A New Efficient Objective Function for Routing in Internet of Things Paradigm

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Abstract—Low Power and Lossy Networks (LLNs) have a crucial role in the Internet of Things (IoT) paradigm. For the IPv6 Routing Protocol for LLNs (RPL), two objective functions (OF) have been standardized so far, namely (Objective Function zero (OF0), and the Minimum Rank with Hysteresis Objective Function (MRHOF). However, these particular objective functions are used to build a topology where bottleneck nodes may suffer from an excessive unbalanced traffic load. As a result, a part of the network may be disconnected as the energy of the overburdened preferred parent node will drain much faster than other candidate parent nodes. Thus, in this paper, we propose a new objective function that balances the number of children nodes for the overburdened nodes to ensure node lifetime maximization. To implement this OF, we amended the DIO message format. By using a new utilization technique, we also mitigated any potential extra overhead. Finally, a new RPL metric has been introduced to balance the traffic load over the network. Simulation experiments have been conducted to examine the performance of our new approach. Collected results corroborate the superiority of our objective function over the existing ones in terms of lifetime, power consumption and packet delivery ratio.

Keywords—RPL, Objective Function, Low Power and Lossy Networks, Load balancing, Internet of Things.

I. INTRODUCTION

The potential applications of Internet of Things (IoT) are ample, starting from smart homes to smart cities. In this context, the Low Power and Lossy Networks (LLNs) play an essential role to underpin the deployment infrastructure for IoT. Thus, the different international standardisation bodies standardized new protocols across all OSI layers to meet the requirements and emerging applications of IoT.

One of the major driving forces behind those standards is to deal with the scarcity of energy in LLNs. This has been anticipated by the Internet Engineering Task Force (IETF), thus, they created the IPv6 over Low power WPAN (6LoWPAN) Working Group [1][2]. This group provides an adaptation layer to permit and optimize the transmission of IPv6 packets on top of IEEE 802.15.4 networks with different compression and translation techniques. However, 6LoWPAN required a companion technique to enable the end-to-end delivery of IP packets, i.e. a routing protocol, as most LLNs configurations are multi-hop.

To this end, the IETF Routing over Low power and Lossy networks working group (ROLL) standardized a new routing protocol called IPv6 Routing Protocol for LLNs (RPL) [1]. Up to now, two objective functions have been standardized in RPL to optimize the path selections towards the root node. The Destination Oriented Directed Acyclic Graph (DODAG) construction is influenced by the RPL objective function, which selects the preferred parent node by translating one or more metrics into the rank value. The used objective function calculates the rank based on some routing metrics such as hop-count, delay, energy, and so forth. The parent node in RPL can serve more than one child if it is chosen as preferred parent. Consequently, the overburdened preferred parents will become fragile nodes as their energy risks to drain much quicker than other nodes. After conducting an exhaustive performance evaluation, it is concluded that the current objective functions lead to build a topology that suffers from an excessive unbalanced load traffic in bottleneck nodes especially for those with the first hop nodes from the root. Subsequently, this problem has a crucial impact on the lifetime of these types of nodes. The battery depletion of that overloaded parent node may cause the disconnection of a part of the network and therefore the reconstruction of the DODAG.

To the best of our knowledge, this challenging problem is still unsolved as the existing works provide an inadequate lifetime for sensor nodes. To overcome this problem, we propose a new objective function to mitigate the overusing of the bottleneck node to prolong its battery lifetime.

Our contributions can be summarized as follows. First, we amend the DODAG Information Object (DIO) message by injecting the ID of the chosen parent before broadcasting it as detailed in section III. Second, we propose a new utilization technique for the amended DIO message to avoid increasing the overhead of the handshaking and acknowledgment processes. Third, a new RPL metric has been used to balance the load traffic between the bottlenecks nodes. Finally, we conducted excessive experiments to validate our objective function performance. The rest of the paper is structured as follows. Section II represents the related work. Section III describes the problem statement. Section IV covers the proposed load balanced objective function. Section V represents the performance evaluation. Finally, the conclusion and future work are given in Section VI.
II. RELATED WORK

The growing attention of the research and industrial communities towards RPL is sworn from the amount of the recently published research, where RPL has been studied under the umbrella of different contexts and platforms. The authors in [3] [4] show the effectiveness of RPL pertaining to exiguous delay, quick configuration, loop-free topology, and self-healing.

a. Objective Functions

Up to now, the IETF ROLL working group standardized only two different objective functions, namely, the Objective Function zero (OF0) [5], and the Minimum Rank with Hysteresis Objective Function (MRHOF) [1][6].

In [7] an optimization of the objective function was proposed to tackle the network scalability problem where large-scale networks suffer from long single hop. The authors in [7] developed a new metric by taking into account the link state and the number of hops of the potential routing path. Combining more than one routing metrics is applicable as suggested by [8]. The authors in this study proposed a composite metric including the remaining energy, the hop count, the RSSI (Received Signal Strength Indicator), and the ETX. The rank in this protocol is evaluated according to a composition function and then injected into the DIO message. Each metric will be given a weight, and the rank is driven from the sum of these weights based on the aforementioned function. Although combining two routing metrics or more could ameliorate the performance in the DAG, it might, in return, degenerates other performance parameters. To overcome the limitations discussed in [7], the authors in [9] proposed a QoS-aware fuzzy logic objective function. The holistic objective function combines four different metrics, namely, battery level, hop count, delay, and ETX which can categorize the quality of the route effectively using fuzzy logic techniques. In [3] [10] the authors analyzed the performance of the network formation process using a ContikiRPL simulator. Among other parameters, they verified how the two different OFs (i.e. OF0 and MRHOF) influence the average number of hops and the average node energy. The observed differences are insignificant due to the choice of the OFs and their specific parametrization, which results in similar outcomes when computing the rank. Authors in [11] indicated initial simulation results on the performance of RPL and loading in centralized architecture and scenarios that used less than or equal 50 nodes. However, the traffic patterns, as well as the size of the network tested are still limited. Several researchers have also tried different methods to optimize routing metrics, and OFs for RPL to meet different requirements in specific application scenarios [7] [12].

In [13] the authors investigated a case where the two OFs were run in the simulator as well as in a remote testbed. The results of the simulation and experimental measurements revealed that a simple hop-count OF leads to a shorter path length at the cost of a higher power consumption. Recently, several RPL simulations and implementations have been provided. In order to increase the lifetime of the network as well as the efficient packet delivery ratio, both the energy metric of nodes as well as the link quality metric should be used in the OF to obtain an energy efficient network performance. However, if the energy routing metric has been used alone in the OF then it may result in a high packet loss ratio [14].

b. Load balance routing protocols

It is obvious that minimizing the power consumption in LLNs plays a key role to extend the network lifetime, which is the focus of the most existing protocols. However, the traffic load balancing is also obligatory to improve the entire network lifetime, where each node consumes the comparable amount of energy. The load balanced routing protocols for LLNs have been studied extensively.

In [15] the authors proposed a dynamic parent selection, taking into account the recent traffic on the path to the root and the remaining energy as a composite metric. The collected information from DIO and beacon in MAC keeps those metrics updated. Another proposed protocol for load balanced in LLNs can be found in [16]. This protocol spread the load through a set of braided paths to minimize the holistic transmission cost. However, the minimum cost load balanced multipath protocol omitted the QoS with the multi-class minimum cost load distribution scheme. The proposed mechanism in [17] is to anticipate the remaining energy in bottleneck nodes and proposed a new metric called expected lifetime metric. Accordingly, the authors proposed multiple parents in RPL to boost the network lifetime. That can be achieved through mitigating the number of DODAG reconstructions.

c. DODAG construction in nutshell

RPL is a proactive distance vector routing protocol designed for LLNs [1], it constructs a DODAG using a certain objective function that suits the application requirements. Essentially, RPL relies on a DODAG Information Object (DIO) control message to build the DODAG. Thus, the starting point begins when the root (root) node broadcasts the DIO message to the neighbour nodes. As soon as the closest node receives the message, it can decide whether to join this DODAG or not based on the calculated rank according to the equations (1) and (2) [6].

\[
\text{Rank}(N) = \text{Rank}(PN) + \text{Rank increase}
\]

\[
\text{Rank increase} = \text{Step} \times \text{MinHopRankIncrease}
\]

Where Step represents a scalar value and MinHopRankIncrease represents the minimum RPL parameter. If the node decides to join, then it adds the sender to the candidate parent list. Next, the preferred parent, i.e. the next hop to the root, will be chosen based on the rank from this list to receive all traffics from the child node. Then, it computes its own rank according to the selected objective function. The selected objective function defines the way of calculating the rank with a monotonical increase to guarantee loop-free topology. After that, the node propagates its own DIO with all updated information to his neighbours as shown in Fig 1(b). An example of the sequence of DIO messages in DoDAG construction is depicted in Fig 1.
Two objective functions have been standardized by IETF, OF0 [5] and MRHOF [6] relying on the metrics hop count and ETX respectively. More metrics have been proposed in [7] such as node energy, throughput and latency and others as aforementioned in section II.a.

III. THE PROBLEM STATEMENT

RPL is designed with several robust features such as exiguous delay, quick configuration, loop-free topology, and self-healing. However, the load imbalance is considered as a significant weakness in this protocol. More specifically, RPL is dealing with non-uniform distribution in large-scale LLNs in addition to the uniform ones, which leads to unequal data traffic. Consequently, the energy of the overburdened nodes will be drained much faster than other nodes. Nevertheless, this problem has more harmful impacts if the overloaded node is a bottleneck node (i.e. those are with the first hop to the root) as depicted in Fig. 2. It is notable that the connection of the entire nodes through node 3 is fragile as it is the only link to the root. This leads to disconnecting this part of the network if node 3 dies. In particular, this serious problem befalls in RPL due to the parent selection technique. When the first DIO is received, the node chooses the sender as preferred parent.

To this end, the node sticks with the current parent as the quality of the link (represented in ETX metric) will keep getting better and influences the rank of this parent even if it deteriorates with more load (i.e. being a parent for more children). The ETX metric is calculated as follows:

\[
ETX_{\text{new}} = \beta \cdot ETX_{\text{old}} + (1 - \beta) \cdot ETX_{\text{packet}}
\]

(3)

where ETX_{packet} is the total number of transmissions of a packet before being successfully received or dropped and \( \beta \) is the learning ratio (\( \beta = 0.9 \) in ContikiRPL).

Back to our example, the only conceivable scenarios to change the current parent (i.e. node 3) to another candidate parent (node 2) are as follow: first, if the current parent dies due to battery depletion. The second possibility, when the lossy percentage becomes higher than before, so no acknowledgement message can be heard from the preferred parent for a certain period of time.

IV. THE PROPOSED LOAD BALANCED OBJECTIVE FUNCTION

Our proposed objective function leverages the lifetime of the entire network routed by RPL. Our load balanced objective function (LB-OF) balances the data traffic by taking into account the number of children for each candidate parent. Basically, several steps have been put forward as follows:
(1) Amended the DIO, (2) A new utilization technique for the amended DIO, (3) New RPL metric to balance the traffic load. A summary of LB-OF operation is described in Algorithm 1.

(1) The amended DIO: Typically, the DIO carries the RPL InstanceID, DODAG identifier, version number, Rank and the objective function that has been used to calculate the rank. We amended the DIO by injecting the chosen parent ID into the broadcasted DIO as illustrated in Fig. 1.

(2) A new utilization technique for the amended DIO: Generally, in the upward routes the root initiates the DODAG construction by sending the first DIO message as shown in Fig. 1 (a). Once other nodes receive this DIO, they select the sender as a preferred parent, and then they start calculating their own ranks based on the assigned objective function. After that, each node broadcasts its own DIO message (i.e. the updated DIO that contains the new calculated rank value) to all neighbours.
including the chosen preferred parent who sent the original DIO message as Fig. 1(b) depicts. In the standard objective functions, the preferred parent ignores the DIOs that come from its child. So here in our example, the root drops any DIO, whether this DIO message is sent by node 2 in Fig. 1(b) or sent by node 4 in Fig. 1(c). In this stage, we aim to allow each parent to count its number of children to normalize the load balance based on it. However, that is not possible in the upward routes, as the only control message that can be acknowledged by the destination is the Destination Advertisement Object (DAO) message in the downward routes.

Moreover, the DAO messages can be only sent if the DODAG has been already constructed, and our aim is to recognize the number of children for each parent while the DODAG is under construction not after that (i.e., in the upwards routes not in the downwards routes). Alternatively, a handshaking mechanism between parent and children can be set up, but this also brings extra overhead for the entire network and subsequently increases the power consumption massively. To overcome this problem, we propose LB-OF using a new technique as detailed below.

In LB-OF algorithm, the received DIO from the child node is counted by the preferred parent node using a special buffer (set) created for this purpose. As mentioned in step (1) the amended DIO contains the ID of the chosen preferred parent. Thus, the node matches its own ID with the preferred parent ID that is inserted in the DIO message, then increments the number of children set by one for this node if there is a matching.

Hence, this technique evades increasing the overhead that can be caused by the handshaking process for the entire network. In addition, we utilize the coming DIO and allow each preferred parent to distinguish the number of its children during the DODAG construction stage.

![Algorithm 1: LB-OF Algorithm](image)

Based on that, we consider the number of children in the rank calculation formula (1) rather than ETX.

![Fig. 3. The bottleneck nodes](image)

In more specific words, the parent with the least number of children will be elected as preferred parent. To this end, the balance has been achieved by declining the number of children of the overloaded bottleneck node. As a result, the majority of children will choose another preferred parent according to the lower rank, and surely has less number of children. An illustrative example is given in Fig. 3, where the unbalanced load traffic can be noticed in MRHOF, where node 3 has 16 children and node 2 has only one child. On the contrary, using LB-OF both bottleneck candidate parents have almost the same number of children, node 3 would have 9 children and node 2 would have 8 children.

V. PERFORMANCE EVALUATION

To evaluate our objective function, we conduct simulation experiments using the Cooja simulator [19]. This simulator can be considered as a hybrid approach in terms of the cross-level emulation and simulation tool based on Instant Contiki 2.7 operating system [19]. Contiki is a lightweight, highly portable open source operating system and dedicated for WSNs and IoT. The simulation parameters are given in Table 1.

![Table 1. Simulation configurations for experiments](image)
Fig. 4 compares the power consumption between the two critical nodes (i.e. node 2 and node 3) using two different objective functions. In the conventional objective functions MRHOF and OF0, the traffic load is concentrated on the node 2 as it has more children than node 3. This is because the rank of node 2 is always better than node 3 in terms of ETX. Consequently, this leads to a significant difference in power consumption. In contrast, in LB-OF, the load balancing has been achieved by taking into account the number of children for each node as a metric. Clearly, the power consumption of node 2 is mitigated in LO-OF and then relatively stabilized. The main reason behind that is the regression in the number of children from 14 to only 8 children for node 2. On the other hand, node’s 3 power consumption is increased as it became parent for more children (i.e. 6 children) than before (1 child). Therefore, the gap between those two critical nodes has been massively declined using the new LB-OF objection function, and undoubtedly the traffic load is balanced.

Likewise, in Fig. 5 we increased the density of network to 50 nodes rather than 17 as the previous scenario. Thus, we ended up with the same behavior in Fig. 4. However, the power consumption levels for both nodes using LB-OF has been raised compared to the results illustrated in Fig. 4. The main reason behind this is the parent churn i.e. the fluctuation in the number of children for each parent is quite frequent. That can be concluded from Fig. 6, where the high fluctuation can be observed at the first 12 mins.

Subsequently, node 2 and node 3 became parents for 8 nodes and 6 nodes respectively. Hence, the churn stabilized until the end of the second period (33-52) mins, then fluctuated again but with less oscillation. After that, each parent sticks with its number of children with a churn equals to zero as clearly exhibited in Fig. 6.

The ultimate goal of this protocol is to guarantee the load balancing for the critical nodes in order to avoid the negative impact on the lifetime of one node at the expense of another node lifetime, subsequently allows evading bottleneck nodes. So, we evaluated the network lifetime where Fig. 7 compares the lifetime between the two critical nodes. The unbalanced lifetime is obvious when MRHOF or OF0 is used.

Contrariwise, LB-OF balances both nodes which allow node 2 to sustain longer and minimizing the probability of disconnecting the fragile nodes. Overall, our objective function outperforms the standard RPL MRHOF and OF0 in terms of lifetime. Fig. 8 illustrates the packet delivery ratio (PDR) versus network density. The PDR is calculated as the ratio of the number of packets received by the border router and transmitted.
by each node. It can be noticed that the results of MRHOF, OF0 and LB-OF are nearly identical in terms of PDR when the network density is 17 and with a slightly difference when 50 nodes. However, LB-OF presents a better PDR than MRHOF and OF0 when the density is 100. As the number of lost packet is increased when one critical node serves the majority of nodes and acts as a hub to the root.

VI. CONCLUSION AND FUTURE WORK

Load balancing is a key issue, but it was not properly addressed when designing existing objective functions in LLNs. Thus, we propose a new load balanced objective function for RPL protocol to achieve a better workload distribution among all nodes in LLNs. Simulation results show that the proposed load balanced objective function is better than the MRHOF and OF0 in terms of balanced power consumption, packet delivery rate, balanced lifetime, and a number of children for each node. Future work will address the best combination of different metrics in addition to the number of child metric to fulfill the application requirements.

REFERENCES