Analysis of Energy Consumption and Topology of Routing Protocol for Low-Power and Lossy Networks

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Abstract. Internet of things (IoT) are getting more deployed in different environment where they provide many benefits for industrial and home automation, smart buildings, medical and environmental monitoring. Sensors are low cost devices with limited storage, computation, and power. Finding optimal based routing solutions is a challenging task in IoT because of constraint over nodes and lossy links. IETF standardized the IPv6 based RPL routing protocol for Low power and Lossy Networks (LLNs) in 2012. It selects the ideal routes from a source to a destination node based on certain metrics injected into the Objective Function (OF). Because RPL uses the DODAG topology, it is easy to lead to the rapid depletion of node power at the upper level of the routing topology. Reducing the network energy consumption to prolong the life cycle of network is very important for IoT. In this paper, we investigate the energy consumption and topology of RPL routing protocol and put up some proposals for a plethora of IoT applications.

1. Introduction
At present, the development of Internet of Things (IoT), in which devices or things are connected via the IP protocol stack, has given rise to a lot of interesting fields of research. Most of those devices are characterized by limited hardware resources such as low processing capability, little memory, low power and limited communication capabilities such as short range, low bitrate and short frame size. The common communication technologies for IoT are IEEE 802.15.4, Low Power Wi-Fi and theses types of network are called Low Power and Lossy Networks (LLNs) [1]. In 2012, the IETF ROLL working group [2] came up with the IPv6 Routing Protocol for Low power and Lossy Networks (RPL) routing protocol in an attempt to standardize the routing process for LLNs. The inherent LLNs of low data rates, high probability of node and link failures, and scarce energy resources, have turned the design of RPL challenging and different from previous routing proposals.

Energy consumption is the first order constraints of IoT, and it is indispensable to evaluate the energy consumption of an IoT running RPL. The energy consumption of the IoT includes the energy consumption of a single node and the energy consumption of the whole network. A single node works in five ways, including full function operation, low power operation, sending, listening, and receiving. Full function operation uses maximum energy consumption. The energy consumption of a single node is also related to the transmission distance of radio frequency signals. The IoT mainly relies on multi-hop forwarding data, the nodes near the root node assume the data forwarding tasks of other nodes, and the energy consumption is faster, which results in unbalance energy consumption of the network. In this paper, we conduct analysis of energy consumption of IoT running RPL. Firstly, we evaluate the energy consumption of the whole network to get an overall picture on energy. Then we study the energy consumption of individual nodes to get more insights on topology. The difference of
energy consumptions between client nodes is also evaluated and analyzed.

The rest of the paper is structured as follows. Section 2 deals with an overview and background of RPL protocol, Section 3 shows the evaluation environment and methodology, Section 4 is the analysis of network power consumption, and finally the conclusion and future work are given in Section 5.

2. Overview and Background of RPL Protocol

2.1. Overview of RPL

RPL [1] is a distance vector protocol that constructs a Destination-Oriented Directed Acyclic Graph (DODAG) using one or more routing metrics. The DODAG construction is based on the Rank of a node, which depicts its relative distance to the DODAG root (i.e., the border router). An Objective Function defines how the routing metrics should be used to compute the Rank. In order to have a loop-free topology, the Rank must strictly monotonically increase from the root toward the leaves of the DODAG.

The construction and maintenance of the DODAG is ensured by DODAG Information Object (DIO) messages periodically broadcasted by all the nodes. When a node receives a DIO, it inserts the emitter in the list of possible successors (next hops to the border router). From all the successors in this list, the node will choose as preferred parent the one advertising the lowest Rank. It then computes its own Rank with the Objective Function and starts broadcasting itself DIO messages.

Figure 1 shows a simple example of DIO propagation and DAG formation. The DAG root initiates the DAG formation by advertising information about the DAG using the DAG Information Option (DIO), which carries several information regarding the DAG, including the issuing node's distance from the border router. Nodes chose a node as their parent which provides the lowest cost to reach the border router. The solid lines in the figure represent the parent-child relationship in the DODAG, whereas the dotted lines represent other available links. RPL has been standardized to operate on two modes, ‘non-storing’ mode and ‘storing’ mode. In storing mode, a node in the LLN is capable of storing routing tables and next hop information for all the nodes in its sub-tree. In non-storing mode, nodes do not store routes to any destination other than the DAG root. Data routing in RPL non-storing mode is showed in Fig 2.1 and Fig 2.2 shows the Data routing in RPL storing mode.

Figure 1 DIO propagation and DAG formation
2.1. DIO, DIS, DAO

1) DIO: DODAG Information Object (multicast). A DIO packet carries information that allows a node to discover a RPL instance, learn its configuration parameters, select a DODAG parent set, and maintain DODAG. DIO packets are firstly sent by the root (or sink) and then periodically by each node of DODAG. In absence of changes in the DODAG structure, the period duration increases exponentially.

2) DIS: DODAG Information Solicitation (multicast). A DIS packet is used when a node joins the network in order to solicit a DIO from a RPL node.

3) DAO: Destination Advertisement Object (unicast). A DAO packet is used to propagate destination information upwards along the DODAG. The message is unicast by a child to the selected parent to advertise their addresses and prefixes. When a node receives a DAO, it updates its routing table.

2.2. MRHOF and OF0

One of the major driving forces of RPL design is meeting the requirements of WSNs and in particular to suite the IoT. One of the key issues within RPL is selecting the Objective Function which is used to find the suitable path [3]. The Internet Engineering Task Force (IETF) specified two kinds of OFs: Objective Function Zero (OF0) and Minimum Rank with Hysteresis Objective Function (MRHOF). RPL OF defines which parent will be selected for each node, and thus establishing routes. OF0 [3] uses hop count as routing metric meaning that the path with the least number of hops is used and parents are selected to satisfy this goal. MRHOF [4] utilizes the expected number of transmissions (ETX) in its routing metric; parents are selected so that the expected number of required transmissions will be the smallest possible. The use of other metrics or their combinations is left to designers.

3. Evaluation Environments and Methodology

We use the Contiki operating system and Cooja simulator to evaluate the energy consumption of the RPL implementation. Contiki is a flexible and portable OS [5]. For communication, Contiki provides powerful low-power Internet communication. Contiki supports fully standard IPv6 and IPv4, along with the recent low-power wireless standards: 6LoWPAN, RPL, CoAP. With Contiki's ContikiMAC and sleepy routers, even wireless routers can be battery-operated. Cooja is a simulator based on the Contiki OS using sensor nodes [5]. Cooja is open source software, which is compatible with our needs for this study. Cooja offers the possibility to simulate each node independently using either hardware or software. It can operate at the network level, the operating system level, and the machine code instruction level. It can run on different platforms such as Sky, TelosB, and native (etc.) and can simulate each node separately. The flexibility of Cooja makes it possible to add some extensions in the simulator [6].

In this paper, the simulation experiment sets up 10 sub nodes and one root node, all nodes are
randomly deployed in the simulation area, and their location does not change. Among them, the root node is responsible for initiating the network and gathering the data. The root node has enough energy supply, without considering the power problem. The sub node is powered by the battery in practical application. In simulation, finite and identical initial power is set for all the child nodes. All child nodes have the same configuration and are fully functional nodes with routing capabilities. The simulation environment and the simulation parameter settings are shown in the following table 1.

| Parameters                  | Value                                                                 |
|-----------------------------|----------------------------------------------------------------------|
| OS                          | Contiki OS 3.0                                                        |
| Area                        | 400m*400m                                                            |
| Nodes Layout                | Random                                                               |
| Number of Nodes             | 11 and 25                                                            |
| Radio Mediums Model         | Unit Disk Graph Medium(UDGM):Distance Loss                           |
| Ranges of Nodes             | Rx and Tx : 100m                                                      |
| MAC Layer                   | IEEE 802.15.4                                                         |
| Duty Cycle                  | nullRDC                                                              |
| Network protocol            | ContikiRPL                                                            |
| Objective Function          | MRHOF                                                                |
| Application program         | Examples/ipv6/rpl-collect                                            |
| Mote Type                   | Sky Mote                                                             |

4. Analysis of Network Energy Consumption and Topology

Figure 3.1 Nodes in Cooja network panel Figure 3.2 Network topology of Nodes (MRHOF)
Figure 3.1 shows 11 nodes in Cooja network panel and Figure 3.2 is the network topology of those nodes in Figure 3.1 which simulated by using objective function MRHOF. From Figure 4.1 we can conclude that the nodes 2 and 6 consumed more power than other nodes and after about ten minutes the topology of the network change to Figure 4.2. Then we arranged more nodes to simulate the difference of objective function MRHOF and OF0. From Figure 5.1-5.4, we can see that different objective function can affect the topology and lifetime of network apparently.

Since RPL protocol standards appeared in 2012, there is lots of research on the energy consumption of RPL network [7-10]. S. Capone etc. present a RPL compliant composite metric that considers both...
reliability and energy [7]. M. Zhao etc. propose a novel energy-efficient region based routing protocol, called ER-RPL, which attains an energy efficient data delivery without compromising the reliability [8-9]. J. Nurmio etc. present a nodes’ remaining energy-aware objective function in order to equalize the energy distribution among the nodes with the ultimate goal of extending the lifetime of the network. L. Lassouaou et al. survey RPL energy-aware routing metrics [11]. O. Iova etc. take into account both the amount of traffic and the link reliability to estimate how much energy such a bottleneck consumes on average [12]. D. Todoli-Ferrandis etc. design a custom energy efficient objective function and build a WSN composed of real devices, and deployed it in a real use case under two scenarios [13].

5. Conclusions
In this paper, we evaluate and analyze the performance of the IETF RPL routing protocol using COOJA simulator under Contiki operating system. Reducing the network energy consumption to prolong the life cycle of network is very important for IoT. We investigate the energy consumption and topology of RPL routing protocol. We study the energy consumption of individual nodes to get more insights on topology. The difference of energy consumptions between client nodes is also evaluated and analyzed. Balancing node energy consumption and designing reasonable routing metric are the research directions in RPL protocol.

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