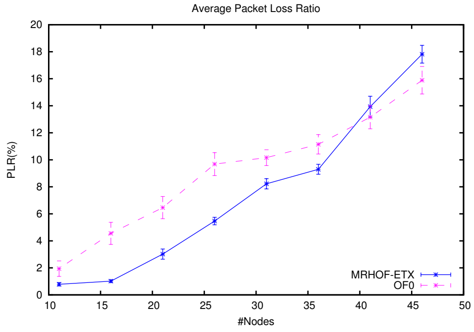

Fig. 7. Packet Loss Ratio (PLR)

MRHOF-ETX because in the metric the latter uses to build the DODAG routes, ETX improves packets delivery. However, as the DODAG starts to get a little denser, at around 41 nodes and onwards, MRHOF-ETX seems to be out performed by OF0. In a dense DODAG, the chance of packet collision is much higher leading to more CSMA retransmissions and hence drops.

3) Average end-to-end latency: In Figure 8, overall MRHOF-ETX outperforms OF0 in terms of average end-to-end latency due to link quality because of the routing metric being used in building the DODAG. However, at around a 36-node DODAG size, the average end-to-end latency of both OFs starts to increase sharply.

Average end-to-end latency is affected by many factors including nodes' distance, buffering time and retransmission time. For DODAG's smaller than 36 nodes the main cause of the average end-to-end latency is the nodes distance and buffering time. As the DODAG starts to get denser after 36 nodes, packet retransmission has a significant impact on the network traffic and therefore the overall latency.

V. CONCLUSION

In this paper, we evaluated the impact of Objective Functions on the network-wide performance of RPL in terms of average power consumption, packet loss ratio, and average end-to-end latency.

We have found that RPL performance using MRHOF-ETX is better in terms of packet loss ratio and average end-to-end latency compared to OF0. However, the opposite is the case for the average power consumption, where it is noticeable that OF0 consumes less power on average and is not affected by the network size compared to MRHOF-ETX where the power consumption increases with the number of nodes.

In general, single metric objective functions perform well against one measure but poorly in others. We next plan to examine whether multi-metric objective functions can successfully combine the best features of several single-metric components.

ACKNOWLEDGMENT

The work has been supported in part by the UK Engineering and Physical Sciences Research Council (EPSRC) projects EP/L026015/1, EP/N033957/1, and EP/P004024/1, and by the European Cooperation in Science and Technology (COST) Action CA 15127: RECODIS – Resilient communication services protecting end-user applications from disaster-based failures.

REFERENCES

[1] Luís M. L. Oliveira, Amaro F. de Sousa, and Joel J. P. C. Rodrigues. Routing and mobility approaches in IPv6 over LoWPAN mesh networks. *Int. J. Commun. Syst.*, 24(11):1445–1466, nov 2011.

[2] Isam Ishaq, David Carels, Girum Teklemariam, Jeroen Hoebeke, Floris Abeele, Eli Poorter, Ingrid Moerman, and Piet Demeester. IETF Standardization in the Field of the Internet of Things (IoT): A Survey. *J. Sens. Actuator Networks*, 2(2):235–287, apr 2013.

[3] Joel J. P. C. Rodrigues and Paulo A. C. S. Neves. A survey on IP-based wireless sensor network solutions. *Int. J. Commun. Syst.*, pages n/a–n/a, 2010.

[4] Luís M. L. Oliveira, Joel J. P. C. Rodrigues, André G. F. Elias, and Guangjie Han. Wireless Sensor Networks in IPv4/IPv6 Transition Scenarios. *Wirel. Pers. Commun.*, 78(4):1849–1862, sep 2014.

[5] N(Intel Corp) Kushalnagar, G (Microsoft Corporation) Montenegro, and C(Danfoss A/S) Schumacher. RFC4919: IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals, 2007.

[6] G (Microsoft Corporation) Montenegro, N(Intel Corp) Kushalnagar, J(Arch Rock Corp) Hui, and D(Arch Rock Corp) Culler. RFC 4944: Transmission of IPv6 Packets over IEEE 802.15.4 Networks, 2007.

[7] Jean-Philippe Vasseur and Adam Dunkels. *Interconnecting Smart Objects with IP*. Elsevier, 2010.

[8] Budi Soediono. RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks. *Internet Eng. Task Force Req. Comments 6550*, pages 1–157, 2012.

[9] Haofei Xie, Guoqi Zhang, Delong Su, Ping Wang, and Feng Zeng. Performance evaluation of RPL routing protocol in 6lowpan. In *2014 IEEE 5th Int. Conf. Softw. Eng. Serv. Sci.*, pages 625–628. IEEE, jun 2014.

[10] Olfa Gaddour, Anis Koubaa, Shafique Chaudhry, Miled Tezeghdanti, Rihab Chaari, and Mohamed Abid. Simulation and performance evaluation of DAG construction with RPL. In *Third Int. Conf. Commun. Netw.*, pages 1–8. IEEE, mar 2012.

[11] Olfa Gaddour, Anis Koubâa, and Mohamed Abid. Quality-of-service aware routing for static and mobile IPv6-based low-power and lossy sensor networks using RPL. *Ad Hoc Networks*, 33:233–256, oct 2015.

[12] Ed. JP. Vasseur, Ed. M. Kim, K. Pister, N. Dejean, and D. Barthel. Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks. *Internet Eng. Task Force Req. Comments 6551*, 2012.

[13] Pascal Thubert. Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL). *Req. Comments 6552*, 2012.

[14] Omprakash Gnawali and P Levis. The ETX Objective Function for RPL. *draft-gnawali-roll-etxof-01*, 2010.

[15] Omprakash Gnawali. The Minimum Rank with Hysteresis Objective Function. *Req. Comments 6719*, 2012.

[16] Agnieszka Brachman. RPL objective function impact on LLNs topology and performance. In *Internet Things, Smart Spaces, Next Gener. Netw.*, volume 8121 LNCS, pages 340–351. Springer-Verlag, 2013.

[17] Panagiotis Karkazis, Helen C. Leligou, Lambros Sarakis, Theodore Zahariadis, Panagiotis Trakadas, Terpsichori H. Velivassaki, and Christos Capsalis. Design of primary and composite routing metrics for RPL-compliant Wireless Sensor Networks. In *2012 Int. Conf. Telecommun. Multimed.*, pages 13–18. IEEE, jul 2012.

[18] InstantContiki. The Cooja Network Simulator. http://www.contiki-os.org/index.html, 2015.