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An improved PDR (Packet Delivery Ratio) Defined Routing Protocol in low-power and lossy networks

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Abstract— This study proposes a link quality aware routing protocol for low-power and lossy networks. The proposed protocol primarily considers the quality of links to determine the node rank for constructing a proper destination-oriented directed acyclic graph, on which a node may have many parents. In the proposed protocol, a node selects the node with the maximum remaining energy from all of its neighbors as the next hop to guarantee that the packet has a high probability of being forwarded toward the destination. Simulation results confirm that, compared with the routing protocol based on the hop count, the proposed protocol improves the packet delivery ratio, especially for environments with a high bit error rate. Results also show that the proposed protocol can balance the energy consumption of nodes in the network.

Keywords: IOT, RPL, IETF.

I. INTRODUCTION

The Internet of Things (IoT) is a novel and promising paradigm which extends the applications of communication networks and the Internet [1]. A large number of IoT devices, called smart objects, such as sensors, actuators, and Radio- Frequency Identification (RFID) tags perform the sensing or identifying task in the real world. They also use wireless network technology to connect with each other to accomplish
common goals in many domains including manufacturing, transportation, and logistics. These devices are constrained by computation capability, memory size, energy supply, and bandwidth. The link in the network formed by these devices typically exhibits a high packet error rate, low data rate, and link outages due to environmental conditions. This network is
therefore called the low-power and lossy network (LLN).

To perform data forwarding in LLNs, the Routing Over Low-power and Lossy networks (ROLL) Working Group, which was created by the Internet Engineering Task Force (IETF), has standardized a routing protocol for LLNs, called RPL, at the network layer [2]. RPL is carried out on the destination-oriented directed acyclic graph (DODAG). This graph is a tree-like topological structure that is rooted at the destination of a path from a non-root node. Each node in DODAGs may have multiple parents and is assigned a rank.

The rank indicates the node’s individual position relative to other nodes with respect to the DODAG root, and can be calculated according to different metric such as hop count or end-to-end latency. In a DODAG, the root is assigned the smallest rank, and the rank of a node is smaller than those of its children. Because RPL is based on the DODAG to determine the routing path, the method used to select the metric and to determine the rank of nodes for the construction of a good DODAG significantly affects the routing performance.

The hop count is regarded as a fundamental metric for determining the routing path [3], [4], but it is not an efficient measurement to represent the rank of nodes in DODAGs because it cannot characterize the link condition. Moreover, existing studies have considered the bandwidth, throughput, delay, link quality, and node’s residual energy as routing metrics [5], [6]. In particular, the expected transmission count (ETX) proposed in [7] is a well-known and widely used metric [8], [9], [10], [11], which indicates the bi-directional transmission quality of a link, and many ETX-based ranks have also been recently proposed for routing in LLNs [6], [8],
[12].

This paper proposes a link quality aware routing protocol, for which the main goal is to construct a proper DODAG based on the link quality to enhance the routing performance in LLNs. This study primarily considers the data collection scenario, in which an LLN node intends to transmit data to the DODAG root. The proposed protocol, called LQA-RPL, includes the rank calculation phase, DODAG construction phase, and data transmission phase. In the rank calculation phase, we use the expected probability of unsuccessful transmissions to indicate the rank of a node. This probability can be derived from the ETX of the link between a node and its neighbor (i.e., the two nodes are within the communication range of each other). The main task of the DODAG construction phase is for a node to derive its parent set. If the rank of a node's neighbour is less than that of the node, the node adds this neighbor to its parent set. To extend the network lifetime, a node selects the parent with the maximum residual energy from its parent set as the next hop for packet transmissions. Simulation results show that LQA-RPL outperforms the RPL, which considers the hop count as the routing metric in terms of packet delivery ratio and network lifetime.

The rest of this paper is organized as follows. Section II gives a brief introduction to the traditional RPL. Section III presents the network model and assumptions. Section IV describes the proposed LQA-RPL in detail. Section V shows the performance evaluation results, and finally, Section VI provides concluding remarks.
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II. RPL OVERVIEW

RPL is a generic distance vector IPv6 routing protocol that is based on source routing for LLNs. It is carried out on a logical topology, which is a directed graph with no directed cycles. The vertices of an edge of this topology maintain the relationship between the parent and the child. A vertex may have many parents. A particular type of graph is the destination-oriented directed acyclic graph (DODAG), which is a tree-like topological structure rooted at a single vertex (i.e., destination). All nodes in an LLN may be constructed as multiple DODAGs. A DODAG is assigned a version number(i.e., DODAGVersionNumber) that is maintained by the DODAG root. When the DODAG root reconstructs a DODAG,it increases its DODAGVersionNumber.

RPL defines three types of nodes: LLN border router, router, and host. The border router is typically the root of a DODAG, and plays the role of a gateway between the Internet and the LLN. In many applications, the border router acts as a data collector to aggregate the data from the vertices of the DODAG. The router takes charge of data relaying, and it is also allowed to generate the RPL traffic. The host, which is also called the RPL leaf node, can generate only the RPL traffic (e.g., sensory data). To calculate the best path for different LLN applications, RPL uses the different metrics and constraints to define the objective function to guarantee their requirements. For example, the objective function may be to minimize the energy consumption, to minimize the transmission delay, or to maximize the packet delivery ratio. In RPL, the set of DODAGs with the same objective function is called an RPL instance. An RPL instance is identified by a unique identifier, which is called the RPLInstance ID.

Because RPL is carried out on the DODAG, the effectiveness of the DODAG affects the performance of packet transmission. The ROLL Working Group assigns to each node a value, which is called a rank, to achieve the construction of the DODAG. The rank is a measurement to indicate the node's individual position relative to other nodes with respect to the DODAG root, and it can be calculated by considering the node status, hop count, throughput, latency, or reliability.

In a DODAG, the rank of the root is 0. Moreover, if node i's rank is smaller than node j's rank, it means that node i is closer than node j to the DODAG root.

Fig. 1 illustrates the example of the construction of a DODAG. Without loss of generality, this example uses the hop count to represent the rank of nodes. We assume that the rank of each node has been determined. As specified in [2], the DODAG construction in RPL is from the root (e.g., node R in Fig. 1). Node R transmits a DODAG Information Object (DIO) message, which includes the rank of node R, as shown in Fig. 1(a). When node A receives the DIO message, it adds the sender of the DIO message (i.e., node R) to its parent set because node A's rank is greater than node R's rank. Meanwhile, nodes B and C also add node R to their respective parent set. Then, nodes A, B, and C rebroadcast the

DIO message, as illustrated in Fig. 1(b). Similarly, nodes

D and *F* add node *A* and *B* to their parent sets, respectively, when receiving the DIO message. On the other hand, when node *G* receives the DIO messages from node *B* and node *C*, it adds nodes *B* and *C* to its parent sets because the rank of the sender of the DIO message is less than the rank of node *G*, as shown in Fig. 1(c). When receiving the DIO message, node *E* adds node *D* and *F* to its parent set. As a result, the DODAG is constructed, as shown in Fig. 1(d).

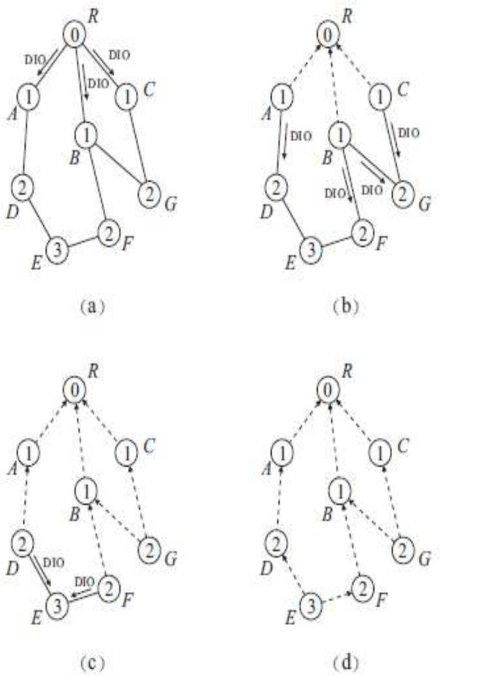

Fig.1. Example of the DODAG construction. The value at each node indicates the rank of this node. (a) The root broadcasts a DIO message to trigger the DODAG construction. (b) Nodes *A*, *B*, and *C* have determined their own parents. (c) Nodes *D*, *F*, and *G* have determined their own parents. (d) Node *E* has determined its parents, and finally the DODAG is constructed

Recall that this study considers the data collection scenario. In RPL, this type of data transmission is typically upward transmission. Using RPL, an LLN node transmits the data packet to all of its parents when it generates the reporting data

(e.g., the monitoring readings or the tracking status). The node

receiving the data packet uses the same method to transmit the received packet to the nodes in its parent lists. Because there may be more than one element in the parent set of a node, RPL is likely to establish many routes from the source to the DODAG root. This can provide a more robust data transmission than can be realized by only considering a single

routing path. For example, in Fig. 1, there are two routing paths from node *E* to node *R*.

III.NETWORK MODEL AND ASSUMPTIONS

The LLN considered in this study is an undirected graph

$G = (V,E)$, where V is the set of nodes and $E \subseteq V \times V$ is

the set of links between two neighbors. Let R_i be the rank of node i. This study aims to construct a graph

$\hat{G} = (V, \hat{E}$

$, u)$, where $u \in V$, satisfying the follow properties:

- $\hat{G}$ is rooted at node u (a pre-determined node), and is a directed graph with no directed cycles.
- All edges are directed towards the root of $\hat{G}$.
- The link $\vec{e}_{(i,j)} \in \hat{E}$ is directed from node i to node j.
- For each $\vec{e}_{(i,j)}\, R_i \geq R_j$.

Assume that all nodes in the network are stationary and have the same communication range. The node periodically exchanges a message with its neighbors. This study assumes that all nodes in the network are identical in terms of the amount of initial energy. For all nodes, the electronics energy

consumption required to process a unit of data is identical, and the amplifier energy required to transmit a unit of data over a unit distance is also the same.

We observed the limitations of IdM by looking into steps provided in Figure 1 such as what will happen if IdM is compromised. In step 4 and 5 (Fig. 1), IdM server generates the token and sends it to cloud, and if IdM is compromised then any illegitimate user can use the same token to access the cloud’s services/data. This compromise could be occurred due to malicious insider or malicious code. Current IdM, in case of being compromised, put all the cloud’s resources on stake.

IV. LINK QUALITY AWARE ROUTING PROTOCOL

The proposed LQA-RPL comprises the rank calculation phase, the DODAG construction phase, and the data transmission phase. The rank calculation phase determines the node rank according to the proposed metric. The DODAG construction phase derives the parent set of each node. In the data transmission phase, each node transmits data packets to the node with the maximum residual energy from all of its parents.

A. Rank Calculation

In general, the channel condition of wireless links in LLNs varies with time. If a routing path includes the unreliable link,
data delivery is likely to fail, thereby leading to unnecessary packet retransmissions. Thus, a node should select the neighbor with a stable link as the next hop for packet transmissions. As an efficient measurement to represent the link quality, the ETX, which measures the expected bi-directional transmission count of a link, is widely used in the existing approaches. Let $E_{(i,j)}$ be the ETX of the link between node i and node j, which is defined as

$$E_{(i,j)} = \frac{1}{p^{r}_{(i,j)} \times p^{f}_{(i,j)}} \quad (1)$$

where $p^{f}_{(i,j)}$ and $p^{r}_{(i,j)}$
denote the forward and reverse delivery ratios from node i to node j, respectively. The forward delivery ratio is the measured probability that indicates that a data packet successfully arrives at the recipient. The reverse delivery ratio is the probability that indicates that the acknowledgment packet is successfully received. Let $p(i,j)$ be the successful probability of a packet transmission on $e^{\rightarrow}_{(i,j)}$

Thus, we obtain

$$p_{(i,j)} = \frac{1}{E_{(i,j)}} \quad (2)$$

Although the ETX is used by the majority of existing approaches as a metric to determine the rank of the node, it only reflects the quality of a single link [6], [8]. To achieve a high packet delivery ratio at the destination, in addition to considering the ETX, a node should also select the node having the highest probability of forwarding the packet to the destination as the next hop. Therefore, this study, which is motivated by the concept of link diversity, considers the successful probability of packet forwarding to calculate the rank of LLN nodes.

Considering the example shown in Fig. 2, nodes S and D are the source and destination, respectively. The value beside the link indicates the probability of realizing successful packet transmission on this link. The value given in the parentheses beside a node indicates the probability of successful packet transmission from the node to the destination. When considering only the probability of successful packet transmission on $e^{\rightarrow}_{(S,A)}$ and $e^{\rightarrow}_{(S,B)}$, node S will select node B as the next hop because $p(S,B) > p(S,A)$. Thus, we determine that the probability of successful packet reception at node D through node B is $0.7\times0.18 = 0.126$. However, this is not an optimal solution because the probability of successful packet reception

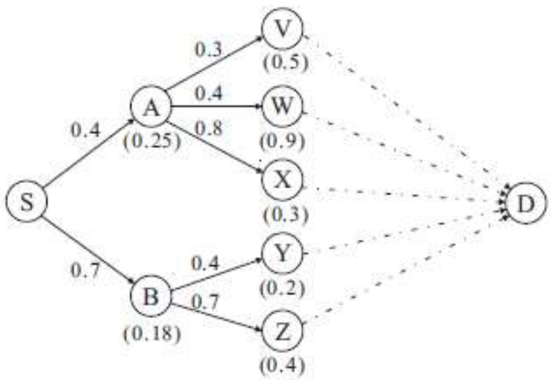

Fig. 2. Basic concept of link diversity.

at node D is $0.4 \times 0.25 = 0.1$ if node S selects node A as
the next hop.

In LQA-RPL, we define the node rank as follows.

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

Let p^{dest}_{i} be the probability of successful packet transmission

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from node i to the destination. Denote the set of neighbors of node i as S_i^{nbr} . We derive p_i^{dest}

$$p_i^{dest} = \frac{\sum_{j\in S_i^{nbr}} p_{(i,j)} \times p_j^{dest}}{N_i^{nbr}} \quad (3)$$

where N_i^{nbr} is the number of neighbors of node i. According to Definition 1, the rank of node i ($i \in V$) can be obtained by

$$R_i = 1 - p_i^{dest} \quad (4)$$

In LQA-RPL, we assign the rank of the destination as because the destination can always successfully transmit the packet to itself. Initially, the ranks of non-destination nodes are assigned as 1. To adhere to the RPL property, in that the node that is near the destination maintains a smaller rank than that far from the destination, we assign the rank of the source as 1.The rank values of the source and the destination are always kept as constant values. When the LLN nodes are deployed, the destination broadcasts a Request to Calculate Rank (RTCR) packet, which includes the current rank of the sender. When receiving an RTCR packet, the non-source or non-destination node recalculates a new rank. Note that if the channel quality of links with respect to this node or the number of neighbors changes, the node rank may change. Thus, in LQA-RPL, if the variation in rank is significant (i.e., the difference between the current rank and the new rank exceeds a pre-determined threshold), the node replaces its current rank by the new one to adapt to the changed circumstances. Algorithm 1 shows the algorithm for the rank calculation of LQA-RPL.

In general, the rank calculation of nodes operates with iterative updates. Based on the discussion in [13], we can use heat-based routing to find the routing path. The rank calculation in LQA-RPL is similar to temperature determination in heat-based routing, which can use the finite difference method to evaluate the solution of partial differential equations on a grid [14]. The literature also shows that this method can always converge in a bounded number of iterations. In addition, the value of each node's rank is between 0 and 1 after convergence.

Algorithm 1: Rank calculation of LLN nodes in LQARPL.

/* To be performed by node i when receiving an RTCR packet. */

Input: N_i^{nbr} : number of node i's neighbors; id(j): node id of the j-th element in S_i^{nbr} ; θ: parameter for convergence.
Output: R_i: node i's rank.

if *node i is not the source* then
  sum $\leftarrow$ 0;
  for j = 1 to N_i^{nbr}3 do
    $E_{(i,id(j))} \leftarrow \frac{1}{\left(1 - p^r_{(i,id(j))}\right) \times \left(1 - p^f_{(i,id(j))}\right)}$
    $p_{i,id(j)} \leftarrow \frac{1}{E_{(i,id(j))}}$
    $sum \leftarrow sum + p_{i,id(j)} \times p^{dest}_{id(j)}$;
  $p_i^{dest} \leftarrow \frac{sum}{N_i^{nbr}}$
  $R_i^{tmp} \leftarrow 1 - p_i^{dest}$
  If $|R_i - R_i^{tmp}|$>0 then
    $R_i > R_i^{tmp}$;
    Send an RTCR packet ;

B. DODAG Construction

Recall that the construction of the DODAG is triggered from the destination. When receiving a DIO message, the node in LQA-RPL performs the parent selection according to the rank included in the DIO message. If the rank of the sender of DIO messages is less than its own rank, the node adds this sender to its parent set. The node then rebroadcasts the received DIO message whether or not its rank is changed. Because the DIO message is flooded throughout the entire whole network, a node may receive many DIO messages from different neighbors. Therefore, a node may have many parents in the constructed DODAG.

C. Data Transmission

LQA-RPL performs the data transmission based on the constructed DODAG. To comply with the operation of the traditional RPL, the node in LQA-RPL also transmits data packets to the destination

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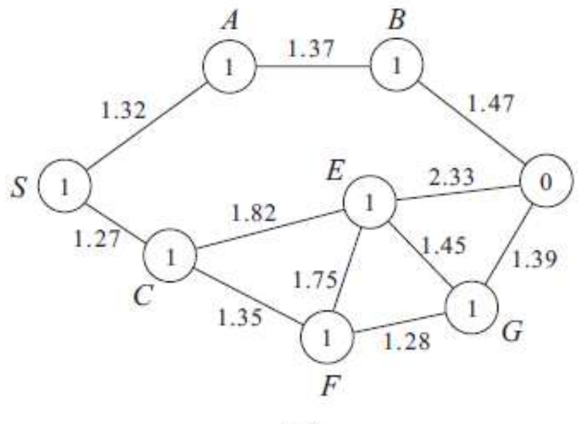
through its parent (i.e., upward transmission). If a node has many parents, this study considers
only one parent to become the next hop to avoid the generation of redundant traffic. We introduce the maximum energy wins strategy, in which the parent node with the maximum residual energy will finally become the relay node. This strategy can support persistent data transmission and can also prolong the network lifetime.

D. LQA-RPL Operation

Fig. 3 shows an example of the LQA-RPL operation. Suppose
that node *S* and node *D* are the source and destination, respectively. The value shown in the circle indicates the rank
of the node, and the value beside a link indicates the ETX of
this link. As shown in Fig. 3(a), the rank of node *D* is initially
assigned as 0, and the ranks of non-destination nodes are initially assigned as 1. Node *D* sends out an RTCR packet to trigger the rank calculation. When receiving the RTCR packet,



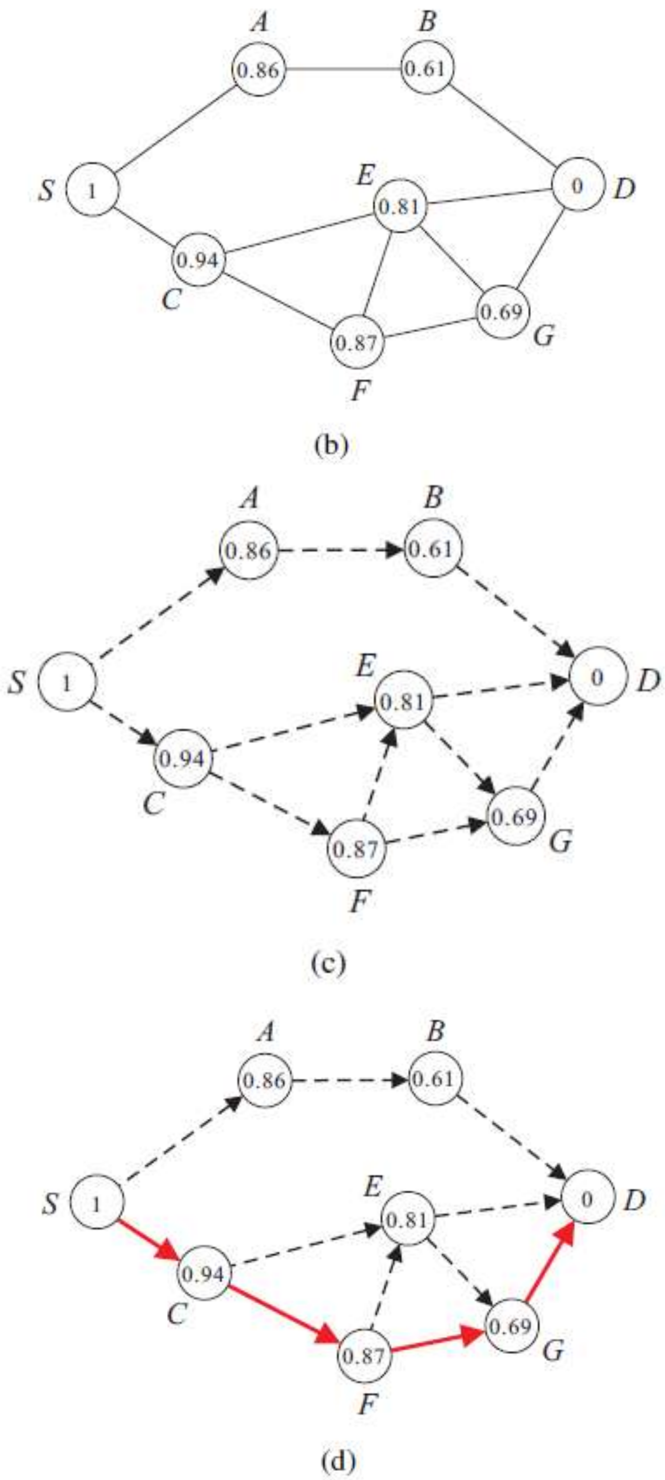


Fig. 3. Example of the operation of LQA-RPL. (a)Assignment of the initial rank of each node. (b) Result of rank calculation. (c) Result of DODAG construction. (d) Result of path determination. Suppose $E_C^{res} > E_A^{res}, E_F^{res} > E_E^{res}, E_G^{res} > E_E^{res}$ where E_i^{res} is the residual energy of node *i*.

the node performs Algorithm 1 to determine its rank. Fig. 3(b) shows the result of rank calculation with different numbers of iterative updates. Then, each node determines its parents to construct the DODAG. The result is illustrated in Fig. 3(c), in which the rank of a node is greater than that of any of its parents. When a node receives a data packet, it selects the parent with the maximum residual energy as the relay node. As a result, the routing path from node *S* to node *D* (i.e., *S-C-F-G-D*) can be established, as shown in Fig. 3(d).

TABLE I
SIMULATION PARAMETERS AND VALUES.

Parameter	Range of values
Network size	500m × 500m
Numbers of nodes	200, 300, 400, 500, 600
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

V. CONCLUSION

In this paper, we considered the quality of links and proposed an efficient routing protocol, called LQA-RPL, for low-power and lossy networks. The key concept of LQA-RPL is that it designs a metric based on the expected probability of unsuccessful transmissions to calculate the node rank. It then uses this rank to construct a proper DODAG. Further, the node with the maximum residual energy is selected as the next hop for packet transmission. The performance evaluation results reveal that LQA-RPL outperforms the RPL based on the hop count in terms of the packet delivery ratio because the node in LQA-RPL has more candidate parents that can become the relay nodes. The results also show that LQARPL can balance the energy consumption of nodes because a node does not always select a specific node as the next hop to which packets should be forwarded, thereby prolonging the network lifetime. Future research should also explore solutions involving multi-source routing and multicasting.

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