Master's Thesis

Towards Efficient Load Balancing Strategy for RPL Routing Protocol in IoT Networks

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ABSTRACT

Towards Efficient Load Balancing Strategy for RPL Routing Protocol in IoT Networks

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The IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) has been considered as the new standard routing protocol designed to meet the requirements of wide range of Low Power and Lossy Networks (LLNs) applications including industrial and environment monitoring, smart grid, and wireless sensor networks. However, due to the uneven deployment of sensor nodes in large-scale networks and the heterogeneous traffic patterns, some sensor nodes have much heavier workload than others. The lack of load balancing mechanism results in these sensor nodes quickly exhausting their energy, therefore shorten the network lifetime of battery-powered wireless sensor networks. To overcome this problem, we propose a skewness and load balancing routing protocol based on the RPL protocol, named SB-RPL that exploits various routing metrics including link quality and skewness among subtrees of the network in support topology construction. In this work, we first investigate the load balancing and related issues of RPL both via numerical simulations and via actual large-scale testbed. Performance analysis results show that RPL trees suffer from severe skewness regardless of routing metrics in both random generated networks. Through extensive computer simulations and actual experiments, we demonstrate that SB-RPL significantly improves end-to-end packet delivery performance and tree balance compared to the standard RPL.

Keywords: Low Power and Lossy Networks (LLNs), RPL, Load Balancing, IEEE 802.15.4, IPv6, Internet of Things.

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Glossary

IoT	Internet of Things
LLN	Low Power and Lossy Networks
LPWN	Low Power Wireless Networks
6LoWPAN	IPv6 Low Power Wireless Personal Area Networks
IETF	Internet Engineering Task Force
ROLL	Routing Over Low-Power and Lossy Networks
RPL	Routing Protocol for Low Power and Lossy Networks
DODAG	Destination Oriented Directed Acyclic Graph
DIO	DODAG Information Object
DAO	DODAG Advertisement Object
DIS	DODAG Information Solicitation
AP	Access Point
VANET	Vehicular Ad-hoc Network
LBR	Low Power and Lossy network Border Router
ETX	Expected Transmission Count
RSSI	Received Signal Strength Indicator
IPv6	Internet Protocol Version 6
MAC	Medium Access Control
MRHOF	Minimum Rank Hysteresis Objective Function
SB-RPL	Skewness and Balancing RPL
UDP	User Datagram Protocol
OF0	Objective Function Zero
OS	Operating System
N	Number of sensor nodes
L	The set of all wireless links

S	Sink (Root)
$R_n(t)$	Rank value of node n at timeslot t
$c_{n,p}(t)$	Logical link-layer channel capacity between node n and node p
$c_{n,p}^{max}$	Maximum channel capacity value
$l_{n,p}(t)$	Link characteristic between node n and node p
$P_n(t)$	Node p is in preferred parent list of node n
RT^S	Routing subtree
N^S	Set of sensor nodes in a subtree
L^S	Set of direct links in a subtree
$ST_p(t)$	Subtree size of node p at timeslot t
$ST_p^{max}\ (t)$	Maximum subtree size of node p at timeslot t
$ST_p^{min}\ (t)$	Minimum subtree size of node p at timeslot t
$ST_p^{avr}\ (t)$	Average subtree size of node p at timeslot t
$NI_{n,p}(t)$	Node Influence of potential parent p to the new joining node n at timeslot t
$NB_n(t)$	Set of neighbors that node n can communicate during timeslot t
$PRR_{n,p}(t)$	Packet Reception Ratio between node n and node p
σ	Parent switch threshold
M1	Skewness metric 1
M2	Skewness metric 2
M3	Skewness metric 3
M4	Skewness metric 4

CHAPTER I: INTRODUCTION

1.1. Overview

Internet of Things (IoT) technology is heterogeneously applied to several environments: buildings, automotive, manufacturing, cites and so on, with the potential to make them more connected, profitable and efficient. With great progress and development made in information and communication technology, Internet of Things (IoT) and Machine-to-Machine (M2M) [1] have merged to provide ubiquitous communication of smart embedded devices, so that retrieving real-time information can become possible [2] [3]. Due to the great potential brought by M2M and IoT communication, they are being considered as the evolutionary change in the field of wireless communications. A potential large number of nodes is able to establish low-power short-range wireless links, thus forming a capillary network infrastructure that can be connected to the global Internet [4]. A new class of multi-hop wireless sensor network has emerged that is generally characterized by a resource constrained failure-prone architecture and subsequently has given rise to new challenges to provide robustness and resilience [5], [6]. These types of WSN are used in natural disaster monitoring, surveillance and industrial management where a certain reliability should be guaranteed while providing robustness in the presence of harsh surroundings [5]–[10]. The analysis of the different application scenarios has demonstrated that the routing protocol for LLNs should be able to cope with resource-constraint, quality of service and scalability issues. Several routing protocols have been introduced to figure out these issues such as AODV [11], Collection Tree Protocol [12], and LOAD [13]. In order to achieve reliable and energy efficient data collection, the Internet Engineering Task Force (IETF) has proposed RPL [7] as an IoT routing standard for

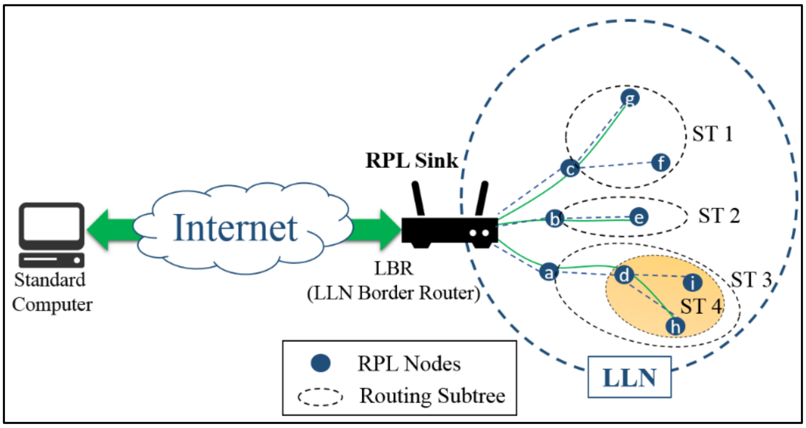


Figure 1.1: **An example of Multi-hop LLN**. The LLN is connected to Wide Area Network (WAN) which might be public global Internet via LBR (LLN Border Router). In this example, the LLN includes one sink (DODAG root), 10 source nodes, and several subtrees namely ST1 ($ST_{(c)}$), ST2 ($ST_{(b)}$), ST3 ($ST_{(a)}$), ST4 ($ST_{(d)}$) and so on.

IPv6 Low-Power and Lossy Networks (LLNs). RPL is an oriented distance vector routing protocol that allows users to establish logical routing topology known as a Destination-Oriented Directed Acyclic Graph (DODAG) structure, meaning that each node may have one or more than one parent towards the sink. RPL is designed to meet the different requirements of 6LoWPANs, it guarantees a fast network establishment which allows the efficient monitoring of critical applications. RPL is one of the most promising routing solution for a wide range of network types as well as industrial applications such as Smart Gird [14], Building Automation [15], Home Automation [16], and Advanced Metering Infrastructure (AMI) [17].

1.2. Motivation

Recently, RPL provisions several robust features such as self-healing, loop-free network, and exiguous delay. However, the load balancing has been considered as a weakness in the RPL standard. The routing protocol for LLNs should be lightweight, specifically in LLNs in which nodes are equipped with highly resource-constraints and featured short range communication abilities. Thus, high protocol overhead associated with path maintenance and discovery might drain resources quickly and interfere with data transmission. On the one hand, depending on the specific requirements, different routing metrics and constraints [18] can be adopted such as hop-count [19], latency, energy consumption or expected transmission count (ETX) [20]. Routing path construction relying solely on a single pairwise transmission quality metric may not be able to capture the real communication scenarios. The sizes of the networks necessitate the need to communicate over multiple hops requiring higher layer protocol support. Reliable and efficient of communications in large LLNs has yet to be sufficiently addressed [4]. Potential future applications will inevitably require the need to communicate beyond the range of sinks and require larger networks than that are supported recently. The fact that large-scale LLNs are not common is likely due to lack of support from current protocols and approaches, so motivating our research. On the other hand, LLNs are resource-constraint networks, it is a requirement of RPL to be energy efficiency. So that, RPL needs to balance not only the traffic load but also the number of connections of each node to provide fair energy consuming among nodes. RPL is designed for LLNs and performs routing in a distributed way, however the load balancing feature is missing in RPL. Without load balancing the data traffic and the distribution of wireless sensor nodes in LLNs may result in significant unbalance for those nodes that have more neighbor nodes than others. As mentioned above, in largescale networks, the nodes close to gateway often handle heavy traffic load even others generate lightly traffic load.

Thus, this results in gaps and holes in the whole network and causes the disconnected of network connection. It leads to RPL needs to address load imbalance problem.

1.3. Key Idea

The key idea of this study is that we investigate the constructing topology of RPL not only using casual metrics as standard RPL but also exploiting the skewness and balancing to apply the combination of metrics. We achieved the balance and the stability by taking into account the size of DODAG subtrees for selecting each parent candidate in the parent selection procedure. We defined a new specific metric representing for the influence of parent candidates to new joining nodes for routing procedure. In detail, a node willing to join DODAG should consider both the link quality with parent candidates and the influence of parent candidates to joining node, so the stability and balancing of routing path are guaranteed and reliable. The detail is described in Section IV.

1.4. Contribution

With the aforementioned motivations and ideas, we propose SB-RPL, standing for Skewness and Balancing of RPL Trees for IoT networks, a new extension of RPL that provides enhanced support for large scale network and incorporates the load balance mechanism into RPL. SB-RPL is able to effectively increase the end-to-end reliability as well as the network balance.

We implemented SB-RPL in ContikiOS [21] and conducted extensive numerical simulations using Contiki Cooja simulator and experiments using actual large-scale testbed FIT-IoT-Lab [22] with 100 nodes Arm-M3-Cortex [23]. In total, our evaluation based on around hundreds individual simulations and experiments, the duration is from one to two hour per experiment. Our evaluation shows that SB-RPL improves not only skewness and balancing of RPL trees but also reliability and end-to-end delay significantly comparison with existing RPL studies in both practical experiments and simulations.

The main contributions of this paper can be summarized as follows:

a) We proposed SB-RPL, the first work that investigates skewness and balancing and evaluate the performance in both Cooja simulation environment and practical largescale FIT-IoT-Lab platform of Lille, France. SB-RPL exploits the combination of multiple metrics and skewness for routing efficiency in RPL DODAG (Chapter IV).

b) SB-RPL uses extended control message structures based on the standard structure defined in the specification of RPL. This makes sure that our proposed scheme SB-RPL is interoperable with standard RPL, thus LLN devices using standard RPL or SB-RPL can operate together seamlessly in a hybrid environment (Chapter IV).

c) Our proposed scheme SB-RPL not only improves the skewness and balancing among subtrees in a DODAG but also supports adaptively and mobility of the network without requiring specific statically assumptions on the Objective Functions. This factor is convenient for implementation in the actual environment because Objective Functions in IoT applications can be widely dissimilar. On the other hand, there is no any constraint on the designs of Objective Functions in the specification of RPL, it keeps opening for new researches (Chapter V).

d) We implemented SB-RPL in ContikiOS which is an open source operating system for IoT and LLNs. Through extensive computer simulations using Contiki’s network simulator and real-world experiments on the FIT-IoT-LAB testbed, we proved that our proposed scheme significantly outperforms the existing methods in terms of reliability, adaptability to network balance of LLNs under various scenarios (Chapter V).

1.5. Thesis Organization

The remainder of our thesis is structured as follows: Chapter II provides background on IPv6 Routing Protocol for Low- Power and Lossy Networks (RPL) and prior works in this area. The network model of RPL is described in Chapter III. Our proposed scheme named SB-RPL is described in Chapter IV. In particular, we describe our SB-RPL protocol more specific. Chapter V presents results from the performance evaluation of SB-RPL and discusses issues that may have a significant impact on its behaviors. The detail of our evaluation method such as information of testbed, simulator, and skewness metrics are explained in detail. Finally, we conclude the paper in Chapter VI.

CHAPTER II: BACKGROUND AND LITERATURE REVIEW

In this section, we describe the RPL protocol and review earlier works on objective functions and load balancing problems in low-power wireless networks.

2.1. RPL Overview

In this section, the overview operation of the RPL protocol is briefly described following. RPL is distance vector routing protocol for Low-Power and Lossy Networks (LLNs), which constructs a logical topology called Destination Oriented Directed Acyclic Graph (DODAG) using an objective function and a set of routing metrics and constraints. The RPL objective functions are based on a combination of metrics and constraints to compute the best routing path. The graph built by RPL is a logical topology built on a physical topology to meet specific requirement. Each network can have multiple RPL routing topologies active at the same time. These topologies are used to handle traffic load with different metrics and constraints.

2.2. DODAG Construction

To build a DODAG, the root node first multicasts DODAG Information Object messages (DIO) which can be visualized as beacon messages. The DIO messages are transmitted through the Trickle Timer [47], [48] to achieve a balance between control overhead and fast recovery. The process of building the DODAG starts at the root node (sink) which is as data collection node in the network, and there could be multiple sinks in the network. Each node is positioned a rank representing its distance to the root using some cost functions. A DODAG is a directed graph wherein all edges are oriented in such a way so as to prevent cycles, the objective being to avoid routing

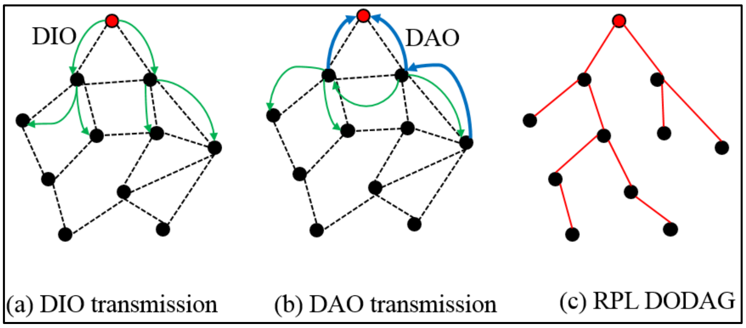


Figure 2.1: **RPL Overview**. (a) The sink broadcasts DIO messages to its neighbors to start building a DODAG. (b) In order to build downstream, the node multicasts DAO message towards the sink. (c) An example of RPL DODAG including 1 sink and 10 other nodes.

loops. Each DODAG is created according to the RPL specification is rooted at a sink node. Each node in the DODAG is associated with a rank value such that the rank of nodes along any path to the DODAG root should be monotonically decreasing. RPL specifies a set of new ICMPv6 control messages to exchange network information to construct DODAG using the DIO message. This DIO message conveys information about objective function identified by an Objective Code Point (OCP) which specifies the metrics used within the DODAG and the method for calculating DODAG rank; a DODAGID used to identify the DODAG as sourced from the DODAG root, related metrics and network information. Different objective functions are proposed in RPL such as Objective Function Zero (OF0) [19] and the Minimum Rank with Hysteresis Objective Function (MRHOF) [20] for the construction of DODAG. RPL strives to minimize the cost for reaching the root from any node in the LLNs using an objective function. Any router node in a DODAG that receives DIO messages and the nodes willing to join the DODAG adds the DIO transmitter to its own parent list, calculates its own rank based on objective function and then broadcasts the DIO messages with

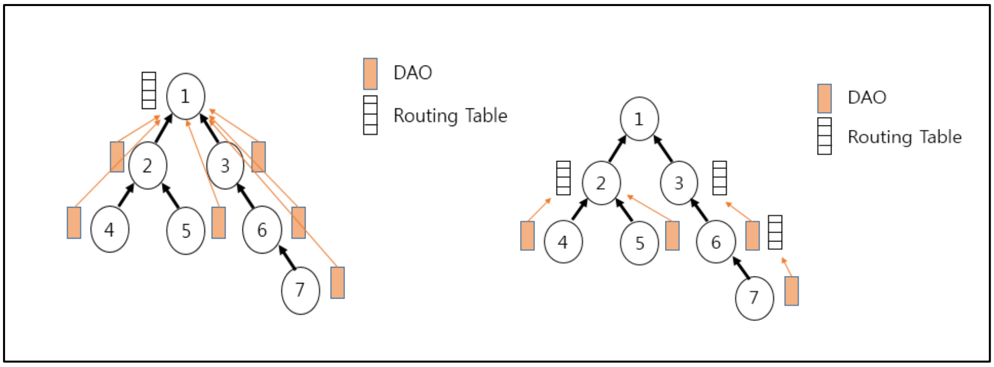


Figure 2.2: **RPL Operation modes**. Non-storing mode and storing mode.

the updated rank information. Neighbor node receiving the announcement will repeat this process. This process continues until it covers all the nodes. Each node of the DODAG has routing entry to its own preferred parent through which this node can read the root of the DODAG.

If a node does not receive DIO message from its neighbors until the timer expires, the node sends a multicast DIS (DODAG Information Solicitation) message to its neighboring nodes to solicit joining the DODAG. DIS message contains 8-bit unused for flags and reserved, with optional field that can be configured to be used by a developer. This message can be broadcasted to other nodes in the network which can in turn triggers DIO transmission from other nodes to the node that sent out the broadcast DIS. When a neighbor receives the DIS message, it resets the DIO timer to send the DIO messages. Since the DODAG is formed, each router node will able to forward upward data traffic to its parent as the next-hop node (Figure 2.1).

To support downstream traffic from the sink to router nodes, the router nodes use a control message named Destination Advertisement Object (DAO). The child nodes periodically unicast DAO messages to their respective parent node to maintain point-to-multipoint and point-to-point connectivity. After passing DAO message to all the paths from the router to the sink according to the upward paths indicated by the

DODAG and all the intermediate nodes record the reverse path information from the DAO message, a complete downstream path is established from the sink to the router nodes. In RFC 6550 [7], storing and non-storing modes are defined. In the non-storing mode, packets use source-routing for downstream traffic.

2.3. Trickle Timer

The RPL control messages are controlled by a trickle timer. Trickle timer allows nodes sharing the transmission medium with high probability of loss as the case of LLNs, exchanging data, energy efficiency and ensuring successful transmission. This trickle timer decreases the frequency of control messages transmissions while maintaining coherent information exchanging in the network. The key idea of a Trickle Timer is to send frequently more DIO messages when detecting inconsistency in a DODAG graph. As long as the RPL nodes receive consistent messages, the timer will increase exponentially its transmission interval until a predetermined minimum frequency. The "consistent" means that DIO messages from a sender with lower rank do not cause any change for parent list, preferred parent or the rank of nodes. If there is an event which changes the state of the network such as receiving a DIO message indicating a new DODAG Version number or RPL instance ID, routing loop detection, new parent or changing parental relationship, the Trickle Timer will be reset and the transmission interval is set to a predetermined minimum value.

The Trickle Timer has three configuration variables as following:

- The maximum size of the interval I_{max} which presents a doubling of the minimum interval size with $I_{max} = I_{min} * 2^{I_{doubling}}$, where $I_{doubling}$ is the value indicating how often the interval I can be doubled.
- The minimum size of the interval I_{min} which indicates the predefined value for sending DIO messages with $I_{min} = 2^{DIO\ IntervalMin}$, I_{min}

presents for the smallest interval between two consecutive DIOs.

- The redundancy constant K

2.4. RPL Operation Modes

In RPL specification, there are two main modes of operations namely storing mode and non-storing mode (Figure 2.2).

- Storing mode: In storing mode, each node keeps a complete list of routing entries for nodes in its sub-DODAG. When a node receives a packet, it forwards the packet to the next hop if the node finds the destination in the routing table. If the destination address is not in routing table, it forwards the packet to the its preferred parent.
- Non-storing mode: In non-storing mode, the sink collects and maintains the topology information of DODAG. All packets are forwarded towards the sink and then the sink computes the routing path to be destination according to topology information. The sink assigns the path in the header of packets and sends it to the next hop. Upon receiving a packet with a path in the header, the node will forward the packet to the next hop as indicated in the header.

RPL specification recently does not support mixed mode operation when some nodes running storing mode and others running non-storing mode. However, RPL also envisions the use of mixed mode in a single and network:" RPL does not support mixed mode operation, where some node source route and other store routing tables: future extensions to RPL may support this mode of operation".

2.5. Literature Review

2.5.1. RPL Objective Functions

RPL standard does not force the use of any specific objective function or any specific metric keeping in open for research. There are various objective functions that are used in the RPL network, the two most important objective functions are MRHOF and Objective Function Zero (OF0),

1) Objective Functions Zero (OF0): OF0 is the first standard objective function which was released by IETF in RFC 6552. Hop count is used as the default routing metric in this objective function. In case of OF0, DODAG is constructed in such a way that the nodes find the shortest path in terms of number of hops to reach the sink node. During the DODAG construction, the rank of nodes is computed and the parents are selected by each node on the basis the minimum rank value. However, RPL is mainly designed for low power and lossy networks, but OF0 neither considers the battery levels of the nodes nor the quality of the links. OF0 uses hop count as the routing metric, so some paths may contain even links which are unreliable and lead to a lot of retransmissions and thus the higher packet loss probability. In addition, nodes in shorter paths might be reused resulting the depletion of their battery levels very soon thus poorly affecting the lifetime of the network.
2) Minimum Rank Hysteresis Objective Function (MRHOF): MRHOPF is another standard objective function using in RPL. MRHOF introduces a new concept of “hysteresis” giving an advantage of network stability. While any change occurs in the DODAG, the node updates neighbor table and parent candidate set, it only changes preferred parent if the difference between the new and the prior metric value is more than a given threshold. MRHOF uses Expected Transmission Count (ETX) as the default routing metric. It gives the measure of an average number of transmissions required for the successful transmission of the packet.

Several approaches were proposed in the literature attempting to develop objective functions for RPL [19], [20], [32]. In order to handle congestion problems that occur in terms of heavy data transmission, the work in [33] introduced a congestion-aware objective function CA-OF which considered buffer occupancy as the routing factor. CA-OF showed an improvement of packet delivery ratio by avoiding congested nodes in routing paths in case of heavy data traffic. However, the routing stability is not considered in this research. Iova et al. [34] proposed a new metric named Expected Lifetime and combined it in the calculation with data traffic load and link reliability when estimating how long a node could stay before exhausting its own residual energy. The purpose of this method was to maximize the lifetime of most constrained nodes. However, the proposed method showed a high computational overhead that is unfeasible in LLNs environment. To address the limitations of network scalability, Songhua et al. [35] proposed a QoS-aware fuzzy logic objective function. This objective function includes four metrics namely hop count, delay, ETX and battery level which can estimate the path quality using fuzzy logic techniques. Several studies introduced different mechanism to optimize routing metrics efficiently and new objective functions for RPL to meet vary requirements in specific application environments [36], [37].

2.5.2. Balanced Routing protocols

The RPL balancing problem has been investigated in several prior studies such as [38]– [41]. In [41], the authors proposed a new parent selection procedure. In which, generated parent set considers both Received Signal Strength Indicator (RSSI) and residual energy, the proposed method selects probabilistically the parent node for every data transmission. The authors in [36] combined queue information with Objective Function Zero to enhance load-balancing of RPL routing under heavy traffic scenarios. Manually setting parameters, as suggested in QU-RPL, is challenging in dynamic and large-scale IoT networks and it is limited to OF0. To address load imbalance of ORPL [42], Michel et al. [43] proposed ORPL-LB which achieved load balancing by using a sleep interval control mechanism and selective ACK transmission. Via various experiments, the authors proved that ORPL-LB have a better battery lifetime among nodes than standard RPL and ORPL. The authors [38] proposed LB-RPL which improves load balancing of RPL by allowing a node to prioritize its parent candidates based on their queue utilization. The queue utilization information is collected from its neighbor nodes through DIO transmission. If congestion is detected, then the nodes delay the dissemination of routing information. M-RPL [40] detects traffic congestion problem by using RPL control messages and provides two preferred parent nodes for traffic distribution. The work in [44], ALABAMO was proposed which supports MRHOF in load balancing capacity. With ALABAMO, RPL nodes consider parent selection process using both ETX and traffic load value. Through actual experiments, the authors demonstrated the improvement in load balancing of ALABAMO but they did not consider a duty cycling mechanism for evaluation and they assumed simply that fair relay burden can balance routing lifetime.

CHAPTER III: SYSTEM MODELING

In this section, we model RPL in detail and describe our proposed named SB-RPL, aiming to enhance the skewness and balancing of RPL DODAG as well as improve the performance of RPL in terms of reliability, end-to-end delay and adaptive to the dynamics of resource-constraint networks.

3.1. System Models

The suggested SB-RPL approach is designed for LLN networks organized in a single DODAG. Thus, we consider a LLN as a set of multiple IoT devices. The network graph G=(N, L) with N is set of sensor nodes, L is set of direct links, operates in discrete time slots (e.g., seconds): t = {0,1,2,3, …m}.

Low-Power and Lossy Network (LLN): To model the unreliable and lossy wireless transmissions, we use packet reception ratio (PRR) over the wireless link from node n to node p as (n, p), 0 ≤ $PRR_{n,p}(t)$ ≤ 1. The PRR is as the probability of successfully transmitting a packet and then receiving an acknowledgment between node n and node p at timeslot t. For RPL, we can calculate ETX (Expected Transmission Count) from PRR. ET X is the measure for determining total number of retransmissions required to successfully transmit data packet to next node with an acknowledge. Considering a given PRR value between node n and node p as $PRR_{n,p}(t)$, the corresponding ETX value $ETX_{n,p}(t)$ can be achieved as followed:

$$ETX_{n,p}(t) = \frac{1}{PRR_{n,p}(t)} \tag{1}$$

RPL smooths ETX using an exponential weighted moving average (EWMA) filter [46] which is widely used method to update statistics such as average and standard deviation, making it robust to sudden changes in RPL DODAG. It updates ETX as:

$$ETX_{n,p}(new) = \gamma ETX_{n,p}(current) + (1-\gamma)ETX_{n,p}(packet) \quad (2)$$

where $ETX_{n,p}(current)$ is the ETX metric that node n currently has for its parent node p, and $ETX_{n,p}(new)$ is the ETX value obtained from the last single transmission from the child nodes. The default value of γ is set to 0.1. We define the logical link-layer channel capacity $c_{n,p}(t)$ of a wireless link from node n to node p at time slot t as followed:

$$c_{n,p}(t) = c_{n,p}^{max} PRR_{n,p}(t) = \frac{c_{n,p}^{max}}{ETX_{n,p}(t)} \quad (3)$$

$c_{n,p}(t)$ presents the number of acknowledgment packets trans- mitted from node n to node p with timeslot t, $c_{n,p}^{max} \geq c_{n,p}(t) \geq 0$; $c_{n,p}^{max}$ is the maximum value of $c_{n,p}(t)$, ∀t. If capacity channel value $c_{n,p}(t) > 0$, it means that node n and node p are in communication at time slot t; otherwise, they are not in communication at timeslot t. We denote that $NB_n(t)$ is set of all neighbors that node n can communicate during timeslot t, $NB_n(t) \in$ N:

$$NB_n(t) = \{\mathrm{p} | c_{n,p}(t) > 0, c_{p.n}(t) > 0, \mathrm{p} \in \mathrm{N} - \{\mathrm{n}\} \} \quad (4)$$

As specification of original RPL, neighbor table have several main policies as followed:

NP1*: A node n adds the neighbor k if there is indication that this is better parent than the worst of the current parent.*

NP2*: When a node n has empty neighbor table $NB_n(t)$, it can always add new neighboring nodes to its neighbor table.*

NP3*: Node n will add node k $\in NB_n(t)$ to its neighbor table if there is enough space for other children and send a DAO-ACK message. The nodes already in the table of node n are not deleted except the lifetime timeout is expired.*

NP4*: When node n receives a DIS message of node k, if this DIS is a unicast transmission, node n will add node k to $NB_n(t)$; otherwise, node n ignores the DIS.*

The state of low-power and lossy network at a given timeslot t > 0 can be presented as a directed and modeled as a time- varying weighted graph *G (N, L, c(t))* where N is the set of sensor nodes and L is all possible links for all nodes pairs in N.

Each RPL nodes recognizes its neighbors by receiving DIO messages. Then, each node generates its own parent candidate set P_n from its neighbor set $NB_n(t)$ as followed:

$$P_n(t) = \{\mathrm{p} \in NB_n(t) \mid R_n < R_p, ETX_{n,p}(t) < \delta\} \tag{5}$$

where δ is a threshold to remove neighbors which are connected through unreliable links.

3.2. RPL Objective Function:

RPL constructs a DODAG by using a specific Objective Function which defines a routing optimization objective that translates one or more metrics and constraints such as latency, minimizing energy consumption or ETX into a value called rank. RPL defines rank to indicate the routing distance from a node to sink, which is attached in DIO messages and used to parent selection procedure. In ContikiRPL, MRHOF is used as default objective function where rank is computed based on ETX information.

The rank value of new device n ∈ N is determined by the following formula:

$$R_n(t) = \begin{cases} \min\limits_{p \in NB_n(t)} \left(l_{n,p}(t) + R_p(t) \right) & n \neq S \quad \text{(6a)} \\ R_S & n = S \quad \text{(6b)} \end{cases}$$

where $R_p(t)$ is the rank of node *n*, $R_p(t)$is the rank of the potential parent DODAG node *p* of the node n, and $l_{n,p}(t)$ is a function of the characteristics of node *p* and of the link between node n and node p at timeslot t. $R_S \geq 0$ is rank of the sink, the smallest rank value in the DODAG architecture. Thus, when a new device n willing to join DODAG, its rank is computed by searching a one-hop neighbor that gives the smallest sum of link characteristic $l_{n,p}(t)$ and neighbor rank $R_p(t)$. In ContikiRPL, $l_{n,p}(t)$ represents for $ETX_{n,p}(t)$.

In parent selection process, each node selects its best parent $P'_n(t)$ from parent candidate $P_n(t)$:

$$P'_n(t) = \underset{p \in P_n(t)}{\arg min}(R_p(t)) \quad (7)$$

if the smallest path cost for paths through the candidate neighbors is smaller than the current path cost by less than a threshold, the node may continue to use the current preferred parent. This is considered as hysteresis component of MRHOF objective function. Then a node may change its preferred parent if its information on parent candidates has been changed if:

$$R(P'_n) < R(P'_n) + \sigma \quad (8)$$

where σ is a stability bound to mitigate unnecessarily and inefficiently the parent change, which is set to 96 by default. This σ is the difference between ETX of the route through the preferred parent and the minimum-ETX route to trigger a new preferred parent procedure. Each RPL node selects a parent node which has a reliable link or minimum hop distance to the sink, regardless of traffic load and balancing for DODAG. The RPL objective functions have several main properties as follows:

P1*: If there is a change of $NB_n(t)$ such as adding or removing entries or the entries are changed, then the node n will eventually re-compute $R_n(t)$ and re-select P'_n :*

P2*: When the node n re-selects its preferred parent P'_n, and $R_n(t)$, a non-sink node adopts NULL as P'_n, if it also adopts infinite rank. There are the initial values of preferred parent and rank at the non-sink node when the node needs to (re)start.*

***P3**: Similarly, when the node n re-selects its preferred parent P'_n and Rn, the sink adopts NULL and MinHopRankIncrease, respectively.*

***P4**: When node n re-selects P'_n, the non-sink node will adopts NULL and infinity, respectively. And if its $NB_n(t)$ does not include any entry, for which $R_n(t)$, can be calculated by an objective function, and these following constraints should be satisfied:*

- $R_{NB_n}(t)$< *infinity*
- $R_n(t) \leq R_{min}\ (t)$ + *MaxRankIncrease*
- $R_n(t) \geq R_{NB_n}(t)$ + *MinHopRankIncrease*
- *Node n and $NB_n(t)$ are reachable.*

Otherwise, node n will select a neighbor as a preferred parent.

***P5**: The $R_n(t)$ and $P'_n(t)$ change only as a result of re-selection of the node's death and reset; otherwise they keep stably.*

CHAPTER IV: SB-RPL DESIGN

4.1. Topology-Aware Node Influence

We define *Routing Subtree* RT^S for each destination- oriented tree graph RT^S= (N^S, L^S, c(t)), rooted at the LLN sink, s = {1, 2, 3, ...N } with $RT^S \subseteq$ G, $N^S \subseteq$ N, $L^S \subseteq$ L. Note that N^S = {N1, N2, ..., NS } is a partition of the set of all sensor nodes N^S and L^S is the set of direct links between each node I to preferred parent pi so |L^S | = |N^S|− 1. For each node n ∈ N, we can identify the subtree size of node n, $ST_n(t)$ is composed by all the nodes connected to n through multi-hop paths.

$$ST_n(t) = |N^S| \tag{9}$$

We define the notion of *Node Influence* $NI_{n,p}(t)$ to measure the stress of parent candidate p to new joining node n at time t. Intuitively, the *Node Influence* is determined by sum of the subtree size of potential preferred parent and ETX value between the new joining node and the parent candidate.

$$NI_{n,p}(t) = \alpha ST_p(t) + \beta ETX_{n,p}(t) \tag{10}$$

As the above equation, *Node Influence* of potential parent p to new joining node n is a combination of subtree size of node p, $ST_n(t)$, and link quality between n and p, $ETX_{n,p}(t)$. We use two weighted number α and β to control the interaction between the skew of DODAG subtrees and link quality, this problem is described more detail in Section IV.

4.2. RPL Control Message DIO extension in support of balancing routing

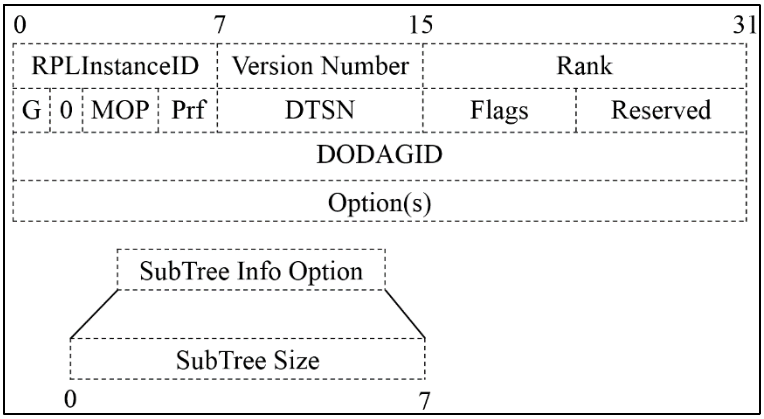


Figure 4.1: Amended RPL DIO control message structure using in SB-RPL.

Basically, RPL supports various routing metric such as hop-count, ETX, latency, and energy. In order to construct a DODAG, the root broadcasts Destination Information Object (DIO) control messages to the other nodes in the downward direction. It plays an important role by helping nodes in discovering RPL Instances with their configuration parameters and in constructing a DODAG. The structure of DIO message is described in Figure 4.1.

In order to achieve topology balance, RPL control message DIO is exploited to broadcast *Routing Subtree* size information $ST_p(t)$ of a node to its own neighbors. SB-RPL makes all nodes transmit amended RPL DIO messages to its neighboring nodes. When a node k receives a DIO message from a neighbor n_k, it records *Routing Subtree* size information $ST_n(t)$ in its neighbor table and uses this value of the received DIO message as a metric to build a multi-hop topology that is free from load imbalance problem.

4.3. SB-RPL Design

In the beginning, the DODAG sink propagates DIO messages periodically to its neighbors, with the information mentioned in section II. After a node receives this

DIO message, it will decide whether it will join the DODAG or not and computes its own rank once it joins DODAG.

In this part, we describe the detail of proposed scheme SB- RPL. In order to optimize the balanced of DODAG routing topology, we exploit the new metric, Node Influence $NI_{n,p}(t)$ which is introduced above (Equation 10). Node Influence $NI_{n,p}(t)$ is considered as a new constraint in the DAG Metric Container included in the DIO control message. In which, the Routing Subtree size information is included, and SB- RPL use the $ST_p(t)$ to avoid traffic congestion as well as balance the DODAG subtrees. For updating ETX and Subtree Size, SB- RPL uses the same EWMA filter as in standard RPL. SB-RPL uses a hysteresis mechanism similar to the one employed in MRHOF to prevent unstable changes during fast fluctuations in routing. Then, each node generates a parent candidate set from its own neighbors according to equation 6, and selects the best parent node according to equation 12. For SB-RPL, SB-RPL nodes compute rank as followed:

$$R_n(t) = R_p(t) + NI_{n,p}(t) = R_p(t) + \alpha ST_n(t) + \beta ETX_{n,p}(t) \quad (11)$$

In standard RPL, the DIO transmission procedure based on Trickle Timer which is reset to a minimum when there are changes in routing topology. Being a preferred parent of many children results in more traffic overhead and imbalanced problem, consequently consuming its own power much faster than other candidate parents. In order to figure out the problem, we exploit the vital information of DODAG subtree sizes as well as consider the quality of transmission medium. In other words, the parent with the lower number of children will be selected as the preferred parent. The skewness and balancing of RPL is achieved by reducing the number of children within each subtree of the overloaded bottleneck node. Consequently, joining node will prefer choosing parent according to the dedicated routing metric and guaranteed that the preferred parent has less number of children, equivalent to less size of the subtree. Besides, SB-RPL also consider the link characteristic in routing procedure. Therefore, SB-RPL guarantees the balance of DODAG trees as well as enhances the reliability. The SB-RPL protocol is described in Algorithm 1.

Table 4.1: SB-RPL Algorithm

Algorithm 1: SB-RPL Algorithm
Require: Received DIO messages **Ensure**: The balance among DODAG subtrees **1. Calculation** 2. n ← DIO; */*Node n receives a DIO message*/* 3. **if** n $\notin P_n$ **then** 4. P_n → n **5. end if** 6. **if** n == P'_n **then** 7. $C_n \leftarrow C_n$ + 1 **8. end if** *// Rank Computation based on 'Node Influence' factor;* // $NI_{n,p}(t) = \alpha ST_n(t) + \beta ETX_{n,p}(t)$ // $ST_n(t)$ and $ETX_{n,p}(t)$ are smoothed by EWMA filter. 9. $R_n(t) = R_p(t) + NI_{n,p}(t)$ */* Parent Selection Procedure */* 10. **if** $R_n(t) > R_{receivedDIO}(t)$ **then** **11. Maintain the location of node n in the DODAG** **12. Break** **13. Else**

14. **Get the parent with lower rank and Discard the current rank**

15. $R_{n,p1}(t) \leftarrow$ *parent_path_metric(p1)*

16. $R_{n,p2}(t) \leftarrow$ *parent_path_metric(p2)*

17. **If** $p1 == currentParent$ **||** $p2 == currentParent$ **then**

18. **If**

19. **Return** P'_n /*Preferred Parent*/

20. **End if**

21. **End if**

22. **End if**

23. **Broadcast** the updated DIO messages

CHAPTER V: EVALUATION

In this section, we perform an extensive experimental evaluation of the proposed scheme. We compare our proposed scheme to the state-of-the-art, including Objective Function Zero, MRHOF in various scenarios with the numerical simulation environment and real-world platform.

5.1. RPL in Contiki OS

Contiki is an open source operating system for wireless sensor network, dedicated to support simulate Internet of Things. The Contiki OS has the ContikiRPL protocol as the default RPL protocol designed by Swedish Institute of Computer Science (SICS). Contiki provides dynamic load ding and unloading of individual programs and service with event-driven kernel, but the system supporting multi-threading that can be applied on a per process basis. The most of components of Contiki are implemented in C language and has been ported to various microcontroller architectures, such as Atmel AVR or Texas Instruments MSP430. The implementation of ContikiRPL consists of some main submodules:

- rpl.c: The main RPL function for modifying the IPV6 routing features of ContikiRPL
- rpl-dag.c: This file contains the necessary functions for DAG manipulations
- rpl-icmp6.c: The function defines ICMP message for RPL protocol
- rpl-timers.c: The function defines sending periodic updates for RPL.
- rpl-mrhof.c: The Minimum Rank with Hysteresis Objective Function of RPL which contains ETX and battery metrics.
- rpl-of0.c: The implementation of RPL Objective Function 0

5.2. Methodology

We evaluate the performance of compared routing strategy by employing both testbed experiments and simulations.

5.2.1. Testbed Experiments:

Table 5.1: Experimental Setup

Experimental Parameters	**Values**
Environment	Indoor
Network Scale	1 sink and 99 nodes
Node Spacement	Uniform random
Deployed nodes	100 random nodes
Platform	ContikiOS/M3 Cortex Arm
Duration	60 minutes per instance
Application Traffic	UDP/IPv6 Traffic
Payload Size	16 bytes
Number of hops	Multi-hop network
Embedded Network stack	ContikiMac
Number of retransmission	10 retransmissions
Compared Objective Functions	RPL (OF0, MRHOF), SB-RPL
Hardware Parameters	**Values**
Antena Model	Omni-directional
MAC	802.15.4 beacon enabled
Radio chip	TI CC2420
Radio Propagation	2.4 GHz
Transmission Power	-17 dBm

Figure 5.1: **FIT-IoT Lab Testbed**. Node Deployment in Lille site.

Setting up a complete WSN deployment is a very complex task. In this part, we present our study on the FIT IoT-LAB testbed. In our experiments, we used the platform installed in Lille site, France. We used 100 nodes (M3 ARM-Cortex) from Lille site offered by the FIT IoT-Lab testbed, shown in Figure 5.1. The topology includes 1 sink located at the center and 99 random sensor nodes generating UDP packets on a predefined time interval. The M3 node has one ARM M3-Cortex micro-controller, one 64kB RAM, one IEEE 802.15.4 radio AT86RF231, one rechargeable 3.7V LiPo Battery and several types of sensors. In order to ensure multi-hop topology is constructed, we set transmission power to -17dBm as in the tutorial of FIT IoT-Lab testbed. The detail of parameters is described in Table 5.1.

5.2.2. Cooja Simulation

To compare our proposed scheme against prior works with full control in network conditions, we use Cooja - the network simulator of Contiki. Cooja provides three different radio models namely UDGM (Unit Disc Graph Mode) - distance loss, UDGM (Unit Disc Graph Model)- constant loss, Multi-Path Ray-Tracer Medium (MRM). In this paper, we use MRM model because MRM it the most realistic model for wireless sensor network implementation. MRM considers concepts such as reflection, refraction, diffraction and fading [49]. Cooja emulates nodes running compiled MSP430 firmware. Cooja allows us to have completed control over network conditions and emulate varying connectivity. However, as soon as the growth up of network scales, the neighbor tables of nodes start falling apart. Therefore, a straightforward method to solve this issue is to scale up the RAM beyond the expected size of the network. Running simulation with lots of nodes is very CPU consuming. To speed up Cooja simulator, we run all out non-GUI simulations on cloud servers. Each server runs Ubuntu 13.04 LTS with 32 GB of RAM. We evaluate the impact of network scale and density to DODAG topology constructing as well as skewness in various scenarios.

5.3. Compared Objective Functions

We compare our proposed scheme to Objective Function Zero, MRHOF using ETX and MRHOF using ETX^2, three state-of-the-art objective functions, which are all implemented in ContikiOS.

1) Objective Function Zero (OF0): OF0 uses hop-count as a routing metric. A node calculates its rank by adding a positive and indirectly normalized scalar value to its preferred parent rank. This objective function can also be called as minimum hop-count objective function.
2) Minimum Rank with Hysteresis Objective Function using ETX (MH_ETX):

MRHOF selects routes that minimize additive routing metrics such as energy, latency and ETX. In addition, MRHOF uses hysteresis to reduce instability is used with ETX routing metric as default objective function.

3) Minimum Rank with Hysteresis Objective Function using ETX^2 (MH_ETXSQ): An extended version of MRHOF, however, MH_ETXSQ uses ETX^2 as the routing metric.

The source code of objective functions is fairly provided on ContikiOS homepage [45].

5.4. Metrics

We focus on 3 types of metrics to compare the performance of the objective functions: skewness metrics, reliability and latency.

5.4.1. Skewness metrics

In order to compare the skewness of our proposed routing scheme to existing objective functions of RPL standard (OF0, MRHOF), we define 4 skewness indexes namely M1, M2, M3 and M4 for each rank of DODAG. The skewness indexes determine the extension of asymmetry or lack of symmetry among subtrees of a DODAG. The definitions of skewness indexes are defined as follows:

$$M1 = \frac{ST^{max}(t) - ST^{min}(t)}{ST^{avr}(t)} \qquad M2 = \frac{ST^{max}(t)}{ST^{min}(t)}$$

$$M3 = \frac{\sum_{i=1}^{N} | ST_i(t) - ST^{avr}(t) |}{ST^{avr}(t)} \qquad M4 = \frac{ST^{max}(t) - ST^{min}(t)}{ST^{min}(t)}$$

where $ST^{max}(t)$, $ST^{min}(t)$ and $ST^{avr}(t)$ are the maximum value, minimum value and average value of the subtree sizes in a DODAG, respectively. For example, in Figure 1, DODAG includes 1 RPL sink and 10 source nodes. Nodes {a; b, c} are level 1, nodes {d, e, f, g} are level 2 and nodes {h, i} are level 3. For level 1 at time t, ST^{max}= $ST_{(a)}$ = 3, ST^{min}= $ST_{(b)}$= $ST_{(c)}$= 2, ST^{avr} = 2:34, so M1 = 0.43, M2 = 0.86, M3 = 1.5 and M4 = 0.5. The skewness value of higher is computed similarly. In this paper, we compute the skewness values of three levels {1, 2, 3} and aim to minimize the value of skewness indexes. In this paper, we aim to minimize the four skewness indexes subject to number of nodes in each DODAG subtree:

$$\text{minimize} \quad \text{M1, M2, M3, M4}$$
$$\text{subject to} \quad ST_p(t)$$

In our experiments, we also use two specify metrics namely Packet Delivery Ratio and Latency to evaluate the performance of SB-RPL.

Packet Delivery Ratio: (PDR) is the ratio of the number of packets that are successfully delivered to a destination over the number of packets that are sent by the transmitter in an end-to-end communication. PDR represents the reliability of the routing protocol. In most cases, PDR is the important evaluation metric of a network.

$$Average\ PDR = \frac{Total\ Received\ Packets}{Total\ Sent\ Packts} * 100\%$$

3) Average Latency: represent the end-to-end latency on the application. Latency is the time elapsed from the application on the source node handling the packet to the MAC layer until the packet arrives at the sink's collection application. Minimizing latency is one of the main targets of routing protocol design.

5.5. Testbed Experiments

The extensive experiments were conducted to compare practical performance of proposed scheme to existing RPL routing standards based on random 100-node topologies in the FIT IoT-LAB tested.

5.5.1. Impact of α and β:

We investigate the impact of the design parameters α and β values on the performance of SB- RPL. Through extensive experiments with different values of α

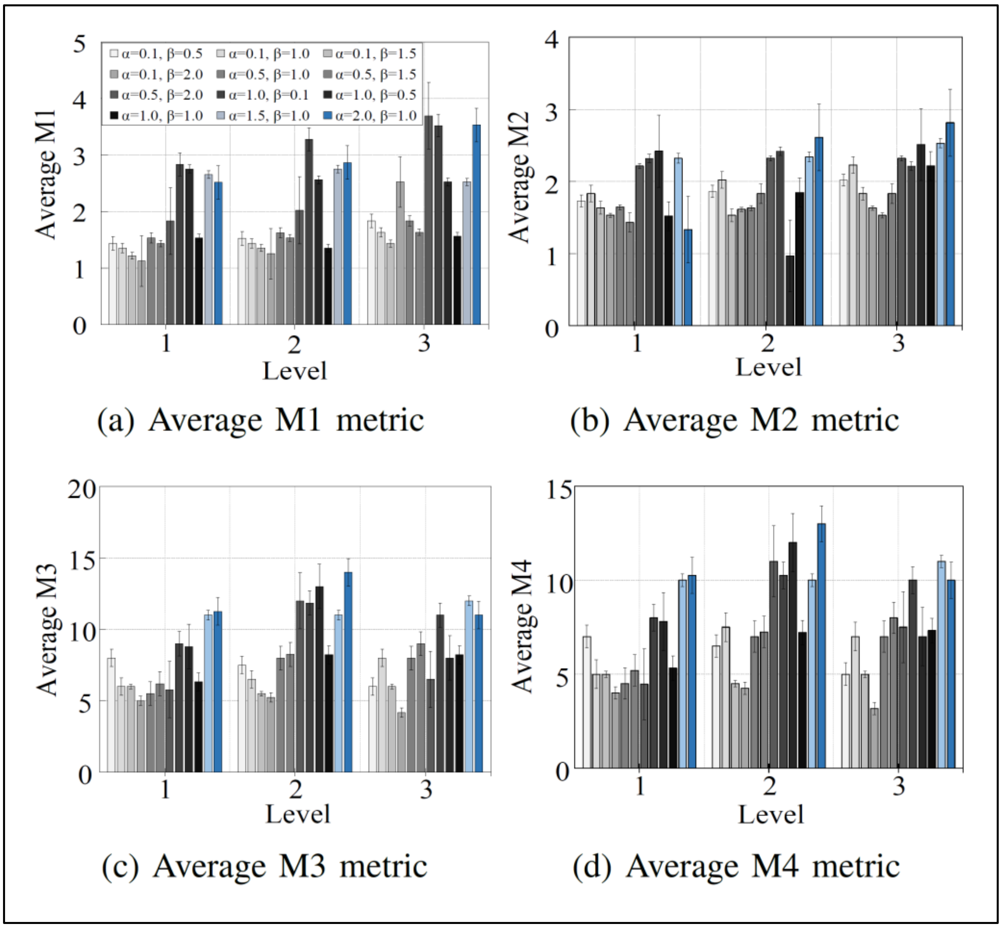


Figure 5. 2: **Impact of α and β**. We evaluate the skewness and balancing of RPL by measuring four skewness indexes with various pair of values of and through FIT-IoT-Lab 100-node topologies. The skewness and balancing of SB-RPL is differentiate in three levels of nodes in the DODAG. From left to right, the order of pair values of and legend is similar with Fig. 5.3.

and β in a range from 0.1 to 2 (Figure 5.2 and Figure 5.3), it shows the trade-off between link quality from new devices willing to join DODAG to parent candidates and the balance of the subtrees. First of all, Figure 5.3(a) shows that the PDR first increases with β, however the PDR also depends on the value of α. This is due to the

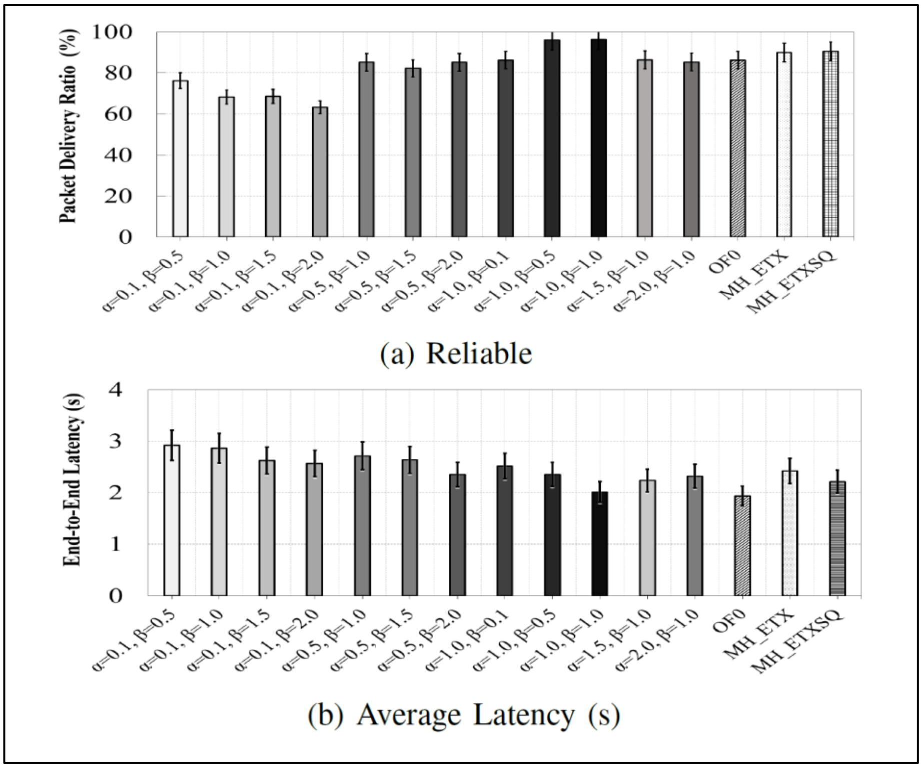


Figure 5.3: **Impact of α and β to PDR and latency**. The average reliability and latency of SB-RPL are affected by the varying of and

trade-off between the routing direction and congestion control. For a large value of β, a node would mainly consider link quality ETX to potential preferred parent when selecting the best link quality. This leads to a parent node have to handle many child nodes and the length of paths from the source nodes to the sink might be stressed through many links. Thus, traffic congestion is easily occurred. However, a node may select a path that is longer than the shortest path by considering which parent candidate node has the smallest number of children in the routing table, and connect to that parent node to avoid traffic congestion. This shows the trade-off between load balancing and link quality in routing procedure.

The FIT-IoT-Lab platform allows writing the print outs of each device to a log along with a corresponding timestamp. The timestamp of the time the log is written

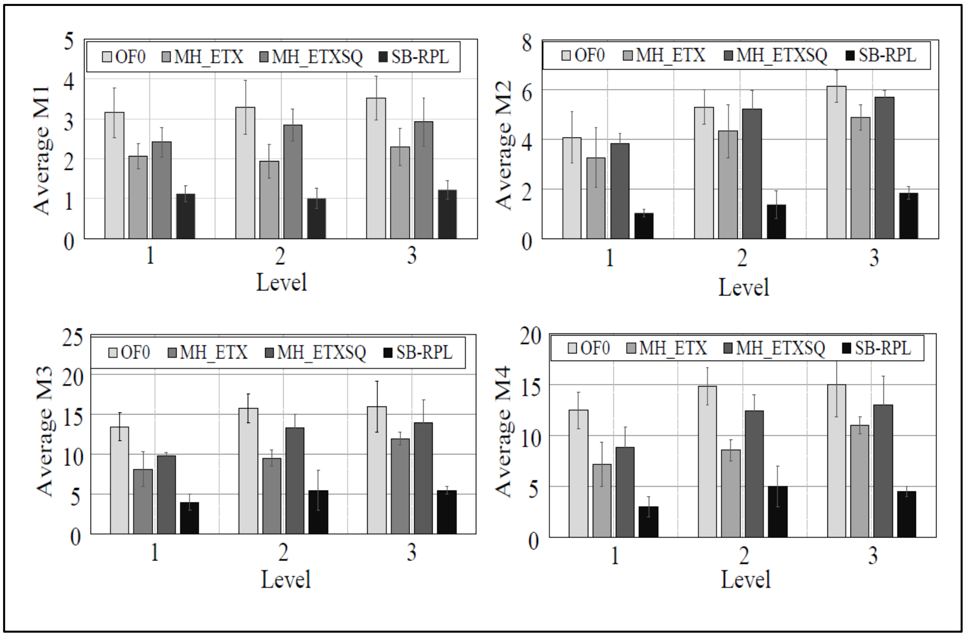
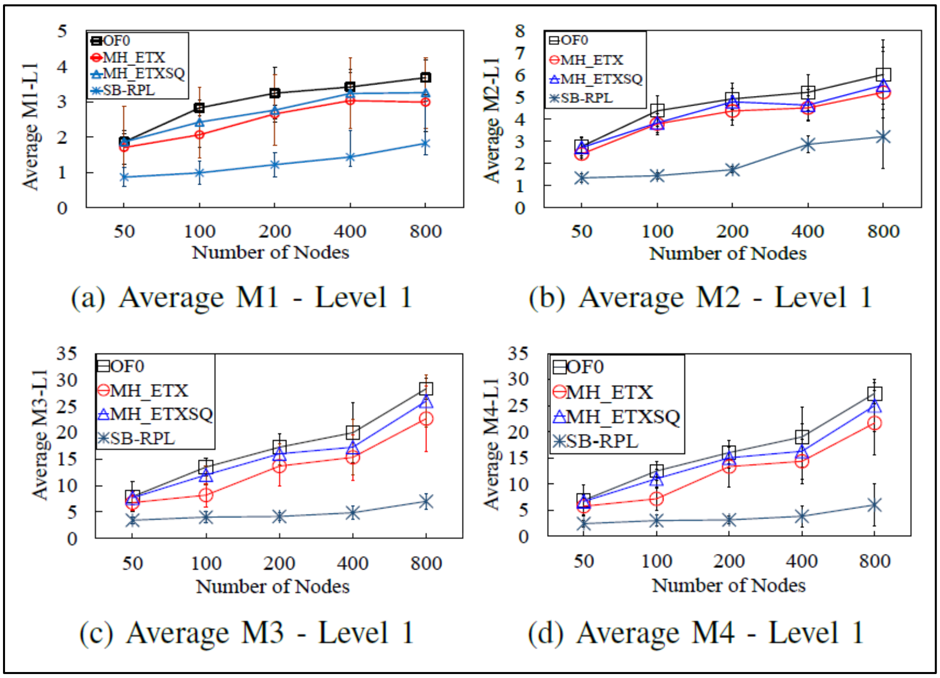
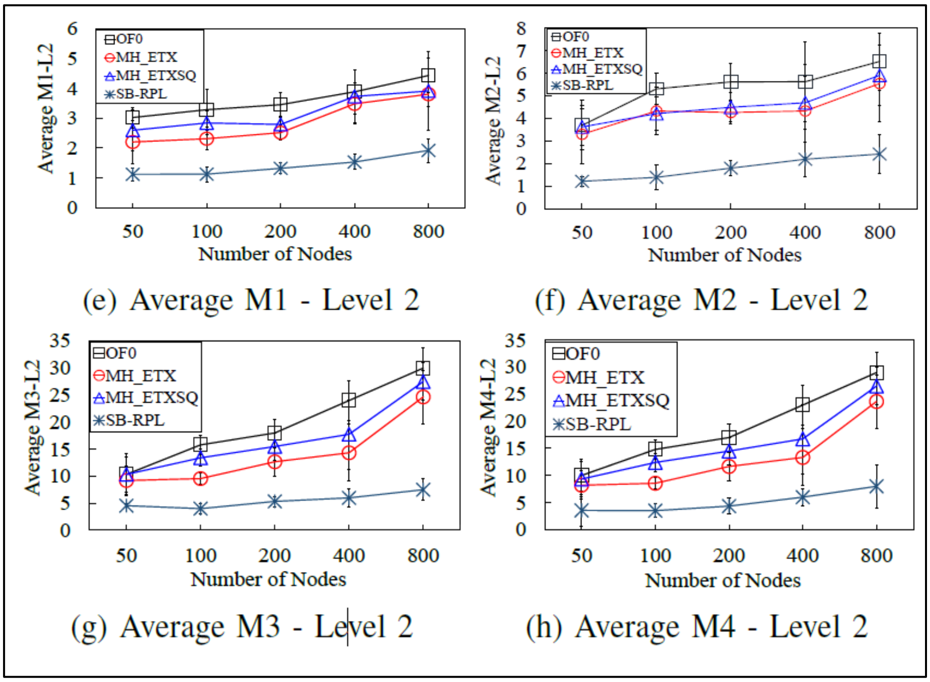


Figure 5.4: **Objective Functions Comparison**. We compare proposed scheme to existing Objective Functions through experiments using FIT-IoT-Lab platform, Lille site. The skew of SB-RPL is lower around 3 times compared to existing objective functions. Thanks to subtree size $ST_p(t)$ metric, SB-RPL reaches balancing among subtrees, the parent node does not need to handle too many children. This leads to the number of parent changes reduces significantly. In fact, the child node may converse the same preferred parent for a long time.

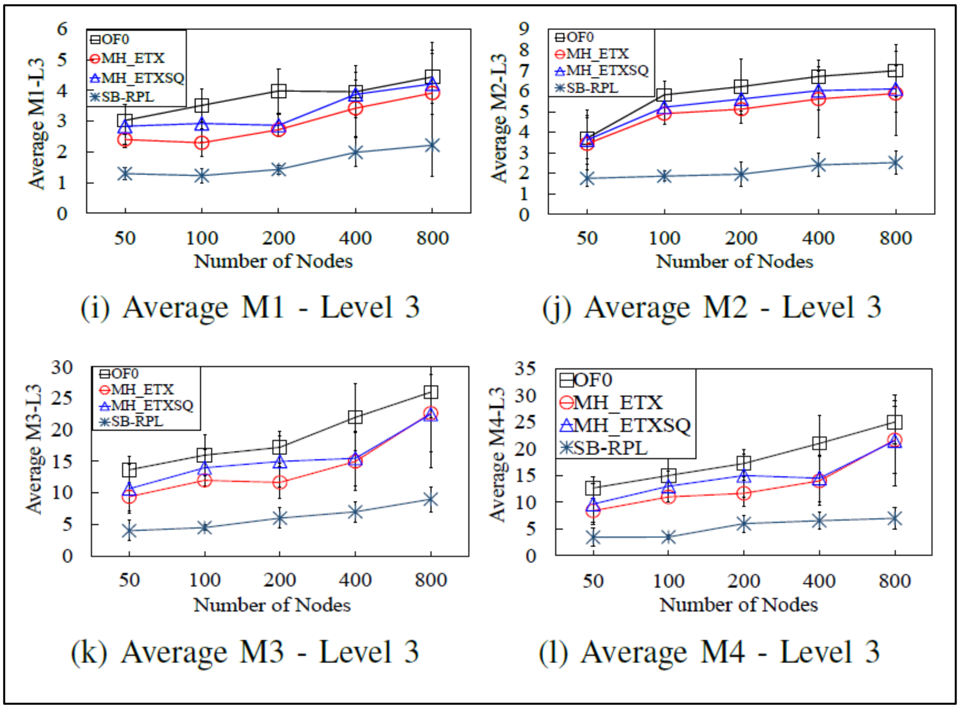
and totally ordered. Therefore, this introduces some latency regarding when the log is written to file. Figure 5.3 (b) demonstrates that the end-to-end latency of SB-RPL is impacted by the varying of α and β, SB-RPL reduces the end-to-end delay with respect to original RPL. Thanks to Node Influence, the node not only considers the ”good enough” link quality path but also refers to the number of connections to the parent candidate for parent selection procedure. Thus, the nodes have fewer children to manage and packet transmission is easy performed without extra waiting time.



(1) Impact of Network Scale at Level 1



(2) Impact of Network Scale at Level 2



(3) Impact of Network Scale at Level 3

Figure 5.5: **Impact of Network Scale**. The balancing of RPL DODAG topology depends on the network size. With traditional objective functions such as OF0 and MRHOF, the skewness of RPL increases exponentially as the growth of network density while the proposed scheme keeps the RPL topology stably.

We believe that both parameters α and β do significant impact on the performance of SB-RPL, and they can be optimized empirically by regarding network performance. Figure 5.3 demonstrates that SB-RPL achieves highest PDR when α =1.0 and β = 1.0. Besides, the latency is significant differentiate among pair values of α and β. In terms of selecting a longer path to avoid traffic congestion, the latency is lightly higher than selecting the shortest path. Therefore, we have exploited these values throughout our practical experiment in actual testbed FIT-IoT Lab as well as simulations and performance evaluation section.

Figure 5.2 compares the skewness indexes of SB-RPL in terms of varying α and β from 0.1 to 2. We evaluate the average skewness indexes in three levels of DODAG. First of all, we observe that the skewness indexes increase as the decrease of α, however in order to achieve a good performance, the effect of β is required. Because when using the large value of α, the skewness indexes also decrease, the SB-RPL mainly focus on exploiting the balance perspective in routing procedure, the DODAG tree willing to reach balancing. However, when the ratio between $\alpha ST_p(t)$ and $\beta ETX_{n,p}(t)$ grows up remarkably, the nodes willing to join DODAG only might not select the preferred parent with good link quality enough for data transmission.

5.5.2. Objective Function Comparison

We compare our proposed scheme to standard RPL objective functions in terms of skewness and balancing via the practical FIT-IoT-Lab platform. Figure 5.4 demonstrates that the average skewness indexes of SB-RPL outperform to the rest objective functions in three levels. With 100-node topologies, the average M1 of SB-RPL is around 1 in three levels while OF0, MH_ETX and MH_ETXSQ are around 3, 2, and 2.5 respectively. Similarly, the skewness indexes M2, M3 and M4 of SB-RPL is less than around 3 times comparison with other methods. This is because both OF0 and MRHOF use simple routing metrics such as hop count or ETX or their combination for path calculation and parent selection, meanwhile SB-RPL considers the skew and balance among subtrees and combines multiple metrics for routing efficiency in RPL DODAG.

Table 5.2 compares the average PDR of routing schemes in three different traffic rates (20 packets per second, 40 packets per second, and 60 packets per second). With SB-RPL, the packet reception rate is enhanced by almost 10% compared to the original RPL. The loss of packets in real test-bed might be due to the interference from the external world. Higher the PDR of the network means that the packets lost in the network are less and the link between the nodes are stable.

Table 5. 2: Packet Delivery Ratio Comparison

	Traffic Rates (# packets per second)		
Compared Schemes	20 pkts/s	40 pkts/s	60 pkts/s
RPL-OF0	62.3 %	87.1 %	91.2 %
RPL-MH_ETX	63.5 %	88.4 %	92.2 %
RPL-MH_ETXSQ	65.6 %	89.2 %	92.4 %
SB-RPL	79.6 %	94.7 %	96.6 %

5.5.3. DODAG Routing Topology

Figure 5.6 shows an example of routing topologies of compared objective functions. In this experiment, we selected randomly 100 nodes in Lille side of FIT-IoT-Lab platform with the sink was located at the center.

In cases of standard objective functions OF0, MRHOF, many nodes have selected same one node as their parent and the number of nodes belongs the subtree of this node becomes larger and larger. With OF0, the nodes choose the preferred parent based on the hop-distance to the sink, so the probability of selecting the same preferred parent which has shortest path to the sink is high. Meanwhile, MRHOF scheme prefers to choose the path with lowest ETX value, so the length of route from the source node to the sink might be too long. Consequently, the parent node experienced a significant overload and dropped a lot of packets transmitted from its child nodes which results significant reliability degradation.

By contrast, SB-RPL considers the balance among subtrees in the DODAG to achieve balanced traffic load distribution. The new nodes willing to join DODAG

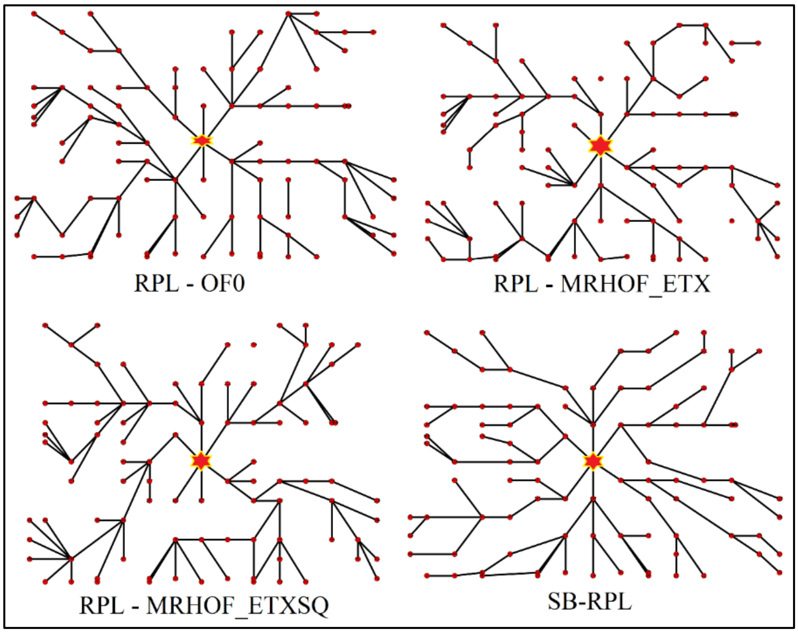
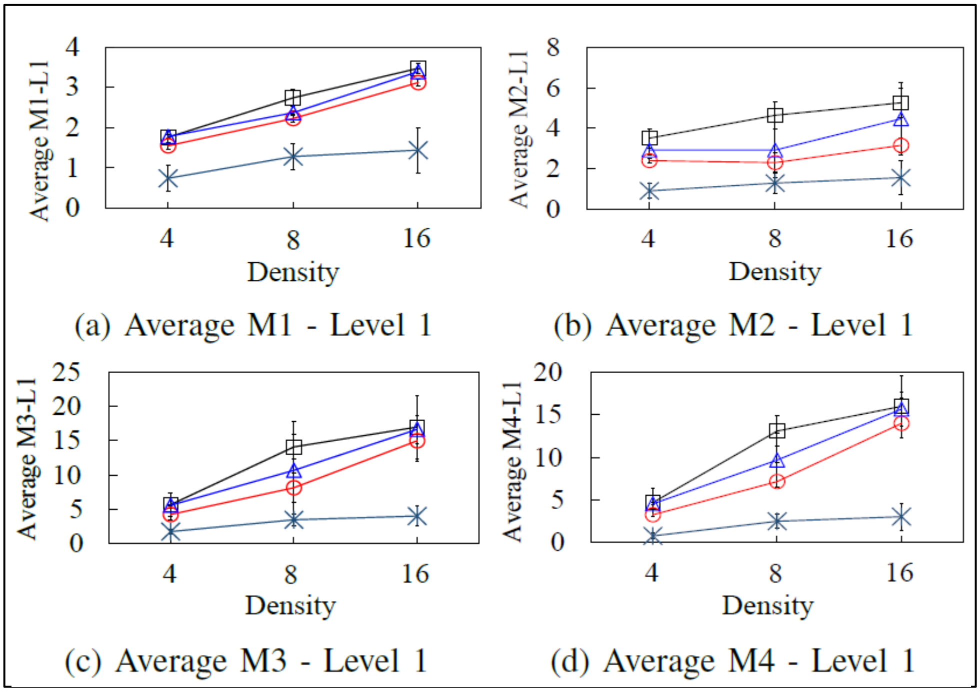


Figure 5.6: **RPL DODAG Routing Topologies**. Snapshots of routing topologies of Objective Functions implemented on FIT-IoT-Lab platform. OF0 and MRHOF show an unbalance among subtrees in DODAG because they use simple routing metrics for parent selection procedure, while SB-RPL not only considers the reliability of data transmission but also the skew and balance of DODAG.

obtain the Subtree Size information from neighbor nodes and select parent candidate list. From parent candidate list, nodes compute their own rank by combing multiple factors, in which Subtree Size is considered seriously to prevent connecting to a parent node which has too many children. The smart use of SB-RPL results in traffic congestion degradation as well as achieves load balancing of children.

5.6. Cooja-based Simulations

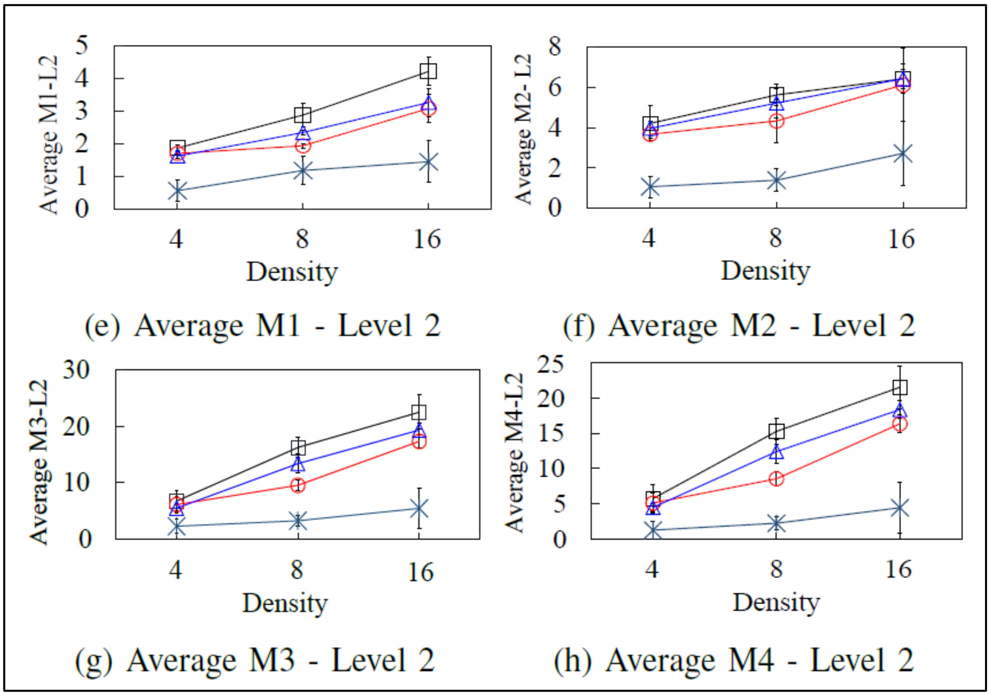
Contiki's network simulator named Cooja is used to provide detail insights about the performance of proposed scheme under other network conditions. First, these



(a) Average M1 - Level 1 (b) Average M2 - Level 1

(c) Average M3 - Level 1 (d) Average M4 - Level 1

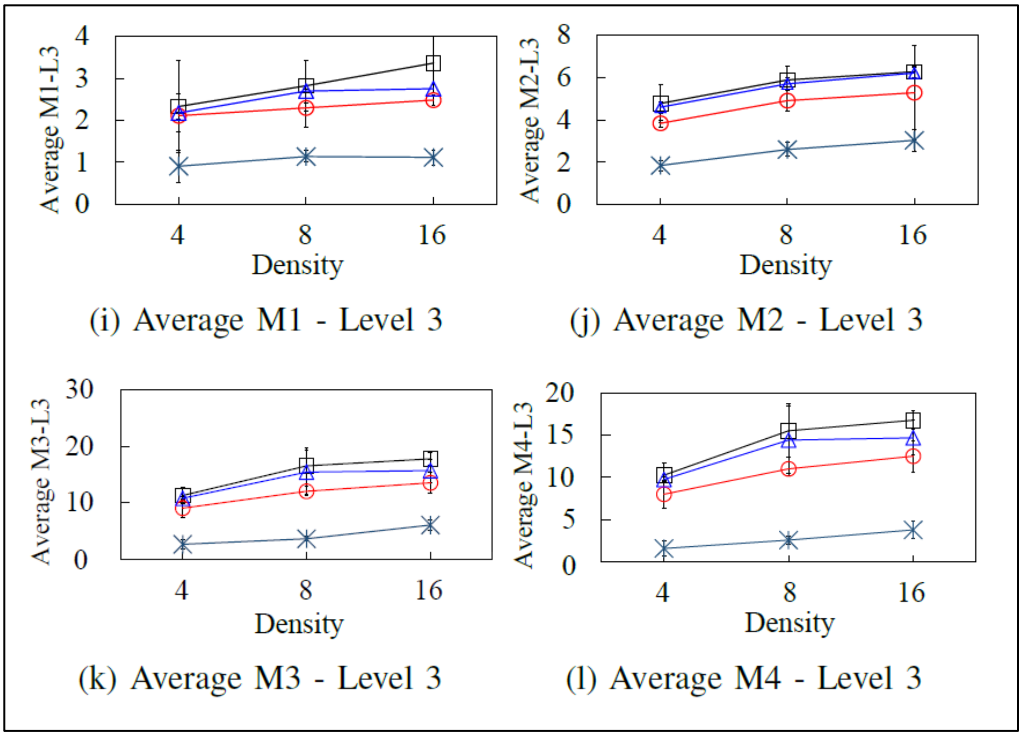
(1) Impact of Network Density at Level 1



(e) Average M1 - Level 2 (f) Average M2 - Level 2

(g) Average M3 - Level 2 (h) Average M4 - Level 2

(2) Impact of Network Density at Level 2



(3) Impact of Network Density at Level 2

Figure 5.7: **Impact of Network Density**. The balancing of RPL DODAG topology depends on the network size. With traditional objective functions such as OF0 and MRHOF, the skewness of RPL increases exponentially as the growth of network density while the proposed scheme keeps the RPL topology stably.

simulations compare performance of proposed scheme for a network following various network sizes with 50, 100, 200, 400 and 800 nodes. Then, we demonstrate that the proposed scheme is outstanding performance under low, medium and dense networks compared to prior approaches.

5.6.1. Impact of Network Scales

Figure 5.5 illustrates the impact of network sizes (50,100, 200, 400 and 800 nodes) to skewness indexes of RPL DODAG topology. As is observed from the graph, the skewness indexes including M1, M2, M3, M4 in three separate levels (1,2,3) of existing routing strategies are higher almost three times our proposed scheme. Overall, the skewness values M1, M2, M3, M4 are significantly lower than existing objective functions such as OF0, MRHOF. As the increasing of the number of nodes, the skewness indexes of OF0 and MRHOF also increasing remarkably while the ones of SB-RPL go up slightly. From Figure 5.5(a), Figure 5.5(b), Figure 5.5(c) and Figure 5.5(d), we compare the average values of M1, M2, M3, M4 at the same Level 1. The skewness indexes M1, M2, M3, M4 of OF0, MH_ETX, MH_ETXSQ are quite similar and much higher than the ones of SB-RPL. Even when the network sizes are large as 400-node networks and 800-node networks, the balancing within SB-RPL DODAG is still quite stable. The reason for this is because SB-RPL considers the skewness and balanced metric in parent selection procedure to balance the size among subtrees in RPL.

5.6.2. Impact of Network Density

One of challenges which effects the stable of DODAG is network density. When network density increases, each node will have more connections with neighbors. Figure 5.7 compares the average skewness indexes under various types of topologies with different densities 4, 8 and 16 which equivalent to low, medium and dense networks respectively. Overall, the skewness indexes increase exponentially as the increasing of density. Figure 5.7(a), Figure 5.7(b), Figure 5.7(c) and Figure 5.7(d) compare the averages skewness indexes in level 1 of DODAG. The average value of skewness indexes increases rapidly as the increment of density in low and medium density. Then the skewness indexes increase slightly when the density increases from

8 to 16. At level 1, in dense networks, the skewness indexes show the big gap between SB-RPL and other schemes. At level 2 and level 2, the nodes are distributed widely, the skewness indexes of OF0, MH ETX and MH ETXSQ still rise gradually. Meanwhile, the M1, M2, M3, M4 of SB-RPL keep stably in various types of networks. First, thanks to $ST_p(t)$sss metric which indicates the size of the subtree, the skewness among subtrees in DODAGs are remain stable and avoid traffic congestion for thoroughly topologies. Second, besides subtree size, the efficiency of routing procedure relies on considering the link quality from joining node and parent candidate to guarantee quality for data transmission, remain the stable for RPL. Consequently, the skewness indexes of SB-RPL is always less than 3 times to existing schemes in low, medium and dense network environment.

CHAPTER VI: CONCLUSION

In conclusion, we have discussed the load balancing problem which is the key issue but it has not addressed efficiently when designing objective functions for RPL, given that scalability, energy efficiency and resource constrained are main characteristics of Low-Power and Lossy Networks. In effect, the load imbalance problems of RPL decrease the performance as well as waste network resources.

To remedy these problems, we have proposed a light-weight but effective solution, called SB-RPL, that aims to achieve balanced workload distribution among nodes in large-scale low power and lossy networks by exploiting the combination of multiple routing metrics as well as the skewness and balance among subtrees in RPL DODAG in support routing procedure. We implement SB-RPL in ContikiOS and conduct an extensive evaluation in computer simulation and on large-scale real-world testbed. We demonstrate the practicality of SB- RPL and its ability to consistently achieve the great balancing RPL trees and high end-to-end packet delivery performance by alleviating the congestion and providing the ability to support large networks.

As a part of future work, we are studying resource fairness issues among multiple RPL DODAGs and we tended to define an SDN-based [50-51] architecture to support RPL routing operation.

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요 약

IoT 네트워크에서 RPL 트리의 효율적 Load Balancing 전략

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저전력 저손실 네트워크(LLN)를 위한 IPv6 라우팅 프로토콜은 산업과 환경의 모니터링, smart grid, 무선 센서 통신 등의 여러 LLN 응용에 있어서 다양한 요구 사항을 충족하는 새로운 표준 라우팅 프로토콜 디자인이라고 여겨진다. 하지만 대규모의 네트워크에서 균형 잡히지 않은 센서 노드의 배치와 혼잡한 트래픽 때문에 특정 센서 노드는 다른 노드에 비하여 높은 작업량을 부여 받을 수 있다. 부하 분산 (load balancing) 메커니즘의 부재는 특정 노드로 하여금 더 많은 에너지를 소모하게 만들고 결과적으로 배터리로 작동되는 네트워크의 수명을 줄인다. 이 연구에서는 RPL 에서의 load balancing 과 이와 관련된 수치적 시뮬레이션과 대규모 테스트베드에서 발생할 수 있는 문제점들을 연구한다. 이러한 문제를 극복하기 위하여 우리는 topology 생성시 네트워크의 subtree 에서 link quality 와 skewness 를 포함한 여러 라우팅 metric 들을 이용한 비대칭 load balancing 라우팅 프로토콜인 SB-RPL 을

제시한다. 성능 평가 결과로는 실재 네트워크와 생성된 네트워크 모두 RPL 트리들이 라우팅 metric 들과 무관하게 심한 비대칭성으로 인하여 손해가 발생함을 확인하였다. 여러 컴퓨터 시뮬레이션과 실재 실험을 통하여 SB-RPL 이 기존의 RPL 에 비하여 end-to-end 패킷 전송에 있어서 트리 균형과 큰 성능 향상을 보였다.

주요어: 저전력 저손실 네트워크 (LLNs), RPL, Load Balancing, IEEE 802.15.4, IPv6, 사물 인터넷

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