EQ-RPL: An Energy-Efficient and Quality-Aware Routing Protocol for IoT-Based Low-Power and Lossy Networks

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Abstract

In recent years, the advances in sensing and communication technologies have led to the rapid development of various applications of the Internet of Things (IoT). The devices in IoT form an autonomous network architecture, in which the device has a limited battery power and the link has a low reliability. This kind of network is called the low-power and lossy network. In this paper, we propose a routing protocol for low-power and lossy networks. The proposed protocol introduces a novel rank value to construct a proper destination-oriented directed acyclic graph for the source node to transmit packets to the destination node. The proposed rank value is mainly derived from the expected transmission count, which is widely used to represent the link quality. Moreover, we consider the residual energy as the metric for a node to select the proper node to relay the packet to the destination node. We conducted simulations for performance evaluation, showing that the proposed routing protocol improves the packet delivery ratio, especially for the environment with a high bit error rate. The result also validated that our approach achieves the balance of energy consumption of nodes, compared to the existing approach.

Keywords: Routing, Internet of Things (IoT), Low-power and lossy network, Expected transmission count

1 Introduction

As an extended architecture of both communication networks and the Internet, the Internet of Things (IoT) is becoming a novel and promising paradigm for many applications in a variety of domains, such as transportation, logistics, public utility, home automation, smart city, and education [1-3]. In IoT applications, many kinds of physical devices perform the sensing, controlling, or identifying task and use wireless network technologies to connect with each other to accomplish the goal of specific applications. These devices are constrained by energy supply, processing capability, and memory size. In addition, interconnects of them typically exhibit a high packet loss rate, a low data rate, and an instability due to environmental conditions. We therefore call this kind of network the low-power and lossy network (LLN) [4].

To support the packet transmission in LLNs, the Internet Engineering Task Force (IETF) considers a routing strategy, called route-over routing, which is standardized by the Routing Over Low-power and Lossy networks (ROLL) working group of IETF [5]. The ROLL working group specifies the routing requirements for industrial, building automation, home automation, and urban sensor network applications, and proposes a standard routing protocol for LLNs [6]. This standard routing protocol (hereafter called RPL for simplicity) is carried out on an underlying destination-oriented directed acyclic graph (DODAG), which is a tree-like topological structure rooted at the application-specific node (i.e., the destination of sensing packets in wireless sensor networks). Each node in RPL is assigned a rank, which indicates its individual position relative to other nodes with respect to the DODAG root. The node determines the set of its candidate parents and constructs the DODAG according to the rank value. When a node in RPL needs to transmit data packets to the DODAG root, it will select one or numerous nodes from its candidate parents for transmitting packets.

In RPL, the node rank significantly dominates the routing performance. It can be derived from different routing metrics according to the application requirement. Existing researchers have proposed many approaches considering various routing metrics, such as hop count, bandwidth, latency, traffic load, mobility, and wakeup duty cycle [7-12]. These routing metrics are generally suitable for the applications with specific requirements. However, they are more unlikely to establish the high-quality routing path for lack of the consideration of link quality. A well-known metric, called the expected transmission count (ETX), is proposed in [13] for reliable routing. The ETX is a measurement to indicate the bi-directional transmission quality of a link and widely used to determine the reliable routing path [14-15]. As an efficient routing metric, many metrics based on ETX have been introduced to determine the reliable routing path for LLNs [16-21].

This paper focuses on the data gathering scenarios and proposes an energy-efficient and quality-aware routing protocol (EQ-RPL) for LLNs. That is, the destination of data of user interest is the DODAG root. The main idea under EQ-RPL is that a node considers the neighbor which has the higher success probability of transmission than itself as its parents. We use the quality of reliability of a path as the metric to derive the node rank. This metric actually indicates the expected success probability of transmission from a node to the destination of a path. The EQ-RPL consists of three phases: rank determination, DODAG construction, and data transmission. Each node calculates its rank according to the diversity level and the quality of links between itself and its

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neighbors. This study uses the node degree (i.e., the number of neighbors) and the ETX to represent the diversity level of a node and link quality respectively. When the rank is assigned, each node determines its parent(s) and constructs the DODAG. To extend the network lifetime, a node selects the node with the maximum residual energy from its candidate parents as the next forwarding node towards the destination. Simulation results show that EQ-RPL outperforms standard RPL in terms of packet delivery ratio and energy consumption.

The rest of this paper is organized as follows. Section 2 introduces the main concept and operation of the standard RPL, aiming to provide the background of our work. Section 3 provides the network model and gives an overview of the proposed EQ-RPL. Section 4 presents the proposed routing protocol in detail. Section 5 shows the simulation results. Finally, Section 6 concludes this paper.

2 RPL: Routing Protocol for LLNs

RPL, a canonical routing protocol for LLNs, is a generic distance vector IPv6 routing protocol on the basis of source routing. It creates a DODAG, which is a directed graph containing no directed cycles, and the vertices of an edge of this graph maintain a parent-child relationship. The DODAG is a tree-like topological structure rooted at a single vertex (i.e., destination). Unlike in the tree topology, vertices in DODAG may have many parents. The node in RPL falls into three types: border router, router, and host [6].The border router is usually the root of the DODAG and represents all nodes attached to that DODAG. It acts as the gateway between the Internet and LLNs to collect the RPL traffic (e.g., sensory data) from the nodes of the DODAG in many applications. The main task of the router is to relay received packets. It can also generate the RPL traffic. The host, also called the RPL leaf node, only generates the RPL traffic.

RPL supports multipoint-to-point (MP2P), point-to-multipoint (P2MP), and point-to-point (P2P) traffic flows. The MP2P traffic is always transmitted toward the DODAG root, while the P2MP traffic always originates from the DODAG root. The typical usage scenarios of MP2P and P2MP transmission types include collecting the sensory data from LLN nodes and advertising control or update messages to the designated LLN nodes, respectively. The P2P traffic flow occurs between nodes inside the LLN.

To satisfy the requirement of LLN applications, RPL considers the necessary objective function(s) that an application requires. This function may be to maximize the packet delivery ratio, to minimize the energy consumption, or to minimize the transmission delay. In RPL, the set of DODAGs with the same objective function is called an RPL instance, which is identified by a unique identifier. Recall that LLN nodes are limited in many resources and links are lossy in inherence. These limitations are likely to raise a difficulty during path calculation. Thus, RPL needs to consider the node constraint (e.g., main-powered node), link constraint (e.g., most reliability link), or path constraint (e.g., minimum transmission latency) when determining the best routing path.

RPL assigns each node a value, called the rank, to construct the proper DODAG. The rank is a measurement to indicate the node's individual position relative to other nodes with respect to the DODAG root. It can be derived from the node status, latency, and reliability according to the application requirement. The rank of the DODAG root is 0. The longer the distance to the DODAG root a node has, the larger the rank that this node has. In RPL, the node rank dominates the direction of packet transmission (i.e., the next hop). For example, if node i's rank is smaller than node j's rank, it means that node i is logically closer than node j to the DODAG root.

The construction of DODAG is triggered by the DODAG root when the rank of each node is determined. The DODAG root transmits a DODAG Information Object (DIO) message to advertise all nodes of the DODAG construction. The DIO message includes the rank of the sender. When receiving a DIO message, a node performs the selection of parents and then rebroadcasts the DIO message. The node adds the sender of the DIO message to its parent set if its rank is larger than the rank of the sender of the received DIO message.

3 Preliminaries

This section first provides the network model and then briefly presents the operation of EQ-RPL.

3.1 Network Model

Table 1 lists the key notations used in this paper. We consider a network modeled as a undirected graph $G = (\mathcal{N}, \mathcal{L})$, where $\mathcal{L} \subseteq \mathcal{N} \times \mathcal{N}$. For two nodes i and j, node i is said to be the neighbor of node j if node i is within the communication range of node j, and vice versa. Assume all nodes in the network are stationary and have the same communication range. The electronics energy consumption to process a unit of data of all nodes are assumed to be identical. The amplifier energy for transmitting a unit of data over a unit distance of all nodes in the network are also assumed to be identical. Moreover, $E^{ini}(i) = E^{ini}(j), \forall\, i, j \in \mathcal{N}$ and $i \neq j$. In EQ-RPL, each node exchanges a message with its neighbors periodically to determine the necessary information of the neighbor.

Table 1. Key notations

Notation	Definition
$\mathcal{N}$	Set of all nodes
$\mathcal{L}$	Set of all links between two neighbors
$\mathcal{R}(i)$	Rank of node i
$d_{(i,j)}$	Euclidean distance between node i and node j
$l_{(i,j)}$	Link between node i and node j
$\vec{l}_{(i,j)}$	Directed link from node i to node j
$E^{ini}(i)$	Initial energy of node i

Notice that the DODAG construction dominates the design of a good routing protocol. To determine the efficient routing path, we aim to construct a graph $\hat{G} = (\mathcal{N}, \hat{\mathcal{L}})$, satisfying the following four properties:

Property 1: $\hat{G}$ is a directed graph with no directed cycles and rooted at a pre-determined node r.

Property 2: All links are directed towards node r.

Property 3: $\forall\, \vec{l}_{(i,j)} \in \hat{\mathcal{L}},\ \mathcal{R}(i) \geq \mathcal{R}(j)$.

Property 4: The set of links of $\hat{\mathcal{L}}$ is the subset of $\mathcal{L}$.

3.2 Basic Concept

Figure 1 presents an example of EQ-RPL operation. Figure 1(a) illustrates the initial topology, in which node R is the destination node (i.e., DODAG root), and the value beside each link indicates the ETX. Recall that, in RPL, the rank of DODAG root is 0. We initially assign the rank of node R as 0, and the rank of non-destination node as 1. Suppose node G is the source node in this example. The rank of node G must be larger than or equal to the rank of each node on the routing path from node R to node G. Therefore, we assign the rank of node G as 1. In EQ-RPL, the destination node R takes charge of triggering the rank calculation by sending out a Request_To_Calculate_Rank (RTCR) packet. When receiving an RTCR packet, a node calculates its rank value according to our proposed method provided in Section 4.1. The result of rank determination is shown in Figure 1(b).

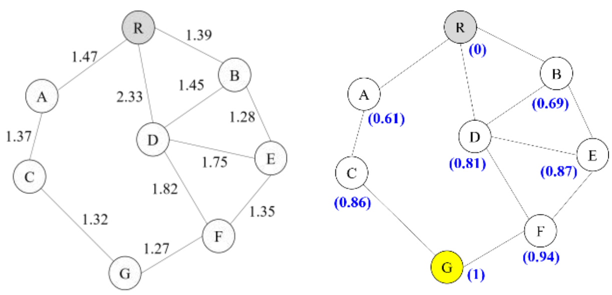
Then, each node constructs a DODAG according to the ranks of its neighbors. Figure 1(c) shows the result of DODAG construction. Note that the rank of a node is greater than those of all of its parents. When the source node (node G) intends to transmit data to the destination node, it selects the node with the maximum residual energy from all the candidate parents as the next forwarding node. In addition, upon the receipt of a data packet, a node determines the next forwarding node having the maximum residual energy from the candidate parents. As illustrated in Figure 1(d), the path from node G to node R is established. The path ($G \rightarrow F \rightarrow E \rightarrow D \rightarrow R$) is composed of the directed links with red color.

4 Energy-Efficient and Quality-Aware Routing Protocol (EQ-RPL)

The proposed EQ-RPL has three phases, including rank determination, DODAG construction, and path establishment. The main operations of these phases are described as follows.

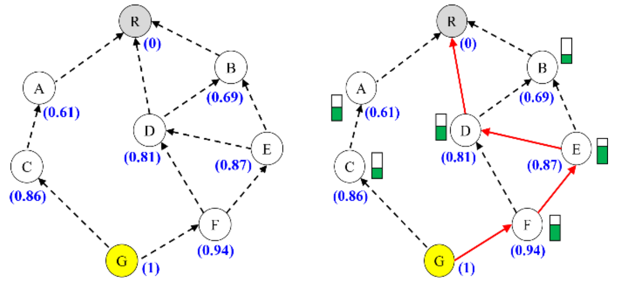
4.1 Rank Determination Phase

In the LLN, the channel condition of wireless links obviously varies with time. The more unreliable links a path includes, the lower packet delivery ratio it will achieve. Significantly, an LLN node (e.g., the source or intermediate node) has to select the node with a stable link from its neighbors as the next forwarding node for data transmission. Recall that ETX is an effective measurement to evaluate the link quality. Thus, we consider the metric to derive the node rank.



(a) Initial network topology

(b) Result of rank determination



(c) Result of DODAG construction

(d) Result of path establishment

Figure 1. Overview of EQ-RPL
The rank value and residual energy of a node are indicated by the blue text in the parentheses and green block respectively.

Let $p^f_{(i,j)}$ and $p^r_{(i,j)}$ be the forward and reverse delivery ratios of $\vec{l}_{(i,j)}$ respectively. The ETX of link $\vec{l}_{(i,j)}$ denoted as $ETX_{(i,j)}$ can be derived as

$$ETX_{(i,j)} = \frac{1}{p^f_{(i,j)} \times p^r_{(i,j)}}. \quad (1)$$

Denote the success probability of packet transmission of $\vec{l}_{(i,j)}$ as $p^{suc}_{(i,j)}$. We have

$$p^{suc}_{(i,j)} = \frac{1}{ETX_{(i,j)}}. \quad (2)$$

Using the link ETX to represent the node rank is a straightforward method, but it is not a proper strategy because it is unable to reflect the suitability of a node. To improve the packet delivery ratio, we also take into account of the link diversity [22]. That is, a larger success probability of packet forwarding to the destination node a node has, a higher opportunity to become a next forwarding node the node obtains. This probability is also used in EQ-RPL to determine the node rank.

Definition 1: The node rank is defined as the expected probability of unsuccessful transmission of packets to the destination node.

Let $P^{suc}(i)$ denote the success probability of packet transmission from node i to the destination node. Let $S^{nbr}(i)$ and $N^{nbr}(i)$ represent the set of neighbors of node i and the number of nodes in $S^{nbr}(i)$ respectively. For any node $i \in \mathcal{N}$, we can determine $P^{suc}(i)$ by

$$P^{suc}(i) = \frac{1}{N^{nbr}(i)} \times \sum_{j \in S^{nbr}(i)} p^{suc}_{(i,j)} \times P^{suc}(j). \quad (3)$$

According to Definition 1, the rank value of node i can be determined as

$$\mathcal{R}(i) = 1 - P^{suc}(i). \quad (4)$$

Initially, the rank of the destination node is set as 0 because the success probability of packet transmission always equals 1. On the other hand, the rank of the source node is also assigned as 1. The ranks of the source and destination nodes always keep constant, thereby guaranteeing that the ranks of nodes on the routing path are all between 0 and 1. Thus, a non-destination node is able to find the node whose rank is smaller than its rank as the next forwarding node to the destination node.

To determine the rank of each node, the destination node broadcasts an RTCR packet, including its current rank when the nodes are deployed. When receiving an RTCR packet, either the non-source or non-destination node u performs Algorithm 1 to determine its rank, and replaces the current rank with the new one if necessary. The main reason to update the node rank is that the channel quality of links with respect to the node may vary with the network condition. In EQ-RPL, a node needs to replace its current rank by the new one if the difference between the current rank and the new one exceeds a pre-determined threshold (i.e., θ in Algorithm 1).

Algorithm 1: Rank determination of LLN nodes in EQ-RPL.

Input: $N^{nbr}(u)$: number of neighbors of node u;
ID(k): node identifier of the k-th element in $S^{nbr}(u)$;
Output: $\mathcal{R}(u)$: rank of node u.
if node u is not the source node **then**
$sum \leftarrow 0$;
for $i = 1$ **to** $N^{nbr}(u)$ **do**
$ETX_{(u,\mathrm{ID}(i))} \leftarrow \frac{1}{(1-p^f_{(u,\mathrm{ID}(i))})\times(1-p^r_{(u,\mathrm{ID}(i))})}$;
$p^{suc}_{(u,\mathrm{ID}(i))} \leftarrow \frac{1}{ETX_{(u,\mathrm{ID}(i))}}$;
$sum \leftarrow sum + p^{suc}_{(u,\mathrm{ID}(i))} \times P^{suc}(\mathrm{ID}(i))$;
endfor
$P^{suc}(u) \leftarrow \frac{sum}{N^{nbr}(u)}$;
$\tilde{\mathcal{R}}(u) \leftarrow 1 - P^{suc}(u)$;
if $|\mathcal{R}(u) - \tilde{\mathcal{R}}(u)| > \theta$ **then**
$\mathcal{R}(u) \leftarrow \tilde{\mathcal{R}}(u)$;
Send an RTCR packet;
endif
endif

4.2 DODAG Construction Phase

Like RPL, the destination node triggers the operation of DODAG construction by transmitting the DIO message including its rank. Upon the receipt of a DIO message, a node determines its candidate parents according to the rank attached in the DIO message. For a node, if the rank of the sender of DIO message is less than that of itself, the sender will be added to the candidate parent set. Then, the node rebroadcasts the received DIO message whether its rank changes or not. Note that a node is likely to receive many DIO messages as the DIO message is flooded throughout the whole network. Consequently, a node may have many candidate parents (i.e., immediate upstream nodes) in the constructed DODAG.

4.3 Path Establishment Phase

The proposed EQ-RPL operates like the on-demand routing protocol. That is, the routing path is established only when the source node intends to transmit the data to the destination node. The source node performs data transmission based on the constructed DODAG. To comply with the standard RPL, the node in EQ-RPL also transmits the data packet to the destination through its parent. Recall that a node may have more than one parent in the constructed DODAG. To avoid redundant traffics, this study considers only one node to become the next forwarding node. On the other hand, to support persistent data transmission and prolong the network lifetime, this study introduces the maximum energy wins strategy, in which the parent node with the maximum residual energy will be selected as the next forwarding node.

To determine the remaining energy, the node exploits the first order model for the radio hardware energy dissipation [23]. The transmitter dissipates energy to run the radio electronics and the power amplifier. Let $E^{Tx}_{elec}(k)$ be the energy consumption of radio electronics for a node to transmit a k-bit packet. Let $E^{Tx}_{amp}(k, d_{(i,j)})$ be the energy consumption of power amplifier for node i to transmit a k-bit packet over distance $d_{(i,j)}$. Denote the energy that node i consumes to transmit a k-bit packet over distance $d_{(i,j)}$ as $E^{Tx}(k, d_{(i,j)})$. A node can calculate the energy consumption of packet transmission according to (5) and derive its remaining energy.

$$E^{Tx}(k, d_{(i,j)}) = E^{Tx}_{elec}(k) + E^{Tx}_{amp}(k, d_{(i,j)}). \quad (5)$$

5 Simulation Results

In this study, we developed a C language program to simulate the routing performance of the proposed EQ-RPL. We conducted numerous simulations to mainly compare the routing performances of the proposed EQ-RPL and RPL which only uses the hop count as the node rank. In the simulation, all LLN nodes are randomly deployed with a uniform distribution in the network, wherein the destination is located at the center. The source node is randomly determined. Simulation results were averaged over 100 runs. Table 2 shows the setting of the simulation parameters.

Table 2. Simulation parameters

Parameter	Value
Network size	500m × 500m
Number of nodes	200, 300, 400, 500
Communication range of nodes	50m
Packet size	127 Bytes
Initial energy of nodes	2 Joule
Bit error rate (BER)	0.001, 0.002, 0.003, 0.004, 0.005
Energy consumption of radio electronics	50 nJ/bit
Energy consumption of power amplifier	10 pJ/bit/m^2

5.1 Packet Delivery Ratio

In general, the small the BER is, the higher packet delivery ratio the routing protocol achieves. In the simulation, the packet delivery ratios of both RPL and EQ-RPL reach 100%

in case of BER values of 0.001, 0.002, and 0.003. Therefore, this paper only shows the packet delivery ratios of the two schemes when BER=0.004 and 0.005. Figure 2 reveals that the packet delivery ratio increases with the decrease of the BER for two schemes. The reason is that a higher BER significantly generates a lower success probability of packet transmission. The result also validates that deploying more nodes in the network results in the obvious improvement of packet delivery ratio. That is because the increase of the number of nodes will increase the number of neighbors (i.e., parents) of a node. Thus, a node has a higher chance to select the better next forwarding node.

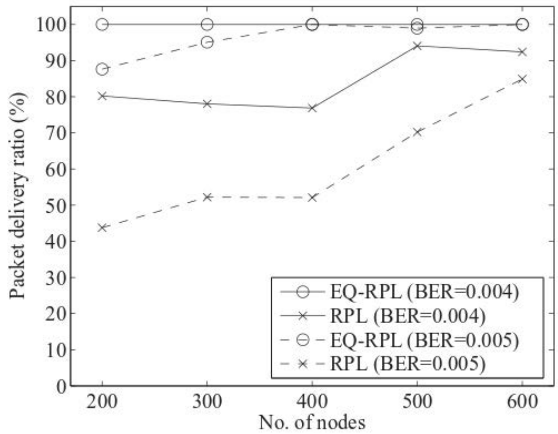


Figure 2. Packet delivery ratios of RPL and EQ-RPL

In Figure 2, EQ-RPL always gains a higher packet delivery ratio than RPL under a certain scenario (i.e., BER). We further investigate this outcome. In the simulation, regardless of BER, the average numbers of neighbors of a node are about 4.75, 7.67, 10.56, 13.39, and 16.25 when the numbers of nodes are 200, 300, 400, 500, and 600, respectively. In general, if having more candidate parents, a node can select one alive node from its candidate parent as the next forwarding node to the destination, especially when the current parent exhausts its energy or the link is broken. Figure 3 shows that, for a node, the number of candidate parents determined by RPL and EQ-RPL are approximately 30% and 50% neighbors respectively. In addition, the number of parents determined by EQ-RPL is significantly larger than the number of parents determined by RPL. This supports us to conclude that the proposed EQ-RPL achieves a higher packet delivery ratio than RPL, as shown in Figure 2.

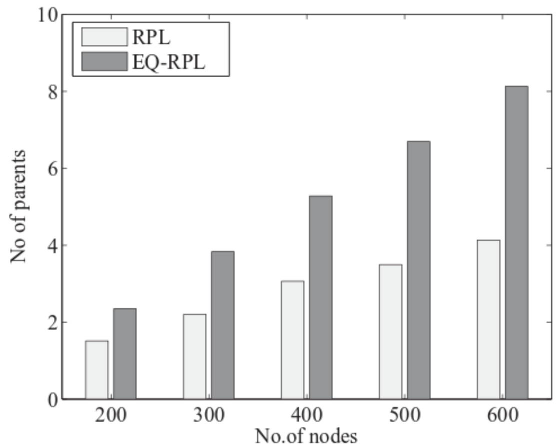


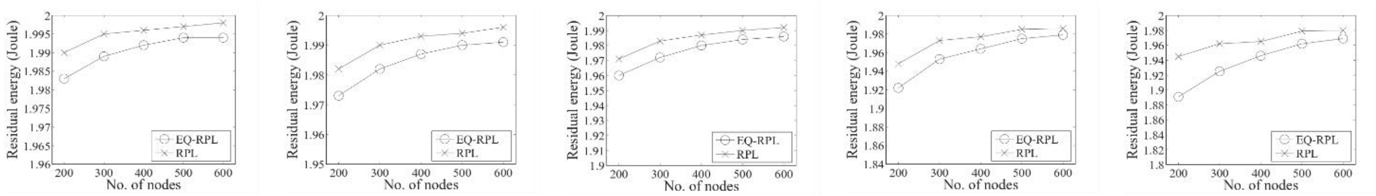
Figure 3. Numbers of parents of a node of RPL and EQ-RPL

5.2 Energy Efficiency

Figure 4 illustrates the mean value of residual energy of all alive nodes under different scenarios when the source node transmits 1000 packets to the destination. The result shows that the energy consumption of both schemes increases with the increase of BER. This is reasonable because a high BER results in a considerable number of packet retransmissions.

In addition, if using the hop count to stand for the node rank, RPL always establishes the route with the minimum length. That is, the routing path determined by RPL is shorter than the path determined by EQ-RPL. This can be verified in Figure 5. Recall that the proposed EQ-RPL aims to determine a reliable and energy-efficient path. Note that the proposed EQ-RPL actually determines the long-distance path, thereby reducing the energy consumption of nodes significantly.

In this study, we consider the transmission overhead to evaluate the level of energy consumption of nodes on the routing path. The transmission overhead here is defined as the mean number of transmissions required for delivering a data packet. In general, the heavier overhead a node has, the more energy the node consumes. Figure 6 illustrates the transmission overhead of RPL and EQ-RPL when 600 nodes are deployed in the network and BER=0.005. The result shows that the transmission overhead of EQ-RPL almost ranges between 8 and 13, regardless of path length, whereas RPL significantly generates more transmission overhead than EQ-RPL.



(a) BER=0.001 (b) BER=0.002 (c) BER=0.003 (d) BER=0.004 (e) BER=0.005

Figure 4. Residual energy of nodes of RPL and EQ-RPL

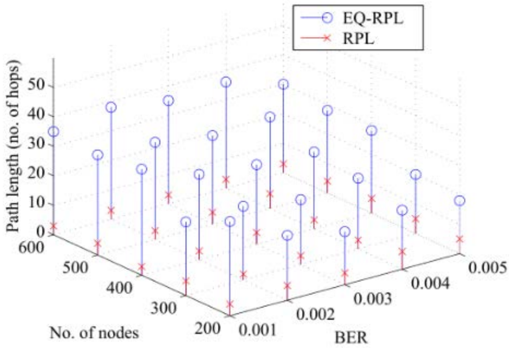


Figure 5. Path lengths of RPL and EQ-RPL

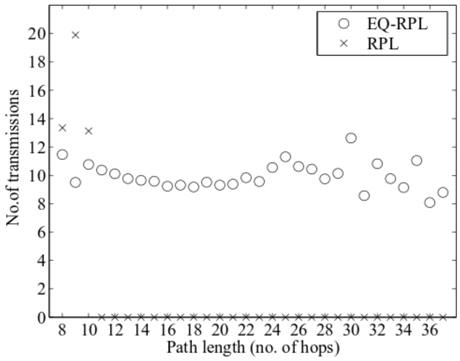


Figure 6. Transmission overhead of nodes of RPL and EQ-RPL

6 Conclusion

This paper proposed a routing protocol, called EQ-RPL, for LLNs to support data gathering services for IoT applications. The proposed EQ-RPL considers the link diversity concept, and uses the expected probability of unsuccessful transmissions as the key metric to derive an efficient strategy to the determination of node rank. In addition, a node takes into account the residual energy of candidate parents to select the node with the maximum residual energy to act as the next forwarding node to relay the data packet to the destination. Performance evaluation results validated that the proposed EQ-RPL not only achieves a higher packet delivery ratio than the standard RPL, but also accomplishes the energy balance of the network. The future research will investigate the solution involving the issues of load balance and mobility.

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