On the Need for Efficient Load Balancing in Large-scale RPL Networks with Multi-Sink Topologies

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Abstract

Low-power and Lossy Networks (LLNs) have become the common network infrastructure for a wide scope of Internet of Things (IoT) applications. For efficient routing in LLNs, IETF provides a standard solution, namely the IPv6 Routing Protocol for LLNs (RPL). It enables effective interconnectivity with IP networks and flexibly can meet the different application requirements of IoT deployments. However, it still suffers from different open issues, particularly in large-scale setups. These include the node unreachability problem which leads to increasing routing losses at RPL sink nodes. It is a result of the event of memory overflow at LLNs devices due to their limited hardware capabilities. Although this can be alleviated by the establishment of multi-sink topologies, RPL still lacks the support for effective load balancing among multiple sinks. In this paper, we address the need for an efficient multi-sink load balancing solution to enhance the performance of PRL in large-scale scenarios and alleviate the node unreachability problem. We propose a new RPL objective function, Multi-Sink Load Balancing Objective Function (MSLBOF), and introduce the Memory Utilization metrics. MSLBOF enables each RPL node to perform optimal sink selection in a way that insure better memory utilization and effective load balancing. Evaluation results demonstrate the efficiency of MSLBOF in decreasing packet loss and enhancing network stability, compared to MRHOF in standard RPL.

Keywords:
Low-power lossy network (LLN), Wireless Sensor Network (WSN), RPL, Load Balancing, Multi-Sink

1. Introduction

Low-power and Lossy Networks (LLNs) consist of resource-constrained devices with limited processing power, memory, and energy resources. Due to the lossy nature of radio links, the constrained devices would be interconnected by unreliable and unstable links, with limited bandwidth and short communication ranges. These restrictions are challenges to developing efficient routing solutions for LLNs. The Internet Engineering Task Force (IETF), specifically the Routing Over Low power and Lossy networks (ROLL) working group, has standardized the IPv6 Routing Protocol for LLNs (RPL). It is designed to meet the requirements of many LLN applications in a customized and flexible manner.

RPL [1] is a distance vector routing protocol that allows bi-directional IPv6 communication on embedded networking devices. It supports three data traffic flows, peer-to-peer (P2P), multipoint-to-point (MP2P), and point-to-multipoint (P2MP) traffic. Moreover, topology in RPL is organized as a Directed Acyclic Graph (DAG) which can be divided into one or more Destination Oriented DAGs (DODAGs) rooted at a sink node. The DODAGs can be associated with one or different RPL instances. Each Instance is established using a certain Objective Function (OF) which specifies how routes are constructed in DODAG and how nodes translate the metrics and constraints into a numeric value, referred to as rank. So far, only two OFs have been supported by standard RPL, the Minimum Rank with Hysteresis Objective Function (MRHOF) and Objective Function Zero (OF0). Due to the flexibility of the RPL OF concept, a new OF can be designed if the existing OFs in standard RPL do not satisfy the requirements of the application. Moreover, RPL supports two modes of operation (MoP), a storing and non-storing mode. In the former, all joining nodes in the RPL network store the routing information in routing table entries for each destination in their sub-DODAG; thus, this mode of communication requires higher memory capacity. In the non-storing mode, only the sink has routing access to all the network destinations, and no routing tables need to be maintained by the non-sink nodes.

RPL was originally designed with consideration of memory limitations. However, memory overflow would occur in dense topologies as a result of the limited hardware capabilities of LLN devices. This leads to the problems of node unreachability and routing failures. Even in the case of having multi-sink setups, RPL fails to efficiently support load balancing among multiple sinks. The absence of an efficient mechanism of load-balancing among the sinks in large-scale scenarios would degrade network stability and reliability. Therefore, in this paper, we propose a novel RPL objective function that addresses such problems. It relies on a practical solution that incorporates existing concepts, such as multi-sink load balancing, memory-overflow avoidance, peer-to-peer communication, and DAG selection. Our mechanism supports multi-sink RPL networks.

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The remainder of this paper is structured as follows; Section 2 discusses the related work of existing proposed solutions for this problem; Section 3 describes the RPL load balancing problem; Section 4 thoroughly describes the proposal; in Section 5 we evaluate the performance; and, finally, Section 6 presents the conclusion and proposals for future work.

2. Related Work

Various enhancements have been achieved to the standard RPL in recent years. The focus has been on introducing several OF and routing metrics to advance its basic functionalities. For instance, [2] proposes a load balancing solution, called QU-RPL, by avoiding queue overflows. It allows each node to use two metrics, queue utilization and hop distance to the sink, during the parent selection process. By evaluating it in a real testbed, the authors have proven the practicality of their proposed protocol over RPL. Moreover, the work in [3] extends the RPL protocol to improve network lifetime and decrease packet loss. This was based on considering the remaining queue and energy level of candidate parents besides the ETX metric in the parent selection mechanism. Similarly, [4] proposed Quell, an alternative objective function which relies on both the queue length and ETX metrics for the selection of parent node.

An energy-balanced RPL was also introduced in [5], which distributes fairly the energy consumption among all the bottleneck nodes by supporting multipath structure. [6]and [7] introduced enhancements to RPL reliability, energy consumption, and load distribution. [6]combined child node count and other primary metrics, such as ETX and hop count in parent selection mechanism. [7] presented ETXPC-RPL which was based on the ETX and parent account metrics.

[8], [9], and [10] have each proposed an OF which prevents overloaded nodes from being rapidly drained, resulting in an increase in network lifetime. Authors in [8] proposes an objective function for efficient routing (OF-ER) to increase the lifetime of all the nodes. It was based on avoiding congested paths by diverting network traffic through the paths with less-congested nodes and fewer energy-constrained nodes. On the other hand, the proposed solution in [9] was based on restricting the selection of overloaded nodes during parent selection and enabling nodes to detach from overloaded parent nodes.

Other solutions were proposed based on sink selection instead of parent selection mechanism in single-sink load balancing. For instance, in [11], the sink-selection process is based on tree size to facilitate tree balancing across the network sinks. However, the greedy selection of the least tree size may give rise to the overloading of bottleneck nodes, since not all the nodes are equal in hardware capabilities. On the other hand, [12] presented a dynamic and distributed load balancing algorithm for multiple sinks based on 6LoWPAN, named MLEq. It was based on distributing the traffic of intersection-area nodes across the sinks to reduce the traffic congestion and satisfy the capacity fairness. Furthermore, [13] introduces different OFs and metrics such as hop count, available bandwidth, delay, buffer occupancy, and ETX; and analyzes the impact of duty-cycling, the number of sinks, and the data traffic load on RPL performance in multi-sink scenarios. The dual objective of single-sink and multi-sink load balancing in WSN is addressed in [14]. The Reactive and Adaptive Load-Balancing (RALB) algorithm is proposed to combine multiple path metrics as well as sink conditions to balance traffic loads in large-scale scenarios.

It can be seen that most of the proposed OFs are specific to the single-sink scenarios without sufficient consideration of multi-sink load balancing. Furthermore, the issue of memory overflow in large-scale scenarios has not been effectively addressed in the context of multi-sink topologies. It is evident that there is a need to address efficient load balancing in conjunction with memory-overflow avoidance. Thus, our proposed work fills this gap and provides an effective OF that satisfies such a need while conforming to the standard RPL.

3. Problem Statement

In standard RPL networks, in particular with the storing mode, each node stores the reachability information in its routing table entries for each RPL node in its sub-DODAG. If any node has no free memory for a new destination, as a result of the limited hardware capabilities of typical LLN, it rejects the route advertisement (DAO message) and becomes unable to forward traffic for that particular destination. In the common RPL implementations, such as in ContikiOS and TinyOS, the DAO message is silently dropped. As a result, the path would be partially built, since the destination remains unreachable to the sink. Consequently, the sink is left with no choice but to drop incoming packets destined to that destination.

To illustrate the impact of this problem in P2P traffic, where the sink is neither source nor destination, we consider the following scenario depicted in Fig. 1. Assuming that node A is unable to act as a packet forwarder due to its lack of memory, therefore node R becomes unreachable to node A and to all higher nodes in the DODAG, including the sink S. If node G sends a data packet destined to node R, the packet is first transmitted to R's preferred parent, then to the common ancestor node A. While there is no routing entry corresponding to node R in A's routing table, node A forwards the packet to its parent node. This process continues until the data packet reaches sink S. Eventually, the packet is dropped as the sink S fails to redirect it to the destination node R without a corresponding routing entry in its routing table. Hence, all the packets sent to unreachable nodes are dropped after they have been forwarded upward to the common ancestor, which is, ultimately, the sink.

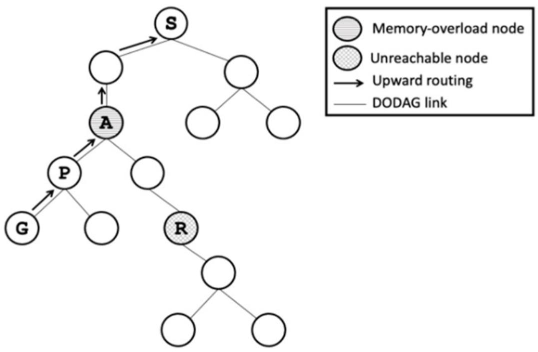

Figure 1: Unreachability problem example

Therefore, this unreachability problem leads to high packet drops which adversely affects the protocol reliability. This is more significant in the cases of large-scale topologies where large sub-DODAGs can be segregated and remain unreachable. In the simple example scenario represented in Fig. 1, the three nodes constituting the sub-DODAG of node R would also become out of reach to all the other nodes.

In addition to memory overflow, there are other causes of packet drops in RPL networks. These include link loss, which happens if the packet exceeds the retransmission limit; and, queue loss, which is caused by buffer overflows. Load balancing is a common approach to address packet loss resulted from limited link capacity and queue size. Nevertheless, less attention was paid to routing loss by RPL sink nodes due to the memory overflow problem. Considering that it may happen earlier than link and queue losses and would occur in even light traffic scenarios, addressing routing loss is perceived more critical to minimize packet loss. According to the results in [15], the packet loss percentage caused by a routing loss in the storing mode is extremely high, compared with link and queue losses. More specifically, RPL with storing mode suffers from high packet drops, routing failures, and unreachable destinations due to having no memory space to store the routing entries for all child nodes in nodes' sub-DODAG.

In standard RPL networks with multiple-sink topologies, memory overflow is not recognized by OF0 and MRHOF. With the existence of memory-overflowed ancestor nodes and continuous occurrence of routing loss, affected RPL nodes do not change their sinks. To the best of our knowledge, neither the standard RPL OFs nor existing proposed OFs take into consideration a sink selection based on minimizing routing loss and avoiding the unreachability problem. To overcome this problem, adopting new routing metrics and applying an effective DODAG selection strategy specified for large-scale scenarios is recommended.

4. The Proposed Load Balancing Objective Function in Multi-Sink

In this section, we present the proposed Multi-Sink Load Balancing OF (MSLBOF) to address the load balancing problem across multiple sinks. It is based on a dynamic update of RPL according to the DAG status in order to achieve effective load balancing across the sinks. MSLBOF aims to extend MRHOF with other parameters along with ETX in a way that helps RPL to distribute the load more evenly across the sinks and avoid unreachability problems. ETX usually offers a channel status estimation that is related to link loss but may not reflect the actual status of the network [2].

Furthermore, routing loss may happen earlier than link loss in resource-constrained RPL networks with hundreds of nodes having limited memory capacity. Therefore, we combine node rank with memory utilization indicators that take into consideration the DODAG status during the sink-selection process.

4.1 Memory Utilization Metrics

In MSLBOF, Memory utilization is modeled by two sink's metrics, that provide composite indicators of the DAG status. The first one is the DODAG size metric which allows balancing the sink's load by considering the number of nodes for each sink. The DODAG size plays a key role in the unreachability problem, as increasing DODAG size leads to memory overload in high-level located nodes. This results in some destinations being unreachable to the sink, which triggers routing drops. MSLBOF allows each sink to count the number of nodes in its DODAG and advertise it. This information is then utilized by each node to achieve optimal DAG size distribution across the sinks in the network. Accordingly, the sink with the least number of nodes will be elected by the node as a preferred sink.

Since not all nodes are equal in respect to hardware capabilities; some nodes may have smaller routing table sizes than other nodes in the same network. Thus, the greedy selection of the lesser loaded sink may lead to overloading some critically placed nodes and give rise to the unreachability problem and routing loss [14]. To overcome this problem, the DODAG-size metric operates in conjunction with another memory utilization metric called reachability metric. It requires each sink to record dropped data packets sent to unreachable destinations, in P2P traffic networks and propagates this information via DIO control messages. This enables a practical way to monitor the reachability of the DODAG nodes by detecting the routing loss that occurs in sink nodes as a result of memory overflows.

Therefore, combining Memory Utilization metrics with ETX provides a better understanding of the DAG status. This allows RPL nodes to perform optimal sink-selection towards achieving effective multi-sink load-balancing.

4.2 Propagation of Load Balancing Information

In MSLBOF, each sink distributes its LB information in transmitted DIO messages to its DODAG nodes. There are several approaches to implementing Information propagation in standard RPL. These include using a Metric Container within the DIO message or adding a new DIO option, then modify the OF to utilize that information during the processing of the DIO messages. Since, both use the existing control message type (i.e., DIO message) and within standard RPL scope, we adopted the second approach for MSLBOF. A new standard ICMP option named Sink Load-Balancing Option (SLBO) is included in each DIO control message. When a sink generates a DIO message, it scans its routing drop counter to get the number of routing drop packets. It then updates the number of nodes that are joint to its DODAG (DODAG size) in order to inject them into the SLBO option as depicted in Fig. 2. This information has to be updated and recorded in each DIO; accordingly, all the nodes have the latest updates. In this way, we utilize the transmitted DIO message with the 4-byte overhead required to carry the SLBO option and evade extra overhead that can be caused by adding a new control message for the entire network.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Type = 0x10   |Opt Length = 2|    DAG Size    | Routing Drops |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

4.3 Sink Selection Mechanism

In standard OFs, the sink-selection process is based on the best rank regardless of other metrics that give information about the stability and reliability of the sinks. However, MSLBOF goes into action when a node *n* that is associated with current DAG s_1 receives a DIO message from a parent in a different DAG s_2. Hence, the sink-selection process starts by adding the Memory Utilization Metrics, including The Dag size metric *dag_size()* and reachability metric *routing_drop()* to the Rank *rank()* in order to select the best sink. The main equations of MSLBOF are shown in (1) and (2):

$$Q(n,s) = \alpha_a\, rank(n) + \alpha_b\, dag\_size(s) + \alpha_c\, routing\_drop(s) \quad (1)$$

Where $\alpha_a + \alpha_b + \alpha_c = 1$, these coefficients are used as weight factors that are defined based on the application requirements. The normalized values *rank(), dag_size(), routing_drop()* are combined as a weighted sum operation. Afterward, the node n selects the best sink as

$$min\ \{Q(n,s_1),\ Q(n,s_2)\} \quad (2)$$

Algorithm 1: Sink Selection Algorithm

```
Function best_sink(s1,s2)
Input: s1,s2
Output: Preferred Sink (PS)
    if s1 = PS Then
        if Q(n,s1) ≤ Q(n,s2) + μ
            return s1
        else
            return s2
        end if
    else if s2 = PS Then
        if Q(n,s2) ≤ Q(n,s1) + μ
            return s2
        else
            return s1
        end if
    end if
end function
```

Algorithm 1: SLBOF Sink-Selection Algorithm

Thus, MSLBOF allows each node to select the sink node having the lower number of nodes in its DODAG and fewer routing drops instead of only Rank-based selection. The details of the sink-selection process are illustrated in Alg. 1. Each node runs a separate instantiation of this algorithm, upon the reception of DIO messages from different DODAGs.

4.4 Avoiding the Herding Problem

Most existing load balancing mechanisms suffer from the instability problem as a result of the continuous switching to reach the load balancing across the network's sinks. This problem is named as Herding Effect and resulted from weakly implemented load-balancing OF. It leads to a high switching rate trying to achieve equal load distribution regardless of the topological stability.

Therefore, an efficient load balancing mechanism implies providing the protocol with a fair distribution among sinks as well as ensuring network stability. To mitigate unnecessary DAG switches, we have taken an approach called stability condition. As each time the node *n* that is joint to DODAG s_1 receives a DIO message from different DODAG s_2 it decides to switch to g_2 if

$$Q(n,s_1) > Q(n,s_2)) + \mu \qquad \text{where } 0 < \mu < 1 \qquad (3)$$

where μ is a stability constant added to sink-selection equation (3) in order to minimize inefficient and useless DODAG switches.

5. Evaluation

5.1 Evaluation Setup

To evaluate the proposed solution, we carried out experimental simulations with the Cooja Simulator. It is an emulation and simulation tool available as a part of Contiki OS and enables working its RPL implantation. Contiki 3.0 was utilized in all the experimental setups. In order to analyze the performance of MSLBOF, we compare it against MRHOF in ContikiRPL. The configuration parameters given in Tab.1 were considered for all the carried out experiments.

Table 1: General configurations in experiments

Parameter	Configuration
Simulation Duration	2100 sec.
Simulation area	110 x 110 m^2
Network Scale	100 nodes (including 2 sinks)
Mote Emulated	Z1 mote
Radio Model	Unit Disk Graph Medium (UDGM)
Node Spacing	10 m
Transmission Range	13 m

In our physical topology, we consider a uniform 2D-grid within an area of size 110m x 110m. The network consists of 100 nodes, each of which is Z1 motes, with two sinks that are placed in the top-left and top-right corners of the topology. The Z1 Zolertia platform is equipped with a 16 MHz MSP430F2617 microcontroller, 8 Kbytes RAM, and 92 Kbytes ROM for storage.

Each sink has two node lists: the sending and receiving lists. Nodes in the sending list continuously generate an IPv6 data packet of 127 bytes in size. The packets are sent to the nodes in receiving list in order to satisfy P2P communication. Each experiment takes 2100 sec. and the simulation results are averaged over 10 simulations.

5.2 Results and Discussion

The comparison was made according to different network measures and considering critical performance aspects. These include Packet Delivery Ratio (PDR), loss ratio, and network overhead.

As depicted in Fig. 3, MSLBOF shows significant improvement in PDR. MSLBOF demonstrates higher PDR, which is about 16% more, compared to MRHOF in standard RPL. MSLBOF helps each common node located between two DODAGs to effectively select the best sink considering memory utilization metrics and avoid the unreachability problem.

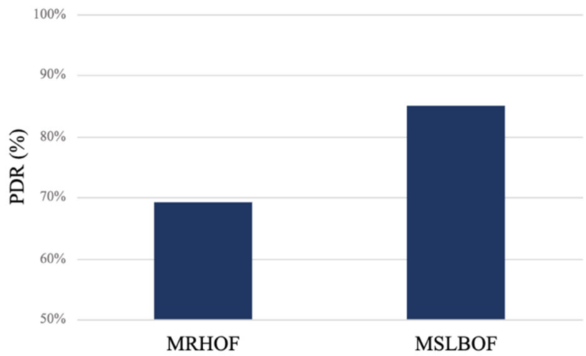

Figure 3: Packet Delivery Ratio

Fig. 4 shows the routing loss ratio for each sink in the cases of MRHOF and MSLBOF. As MSLBOF applies the memory utilization metrics to evenly distribute the nodes across the sinks, it shows a high reduction in routing loss ratio. We observed in MRHOF that sink1 suffered from higher routing loss due to the memory overflow problem. It is evident that MSLBOF succeeded in balancing the load across the sinks and enhancing P2P communication.

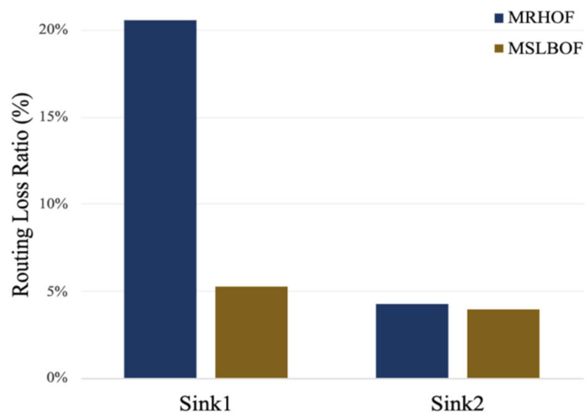

Figure 4: Routing Loss Ratio per sink

Considering the limitations in embedded memories of IoT devices, the majority of the packet loss in MRHOF is routing loss compared to other losses (i.e. queue loss, link loss) as shown in Fig. 5. Higher routing loss resulted in inappropriate DODAG selection in MRHOF. MSLBOF handled this problem by using proper metrics for effective DAG load balancing to avoid overloaded- memory and unreachability problems. In general, MSLBOF achieved a lower packet loss ratio compared to MRHOF.

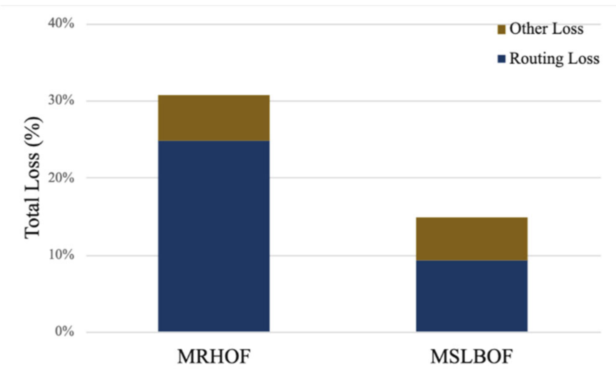

Figure 5: Total Loss Ratio

Network stability is highly affected by DODAG switches, as increasing the number of switches means extra control overhead to the network and less network instability. Fig. 6 presents the number of transmitted DIO and DAO messages. MSLBOF has fewer transmitted control messages, which means that the topology tends to be more stable than MRHOF. Furthermore, MSLBOF showed a reduction in the number of DODAG switches, up to 76%, due to applying the stability-condition approach.

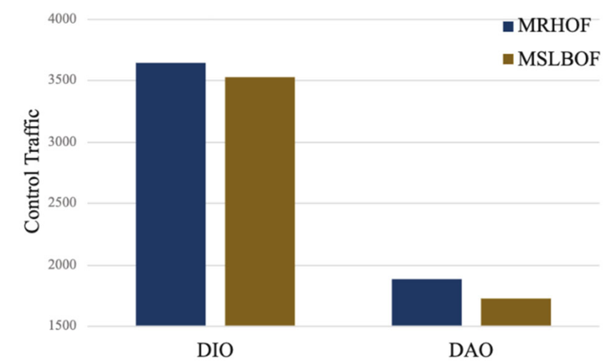

Figure 6: Control message overhead

6. Conclusion

Node unreachability is a common problem in RPL networks, particularly with large-scale setups. It results in critical routing failures due to memory overflows. The proposed solution in this paper enables RPL with an effective objective function, MSLBOF, to alleviates such a problem in RPL multi-sink setups. It allows each node to select its sink according to newly introduced memory utilization metrics. MSLBOF demonstrated significant improvements compared to MRHOF-RPL. It was able to achieve higher PDR and lower packet loss while maintaining better network stability. Expanding the scope of this work in terms of applying other parent selection mechanisms and adopting a different set of metrics will be the primary focus of future work.

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