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Energy balancing RPL protocol with multipath for wireless sensor networks

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Abstract With the rising trend of the incidence and prevalence of chronic diseases all over the world, proactive healthcare systems with wireless sensor network (WSN) technology have attracted people's extensive attention. One of the researches, such as routing protocol for low power and lossy networks (RPL) only takes into consideration a single metric, energy, hops or routing quality, and so on. To extend the survival time of the network effectively and maximize the utilization of energy, we need to consider both node metric and link metric that affect the network, and design IRPL (Improved RPL) protocol. We propose the life cycle index (LCI) as path selection objective function. The index takes node metric (node energy and node hops) and link metric (throughput, packet loss, link quality) into consideration. In order to detect and distribute congestion information, we add congestion detection factor to the index. According to node energy, hop and congestion detection factor, we optimize the calculation method of rank. Our method redesigns parent node selection strategy. Not only does the strategy select the best parent node by using the improved index, but also saves other parent nodes that meet the conditions. Meanwhile, we propose a multipath scheme by using the DODAG structure, and use the scheme to solve the congestion problem. The simulation results show that the scheme shows better performance in terms of network load, end-to-end delay, packet delivery ratio, percentage of the optimal parent node change, energy consumption and network lifetime.

Keywords Wireless sensor network · RPL protocol · Multi-path · Network lifetime

1 Introduction

Along with the improvement of social economy and the change of living style, the incidence and prevalence of chronic diseases are rising trend all over the world [1]. Chronic disease is hazardous to human health. According to 2015 report on Chinese resident's chronic disease and nutrition [2], the prevalence of chronic diseases is entering a "blowout" type of explosive growth state and chronic patients are increasing. The data generated by chronic patients are also in an explosively increasing manner. To monitor their health, there is a need of a proactive healthcare system which helps both patients and doctors to monitor the health. The design and implementation of proactive healthcare system use wireless sensor network (WSN) [3] technology. Therefore, wireless sensor network (WSN) technology has attracted people's extensive attention. Meanwhile, the monitoring of health condition and the integration of ambient information with the health condition by Internet of Things (IoT) [4] are under development.

The sensor nodes that are used in the build process of WSN are some devices with limited memory, processing power and battery [5]. The network constructed by this kind of nodes is called Low power and Lossy Networks (LLN). LLN is a network composed of embedded devices that are limited of resources as power, storage space, processing capacity, energy storage and so on [6]. Due to the above characteristics of LLN, the ROLL (Routing over Low power and Lossy network) working group of

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Internet Engineering Task Force (IETF) evaluated the existing routing protocols, such as OSPF,IS-IS,AODV,OLSR. The existing routing protocol was not suitable for LLN. For this reason, the working group researched and formulated the RPL (Routing Protocol for LLN) Protocol [7].

RPL is a distance vector routing protocol and it uses the Destination Oriented Directed Acyclic Graph (DODAG) [8] to organize network. A node joins a target DODAG by interacting DIS, DIO and DAO information with the neighbor nodes. But RPL routing protocol still has problems such as the rank value's calculation of upward routing is mainly based on the node hop [9] and the objective function is not clearly defined. Some improved schemes have taken factors such as residual energy and link quality into consideration, but this would lead to the premature energy depletion of some nodes. For example, ETX scheme was proposed [10]. The scheme considered forwarding data delay between two nodes as a standard of link quality, selected a node with minimum delay as the parent node, and directly calculated correct data's link quality before sending. This metric was very effective. But load imbalance was caused as there was no consideration of node energy factor. This would lead to the problem that some nodes' time delay was small while certain path transmission efficiency was very high. Thus, the certain path might be frequently used as an available highly efficient one and this resulted in some nodes' energy on the path being consumed too early. The scheme's data transfer rate was high, but it could cause a load imbalance problem and reduce the network lifetime.

Meanwhile, RPL is a flexible and extensible single path protocol. RPL only saves an optimal routing at a time and just chooses one of the best parent nodes. To prevent malfunction, path needs to be updated in real time, and it needs to send more control information. After path failure, RPL uses local repair algorithm to repair, but the process needs to rerun the program to detect and establish path, and the efficiency is not high and energy loss is serious [11]. It is a complex and resource-consuming process.

Furthermore, RPL is mainly designed and used for low rate scenarios, that is, each node generates low rate data. But it also needs to have the ability to handle high rate situation since nodes near a sink have to relay very high rate case even if each node generates low rate data. And most of packet losses under high rate situation are caused by congestion [12]. So congestion also needs to be researched for RPL [13]. Link loss is negligible even in a heavy traffic scenario. And queue loss is inevitable and nonnegligible but can be reduced by designing an enhanced RPL [12]. Hence, queue loss is the main reason for packet reception ratio degradation in a high rate situation, namely congestion of RPL.

Aiming at the problems of RPL protocol, we propose LCI scheme to improve the original RPL in this paper. The main contributions of this paper are as follows:

- We design path life cycle index to replace the original protocol's path selection objective function and change the calculation method of rank with consideration of node energy, power, link quality,successful data transmission rate and congestion detection factor. The congestion detection factor in LCI and rank can distribute nodes' congestion information to its neighbor nodes. We can recognize the congestion information of a node timely by congestion detection factor.
- We redesign parent node selection strategy. Not only does the strategy choose the best parent node, but also selects the parent node with comprehensive consideration of the new index on the premise of estimating link quality. Meanwhile, the strategy not just chooses one of the best, but also saves other parent nodes that meet the conditions.
- We introduce the multipath routing scheme to improve the single path of RPL and solve the congestion problem. Due to the improved scheme, each node can save multiple available parent nodes with consideration of the life cycle index. And when congestion indicator is larger than the threshold value, the child can start multiple routing by splitting their forwarding rate into half, and so on.

The remainder of this paper is organized as follows. Section 2 reviews related work. In Section 3, we illustrate the improved RPL protocol with consideration of node energy, power, link quality, and successful data transmission rate, etc. Section 4 discusses our experimental results and analysis. The paper concludes our findings and looks forward to our future research in Section 5.

2 Related work

2.1 Internet of Things(IoT)

Kevin Ashton, cofounder and executive director of the Auto-ID Center at MIT, first mentioned the Internet of Things in a presentation he made at Procter & Gamble in 1999 [14]. He described "the Internet of Things" as a system where the Internet is connected to the physical world via ubiquitous sensors. In 2005, the International Telecommunication Union (ITU) released the seventh in the series of "ITU Internet Reports" [15]. The report indicated that we are heading towards what can be termed a "ubiquitous network society", in which networks and networked devices are omnipresent. The internet can only link persons and can transmit information. Through the idea of IoT, the IoT can link persons and objects, including patients and the monitoring devices of health condition, and support more wild connection, smartly configure the requirement. It transmits information and controls entity. The application of IoT is shown in Fig. 1.

2.2 Ipv6 routing protocol for low power and lossy network (RPL)

The design of RPL is based on three main concepts defined clearly in RFC 6550 [7]: DODAG, Trickle and Objective Function (OF). Starting from a border router (or root router), RPL constructs a Destination-Oriented Directed Acyclic Graph (DODAG) using one or several routing metrics. The DAG topology is partitioned into one or more DODAG per sink. The topology of DODAG in RPL is established with bidirectional routes, as shown in Fig. 2. The traditional WSN routing usually only conducts point to point communication, however, RPL further provides point-to-multipoint or multipoint-to-point routing. The routing decision is based on the Rank and Objective Function. The Rank of a node depicts the node's relative distance to the DODAG root, and is designed to prevent loop routing. The node with higher rank value travels longer distances than the node with lower rank value to the DODAG root. The adjacent nodes with lower rank value can be called the parent nodes. The Objective Function defines how nodes select and optimize routes. We focus on the Objective Function and Rank which are considered the brain of the routing protocol.

RPL provisions a mechanism, with minimal configuration in the nodes, to disseminate information over the dynamically formed network topology. The control messages in RPL include DODAG Information Object(DIO), Destination Advertisement Object(DAG) and DODAG Information Solicitation(DIS). Through DIO messages, RPL provides routes up towards DODAG roots. On the other hand, RPL employs DAO messages to establish downward routes and the DIS messages could be used to solicit a DIO from a node. The DIO messages, being periodically broadcasted by each node to maintain the DODAG.

IETF RFC 6551 [16] specifies a set of link and node routing metrics and constraints suitable for LLNs to be used by the RPL for routing. The node metric is the individual node status including node energy and node hops. The link metric indicates the routing quality, including throughput, delay and link reliability. Two link reliability metrics are defined: the Link Quality Level (LQL) and the expected transmission count (ETX). The link qualities, including latency and packet loss, may significantly influence the network connectivity. A RPL deployment may use the LQL, the ETX, or both. And based on the different network deployment purposes, the same network may need different link quality requirements. This may lead to multiple objective functions in the same network.

2.3 Energy-efficiency protocol

Sensor nodes of WSN are usually battery powered and deployed in large areas. Changing or replacing batteries may be impractical or even unfeasible. Therefore, the energy efficiency of sensor nodes is a primary issue to be considered. Some discussion and improvements on energy efficiency of RPL can be found in some papers.

To reduce the end-to-end delay and node average energy consumption, ETX scheme [10] was proposed. The scheme considered forwarding data delay between two nodes as a standard of link quality, selected a node with minimum delay as the parent node, and directly calculated correct data's link quality before sending.

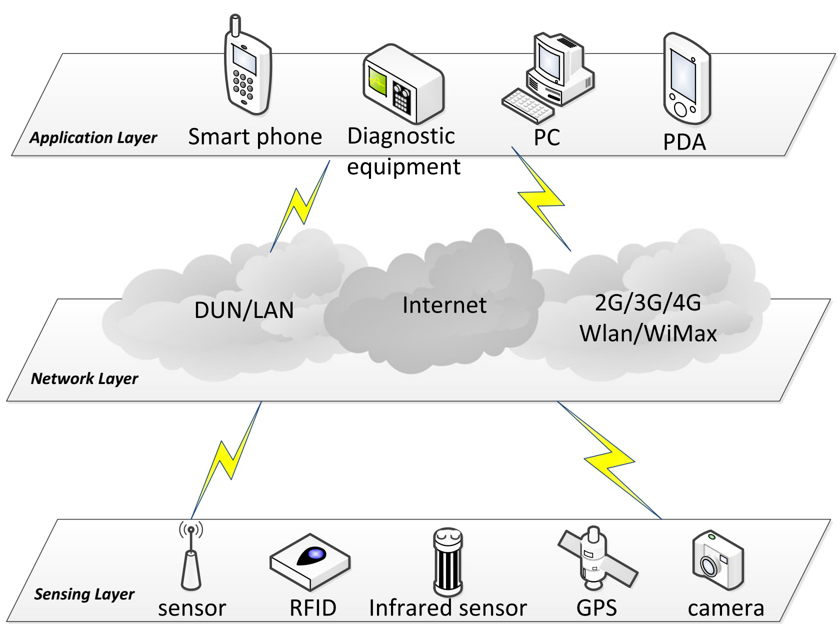

Fig. 1 the application of IoT

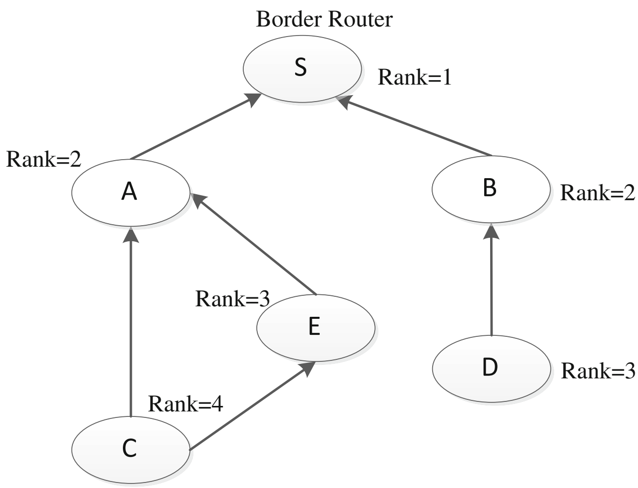

Fig. 2 DODAG topology in RPL

The ETX metric is widely used to estimate the energy budget by using a link. It is the number of transmissions a node expects to make to a destination in order to successfully deliver a packet [16]. In contrast with the LQL routing metric, the ETX provides a discrete value (which may not be an integer) computed according to a specific formula(1):

$$ETX = \frac{1}{PDR_f \times PDR_r} \tag{1}$$

where PDR_f is the measured probability that a packet is received by the neighbor and PDR_r is the measured probability that the acknowledgment packet is successfully received. The ETX value represents the stability of a link. The lower the ETX value, the higher the successful data transmission rate. The node with lower ETX will be given higher priority as the next hop selection.

For node energy consumption, V. Safdar et al. [17] proposed an enhanced algorithm that supports the mobility. Combined with the typical RPL routing protocol, the algorithm added support for mobility, reduced energy loss by the passive method, and balanced energy consumption. In order to reduce the energy consumption rate of nodes, H. Yoo et al. [18] proposed to select the next hop node with consideration of the size of REDR. The method could achieve the balance of energy consumption, and avoided the premature failure of some nodes, but did not consider path quality. Although network lifetime was prolonged, this method could not guarantee data delivery rate. If poor quality path was used frequently, network efficiency would be low. Kamgueu et al. [19] proposed to use the residual energy to construct the RPL DAG. However, they did not consider the radio link quality and the energy budget for a correct reception. Consequently, bad radio links might be used. And this might result in inefficient routes. Considering node energy and link quality, L. H. Chang et al. [20] proposed a method to construct the RPL DAG with residual energy, and used only ETX to restrict link quality. But the method might lead to choosing bad quality link, and eventually led to the selection of the lowest efficiency link. Since ETX does not consider the energy level of the motes, it does not balance the energy consumption between motes. Based on the above reason, Mai et al. [21] developed other routing metrics by taking into consideration the energy consumption of motes as routing metric and a Radio Duty Cycle (RDC) based method to estimate mote energy consumption.

The above routing algorithms have taken node energy and link quality into consideration to pursue the minimum of energy consumption of the network. Even so, some nodes' energy will be consumed too early. To extend the survival time of the network effectively and maximize the utilization of energy, we need to consider many factors that affect the network. Only in this way can the method balance energy consumption to detect link quality in advance, and avoid some nodes premature failure. Besides that, the method should also consider the problem of congestion to reduce packet loss. Aiming at the problems of RPL protocol, we improve the original RPL in this paper.

3 Improved RPL

3.1 Overview of improved RPL

Due to the limitation of wireless sensor network node energy, the key to improving network lifetime is improving the utilization rate of energy, and preventing premature consumption of individual node energy. But if we only consider the energy of nodes, other problems can also happen, such as the link quality that you choose is not high, the node will lead to severe packet loss rate and network time delay. So we must improve the performance of routing with a variety of routing metrics. The synthetic application of multiple indexes would help to solve the problems. The overview of the Improved RPL is shown in Fig. 3.

In this paper, we propose the network life cycle index (LCI). LCI is the time before a node dies if it keeps on forwarding the same quantity of throughput. And we consider the network lifetime as the time before the first node runs out of energy, which is the most frequent definition [18, 19, 22]. The purpose of our scheme is to maximize the network lifetime. We can find the node that the most vulnerable in the path by using the designed LCI, and calculate its LCI, that is the LCI of the path. It's important to note that a node does not know the link quality of its neighbor nodes in the phase of network initialization. To avoid choosing the node that first received DIO as parent node, a node needs to wait a certain time. After receiving several DIOs, a node can use the following strategy for routing calculation.

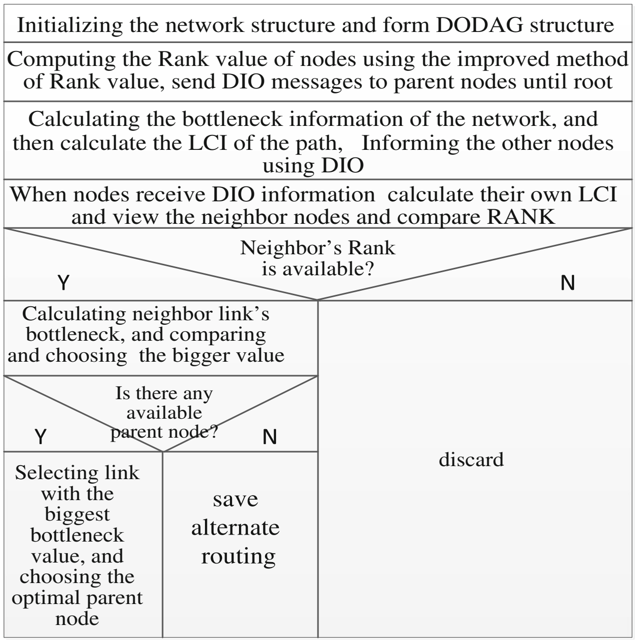

Fig. 3 An overview of the improved RPL

a) To begin with, we initialize the network structure and form the DODAG structure. After that, we compute the Rank value of nodes using the improved method of Rank value (see Section 3.3). At this time, the nodes need to send DIO messages to the parent nodes, and finally the messages will arrive at the root node. The root node will collect the network prefix information in DIO.

b) Each node has saved the path prefix information that received in DIO. We calculate the bottleneck information of the network, and then calculate the LCI of the path (see Section 3.2), after that, use DIO to notify the other nodes. We calculate the LCI of the current node by using the candidate path's LCI. Each parent node can find its own LCI and the LCI of the bottleneck nodes using the DIO control information that sent along the path.

c) If a node need to select the parent node after sending a message to the root node. The node can use the improved selection strategy of parent node (see Section 3.4) and choose the optimal parent node for data transmission. When choosing the optimal parent node, the scheme selects one optimal node according to LCI and Rank value, and stores another optimal route at the same time as alternate routing. When choosing a path after the link and neighbor nodes failure, the node without upward path can directly use the alternate path and don't need to send a new DIS query repair protocol (see Section 3.5).

When a node wants to join the DODAG, the node need to calculate its own LCI value, and compares with the other nodes in the path, then gets the LCI value of bottleneck, and after that notifies the other nodes. The bottleneck node is the node that will be the first one to run out of energy.

3.2 Path selection based on life cycle index(LCI)

The purpose of our scheme is to extend the survival time of the network effectively and maximize the network lifetime rather than minimize the sum of energy and only consider the residual energy. So the index considers node metric and link metric, including node energy, node hops, throughput and link qualities.

We calculate the path's life cycle index(LCI) when we do forward-routing, and choose a path according to LCI value. Meanwhile, we design a congestion detection factor in LCI and rank to broadcast nodes' congestion information to its neighbor nodes.

The improved RPL based on network life cycle index (LCI), changes the traditional objective function that just considers node hop, and puts forward a new routing metric, that is LCI. The improved RPL designs a new routing selection considering the LCI of node, data transmission power and residual energy of nodes.

Since the ETX value represents the stability of a link. The lower the ETX value, the higher the successful data transmission rate. It is the number of transmissions a node expects to make to a destination in order to successfully deliver a packet. In view of the effectiveness of ETX in reducing delay and energy consumption [20], the improved RPL considers link quality by using the existing standard of ETX.

3.2.1 The calculation of LCI

Life cycle index (LCI) represents the price that one node must pay to complete the link transmission. The steps to calculate the LCI of a node are as follows.

a) Evaluating the data throughputM_N of node$N$. $M_N$represents the throughput that the current node generates and the incoming throughput from its new joining children. As shown in formula (2). When calculating the data throughput of a node, we should consider the current node and its new joining children. Only in this way can the data throughput's computing be more representative.

$$M_N = D_N + \sum_{i \in Children(N)} D_i^{\,i} \tag{2}$$

where D_i denotes the data throughput of node$i$.

b) The average number of forwarding.Forwarding value of throughput multiplies the link reliability ETX (N, P) of each node's parent nodes(P is N's parent node) and the throughput ratio that sent to each node's parent nodes. As shown in formula (3).This formula adds link quality index to the throughput rate, at the same time, considers link quality, speed and the children.

$$F_N = M_N \times \sum_{P \in Parents(N)} [\lambda_P \times ETX(N, P)] \quad (3)$$

whereF_N is the average number of forwarding, $\sum_{P \in Parents(N)} \lambda_P = 1$, P is N's parent node, $ETX(N, P)$denotes the link quality index of A to B, $\lambda_P$denotes the throughput ratio of sent to P(parent node).

c) Calculating the ratio of time during which it uses the medium for its transmissions with considering the rate at which the data is sent.As shown in formula (4).

$$T = \frac{F_N}{V_{data}} \quad (4)$$

where V_{data} is the data transmission rate at which the data is sent; all nodes transmit at the same rate, T is the ratio of time during which it uses the medium.

d) Considering energy-delivering rate, the ratio of time multiplies the energy consumption that the node sends all throughputs. Then, the index has the factor of energy-delivering rate. As shown in formula (5).

$$V_{energy} = T \times P_{TX}(N)^{TX} \quad (5)$$

where $P_{TX}(N)$ is the energy consumption rate of sending node N,V_{energy} is energy consumption of N that sends all throughputs.

e) Finally, we compute the rest LCI of a node as a new LCI. We can get the index that we want by dividing the residual energy and sending and receiving data's energy-consumption, then plus congestion detection factorCF(N) at each node N.The smaller the index is, the less optimistic the network situation is. As shown in formula(6) (7).

$$CF(N) = \frac{P_Q(N)}{T_Q(N)} \quad (6)$$

$$LCI(N) = \frac{E_{res}(N)}{V_{energy}} + CF(N) \quad (7)$$

where $E_{res}(N)$ is the residual energy of N, $P_Q(N)$ is the number of data packets in the queue of node N, $T_Q(N)$ is the size of the entire queue of node N.

Because of link losses occur much later than queue losses, ETX is not suited for detection of traffic congestion in LLNs [23].Since the information of downward routing table's nodes number is updated by reception of Destination Advertisement Object (DAO) messages and timeouts of routing table entries, it can not reflect the actual congestion enough. Hence, for detecting and distributing congestion information, we choose to use the congestion detection factorCF(N) at each node N.

3.2.2 Path bottleneck evaluation

Since the purpose of our scheme is to maximize the network lifetime, we should focus on the bottleneck problem of network. The bottleneck is the node that runs out of energy firstly. So the key factor of a path is its bottleneck, namely the node that the easiest to run out of energy on the path.

After we know how to calculate the LCI of a node, we need to evaluate the path bottleneck by using LCI. If a path has the biggest bottleneck in selecting path, this path serves as the optimal path.The node broadcast the bottleneck along the path.

If a node *N* wants to join the DODAG, the node should estimate the impact of its own packets on the bottleneck's lifetime.

For example, as shown in Fig. 4, the path H-D-B-A's bottleneck is the node B. From Section 3.2.1, *The calculation of LCI*, to evaluate the LCI value of bottleneck nodeB, we need to know the following information about B:

- the residual energy of bottleneck nodeB: $E_{res}(B)$;

- the energy consumption of bottleneck node B that send one bit per second:

$$\sum_{P \in Parent(B)} [\lambda_P \times ETX(B, P_B)] \times P_{TX}(B);$$

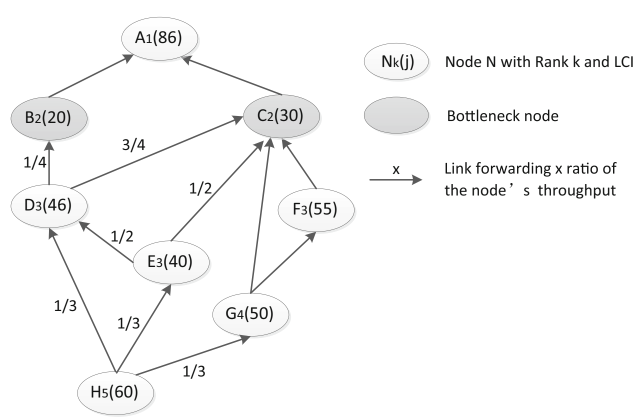

Fig. 4 Path bottleneck evaluation using LCI

- the data throughputM_B of bottleneck nodeB,including the node B and its children's data throughput:

$$M_B = D_B + \sum_{i \in Children(B)} D_i^i$$

- the data transmission rate of bottleneck node: V_{data};
- the congestion detection factorCF(B) at node B.

From the formula of Section 3.2.1, *The calculation of LCI*, we can notice that only the throughput M_B is injected by the new node. So, if we want to evaluate the path bottleneck B, we only need to calculate the current throughput of the bottleneck node B. As shown in Fig. 4 the joining node isH, the current throughput of the bottleneck node B is shown in formula(8):

$$new\_M_B = D_H + D_B \tag{8}$$

Because of the joining node has several parents, we have to take into account that a node sends its throughput to bottleneck node B by several parents. Only a part of the joining node H´s throughput can arrive at bottleneck node B.

We define $\omega_{P,B}$ as the ratio of throughput that H forwards to the bottleneck B by parent nodes P, $\lambda_P$denotes the throughput ratio of sent to P (parent node). We can compute the ratio of throughput that arrives at bottleneck node Bby the proportion of throughput that joining node H sends to parent nodes (λ_P) multiplies the ratio of throughput that parent nodes forward to the bottleneck B($\omega_{P,B}$). In the end, sum over all these values, as shown in formula(9):

$$\omega_{H,B} = \sum_{P \in Parent(N)} \left(\lambda_P \times \omega_{P,B}\right) \tag{9}$$

When a node itself is the bottleneck node, the ratio of the throughput that is forwards to the bottleneck is equal to 1, namely$\omega_{B,B} = 1$.

For example, consider node H and its parents D, E and G in Fig. 4. We can see 1/4 of the throughput of D is forwarded through the bottleneck B. 1/3 of the throughput of H directly arrives at parent node D, 1/3 of the throughput of H reach parent node D through the node E. So

$$\omega_{H,B} = \frac{1}{3} \times \frac{1}{4} + \frac{1}{3} \times \frac{1}{2} \times \frac{1}{4}.$$

Consequently, the new throughput of the bottleneck node B can be estimated in formula(10):

$$new\_M_B = \omega_{H,B} \times D_H + D_B. \tag{10}$$

Then, a node N can evaluate the LCI value of path bottleneck node by adding the new throughput of bottleneck node, and plus the congestion detection factorCF(B): as shown in formula(11)

$$LCI(B) = \frac{E_{res}(B)}{new\_M_B \times \frac{\sum_{P \in Parent(B)} [\lambda_P \times ETX(B, P_B)] \times P_{TX}(B)}{V_{data}}} + CF(B) \tag{11}$$

A node can broadcast the information of the bottleneck node by using DIOs, and stores the list of all its bottlenecks. The list information can be updated by its DIOs. Because of many parent nodes have the same bottleneck, we can determine the bottleneck of same paths.

3.3 Improving the calculation of node's rank value

As an index of judging the link stability, LCI only involves the choice of link, cannot be used as a node's rank index. Rank value is used to select the parent node after selecting a link. The rank value of nodes in traditional RPL is to prevent the loop. When a node chooses the parent node as the next jump, the node can only choose the node with smaller rank than its rank. The calculation of nodes' rank still should consider the energy of nodes. But the calculation of RPL's rank value only considers the node hop, thus network load imbalance may be led to in this way. According to their parent node P, node N calculates the Rank value by using residual energy. As shown in formula (12) and (13).

$$RankInc = Eres(N) + MHR \tag{12}$$

$$Rank(N) = Rank(P) + RankInc \tag{13}$$

where Eres(N)is the residual energy of node N, MHR is 100. We redefine the calculation method of Rank with consideration of the node hop and the node's residual energy. The calculation method of rank also includes congestion detection factor CF(N) to propagate congestion information. During the network initialization, the root nodes' RankInc can be assigned. The Rank value of root node is equal to M, and M is 100. We define the sender node hop asHop(sender). As shown in formula (14). The receiving node hop adds 1 on the basis of the sender node hop.

$$Hop(sender) = \left\lceil \frac{Rank(sender)}{RankInc} \right\rceil \tag{14}$$

Using the residual energy ratio can calculate node level, as shown in formula (15).

$$El(N) = \frac{Energy_{now}}{Energy_{ini}} \times M \tag{15}$$

The calculation formula of a new node Rank value with congestion detection factor CF(N), as shown in formula (16).

$$Rank(\mathrm{N}) = \beta[\mathrm{Hop}(\mathrm{N}) \times RankInc - \mathrm{El}(\mathrm{N})] + (1-\beta)\mathrm{CF}(\mathrm{N}) \tag{16}$$

where β is a cipher parameter used to embed and decode two values from a single numeric field. For our experiments, we have used β = 0.87.

Because of the rank of nodes in the DODAG must monotonically increase from the border router to the leaves. To guarantee the loop freeness, a node needs to:

- Select its optimal parent node using the algorithm 1 that is explained in the next section.
- Compute the value of its own rank based on its optimal parent node's rank.
- If a neighbor node with a higher rank than itself, then remove the neighbor node from the parents list.
- Gather all bottleneck nodes, and update the corresponding information in its DIOs.
- In order to avoid loops, neglect the DIOs of nodes with a higher rank than itself.

3.4 Improved selection strategy of optimal parent node

Our method changes the traditional optimal parent node selection scheme with consideration of nodes' Rank value, reduces change and updates information timely. When selecting the optimal parent node, a node must calculate their LCI value and bottleneck nodes' LCI value, meanwhile judge who is the latest bottleneck, then select the latest bottleneck as the optimal parent node, as shown in the following steps. (see Algorithm 1: The selection strategy of optimal parent node)

a) When more than one available parent node receives DIO information, a node's LCI index can be calculated by the improved objective function. Then the node can compare with the neighbor nodes whose Rank value is smaller than the node. The node's rank value is computed by the method that we have improved. And the node finds the path that all available neighbor nodes represent as candidate parent nodes and stores the information or gives up the neighbors.

b) Calculate neighbor candidate path's bottleneck index, make a comparison, and take several nodes whose value is relatively large. Then compare with its own LCI, after that notify the link's current LCI and bottlenecks' LCI.

c) We select the path with the largest bottleneck LCI value as the selected path by comparing the node's LCI and the parent nodes path bottleneck(the bottleneck is not simply the path's original bottleneck and maybe itself is the current bottleneck), and select the optimal parent node at the same time, then notify the path of update bottleneck.

Algorithm 1. Optimal parent node selection

Algorithm 1. The selection strategy of optimal parent node

Input:
node N, the parent nodes of N
Output:
the optimal parent node of N

for $\mathrm{P} \in \mathrm{parent(N)}$ **do**
  $\mathrm{lci}_{\mathrm{N}} = \mathrm{LCI(N)}$;
  $\mathrm{lci}_{\mathrm{B}} = \mathrm{LCI(B_P)}$;
  $\mathrm{Path_P(B_p)} = \min\{\mathrm{lci}_{\mathrm{B}}, \mathrm{lci}_{\mathrm{N}}\}$;
End
$\mathrm{optimal\_parent} = \mathrm{P}$ such that
$\mathrm{Path_P(B_p)} = \max_{i \in P(N)}\{\mathrm{Path_i(B_p)}\}$
return optimal_ parent;

After the node selects the optimal parent, it needs to compute the new bottleneck of the path and update the corresponding information in its DIO.

3.5 Multi-path routing scheme

In order to achieve multifold objectives, including higher reliability, increasing throughput, fault tolerance, congestion mitigation and hole avoidance, multi-path routing has been widely used in many studies [24]. To provide QoS using multiple paths, multipath opportunistic RPL routing protocol [25] was designed to work over IEEE 802.15.4. G. Xu et al. [26] proposed DAG-based multipath routing protocol for mobile sinks. In order to prevent link failure, the protocol allowed a node to find alternative paths. In order to overcome the resource constraints of sensor nodes and the unreliability of wireless links, Quan Le et al. [27]proposed three multipath schemes based on RPL (Energy Load Balancing-ELB, Fast Local Repair-FLR and theirs combination-ELB-FLR) and integrated them in a modified IPv6 communication stack for IoT.

3.5.1 Multi-path to increase the ability of fault-tolerant

RPL is a single path routing protocol and this protocol only finds an optimal or a better path. To prevent failure, the path needs to be updated in real time, and needs to send more control information. As there is only one path, it is a complex and resource-consuming process to restart the path search when the network has trouble [11]. Since more than one path is found in the route discovery process, we can store other paths. When a failure happens, those paths can be directly used to communicate, and this can save a lot of time. Our scheme designs a multi-path scheme to increase the ability of fault-tolerant in this paper for achieving the multi-path RPL. When choosing the optimal parent node, the scheme selects one optimal node according to LCI and Rank value, and stores another optimal route at the same time as alternate routing. When choosing a path after the link and neighbor nodes failure, the node without upward path can directly use the alternate path and don't need to send a new DIS query repair protocol. Working process is shown in Fig. 5.

Fig. 5 shows the complete working process of multi-path routing. We initialize the network by using the improved network initialization function(explained below). When nodes receive DIO information,the nodes need to calculate their own LCI and view the neighbor nodes and compare the RANK. If the values of neighbor nodes' rank are not available, then discard the neighbor nodes, else calculate neighbor link's bottleneck, and compare and choose the path with the bigger value of bottleneck. If there is no any available parent node, call the standby node that saved, else forward data directly, update the list of parent nodes.

All nodes can receive the DIO information of the neighbor nodes when the network initialization.We can complete the network initialization through the following four steps:

a) The root node sends DIO information to its neighbor nodes when the network initialization, and sets upRankInc = M, namely the rank value of root node is M. The computing method of rank value is the method that we proposed. The root node sends DIO information to notify neighbor nodes that update information. This provides the precondition for multi-path.
b) The nodes that receive the DIO information estimate the rank value of root node. If the rank value of root node is equal or greater than the rank values of the nodes, then discard the root node, else the nodes add the root node to the parent nodes list. This will prevent a loop path. At the same time, the nodes select the parent nodes according to the selection strategy of optimal parent node. The nodes that match the condition will be the parent nodes and will be added to the list of parent nodes. The selection of optimal parent nodes uses the LCI. The index can balance the network energy loss and provide multi-path including the bottleneck nodes of the network.
c) After the nodes select the parent nodes according to the improved selection strategy of optimal parent node and add the nodes to the list of parent nodes, the nodes send DIO information to the surrounding nodes. The new computing method of Rank considers the remaining energy. When the energy is changing, the value of rank needs to be computed again and sends DODAG to update the information.
d) When a node receives the DIO information from the other nodes, it will repeat steps *b)* and *c)* and save multiple paths. When a failure happens, a node can directly select the other parent nodes in the list of parent nodes. Those nodes have considered the network path bottleneck, and can extend the network lifetime.

After the network initialization, each node has saved the list of standby nodes with the same minimum rank value. Each node can select the node according to the selection strategy of optimal parent node as the next jump. Meanwhile, the node deletes the other information incompletely, and chooses a part of the nodes as the standby parent nodes, the node may also be selected as the next hop node. Although this will add a small amount of load, this can realize the multipath. When a failure occurs, the node can firstly find the standby parent nodes. If there is a node can be as the next-hop node directly, the node doesn't need to send the DIS information and other redundant message information. The process of data forwarding is shown in Fig. 6.

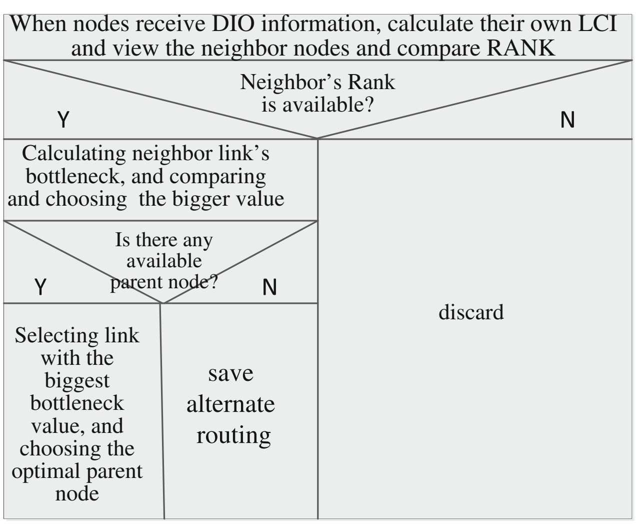

Fig. 5 Multi-path routing working process

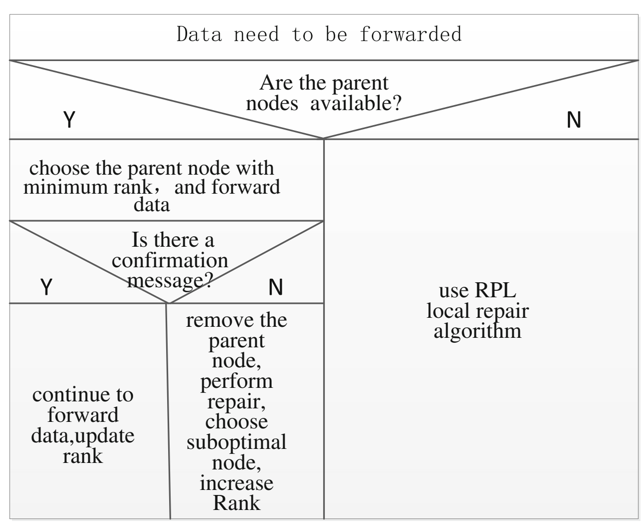

Fig. 6 The process of data forwarding

3.5.2 Multi-path to solve the congestion

Meanwhile, we need to define the congestion indicator ω_N that detects congestion and triggers the multipath routing for congestion. There are some candidates such as CF(N) and $CF(P_N)$. Because of even when P_N experiences a lot of queue losses, the value of CF(N) is much smaller than $CF(P_N)$, and when CF(N) is large, the parent selection of node N cannot help reducing the load, hence CF(N) cannot reflect the traffic congestion properly. $CF(P_N)$ also can't be the congestion indicator. Even if $CF(P_N)$ is better than CF(N), it doesn't meet our conditions. Because once the traffic load is well balanced after a congestion event, the $CF(P_N)$ of each node is low.

Therefore, we consider $CF_{n,max}$ which is the maximun CF(N) among all the parent candidates that node N had in the recent past as the congestion indicator, as shown in formula (17).

$$\omega_N = CF_{n,max} = \max\left\{\max_{i\in\{1,2,3,4\}} CF_{n,max}^{[i]}, \max_{p_n\in P_n}\{CF(p_n)\}\right\} \tag{17}$$

where $CF_{n,max}^{[i]}$ is the $\max_{p_n\in P_n}\{CF(p_n)\}$ in the recent 4 h. P is the parent node of N.

If $\omega_N > 0.5$, that is theCF(N)of a congested node is above 50%, node N needs to start the multipath routing for congestion. The child node forwards one packet to its original parent who is congested and forwards the next packet to any other alternate routing from the parent alternate routing list. Therefore, during congestion mitigation a node drops its forwarding rate to the congested parent node to half. The rest of the data is forwarded through an alternate path by using any other parent node. This method can reduce the congestion at their parent node.

In this section, we carry out a detailed explanation of the improved RPL protocol. Aiming at the problems of RPL protocol and some improved schemes, we design path life cycle index(LCI) to replace the original protocol's path selection objective function with consideration of node energy, power, link quality, success transmission data rate and congestion detection factor. Because of the function considers the node energy and link quality, the improved RPL protocol can ensure load balancing and embody the thought of network lifetime [20]. The energy consumption can be conserved effectively and packet loss rate can be reduced with consideration of transmission data rate [28]. The congestion detection factor in LCI and rank can distribute nodes' congestion information to its neighbor nodes. We can recognize the congestion information of a node timely by congestion detection factor. We can find the bottleneck of a path, namely the node that the easiest to run out of energy on the path by using LCI to maximize the network lifetime. For example, we can avoid some nodes' energy on the path being consumed too early that caused by the ETX scheme [10], and the selection of the lowest efficiency link caused by [20], and so on.

Furthermore, we introduce the multipath routing scheme to improve the single path of RPL and solve the congestion problem. Each node can save multiple available parent nodes to prevent rerunning the program to detect and establish path after malfunction. Because it is a complex and resource-consuming process. The multi-path routing has been widely used in many studies [24], and obtains the predictive effect.

4 The implementation and performance analysis of the improved protocol

CONTIKI is an open-source operating system specifically developed for sensor networks and system with limited memory of internet of things. Its system, libraries and applications are written in C language. COOJA is the simulator of CONTIKI OS applications. It is written in Java language but allows node sensor to be implemented with C language.

In this section, we use COOJA simulator of CONTIKI OS 3.0 to simulate the following four schemes. We first compare the network load, end to end delay and packet delivery ratio of RPL and improved-RPL protocol to evaluate the improved-RPL's performance. Then we compare the three improved schemes to verify the advantage of our scheme relative to other schemes.

- RPL: the original Routing Protocol for LLN.
- ETX [29]: the average number of transmissions for link metric.
- The scheme based on residual energy [19]: the remaining energy of nodes.
- The scheme we improved (IRPL): network life cycle index(LCI).

We place 100 nodes in an area of 500 m × 500 m randomly, and consider using CBR convergecast flows. The simulation time is 10 min, and each packet is 128 Byte. The results can be processed with the complementary cumulative distribution function (CCDF) [30], then we draw after data normalization. We can find the size of node number of this area is relative to the total number of distribution by looking at the slope and proportion. When simulating, the nodes' working range is 50 m in 100 nodes randomly square area. The simulation environment parameters configuration is shown in Table 1.

The Fig. 7 shows a random distribution of nodes in a specific area.

We measure each scheme's network layer load, end-to-end delay, packet delivery ratio, percentage of optimal parent nodes change, energy consumption index and network lifetime in the comparison.

Table 1 Parameters' Configuration in Simulation

Parameter	Value
Simulation area	500 m*500 m
Node initial energy Eo	0.5 J
Sending unit packet loss energy ETX	0.00000005 J
Receiving unit packet loss energy ERX	0.00000005 J
Multipath attenuation energy EDA	0.000000005 J
Size of data Packet	128Byte
Size of control packet	100bits

- Network load: the definition of network layer load is shown in formula (18).

$$LOAD = \frac{\mathrm{Num(DIO)} + \mathrm{Num(DIS)}}{Total(packet)} \tag{18}$$

Num(DIO),Num(DIS), respectively represents the number of two kinds of messages. Total(packet) represents the total number of data packets.

- End-to-end delay: the end-to-end delay represents the time that the data packet spends from generation to its reception by the sink.
- Packet delivery ratio (PDR): the packet delivery ratio (PDR) represents the ratio of packets that a node receives and the total number that source sends.

Numbering for n nodes, totally sending $S_i$packets and the destination node receivesT packets from inode, using the formula (19) to calculate PDR.

$$\mathrm{PDR} = \frac{\mathrm{T}}{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{S_i}} \tag{19}$$

- Stability: the percentages of the optimal parent nodes change mainly measure the stability of the network. Its meaning is calculating the changing times of parent nodes in the experiment. The parent nodes that change frequently will lead to the network producing too much DIS, DIO control message. The fewer the changing is, the more stable the selected parent node is, and energy consumption will be less.
- Energy consumption index shows the remaining energy of the network as time goes by. The more residual energy the node has at the same time, the more balanced the network load is.

  Energy model:

  Due to the remaining energy of the node can't get directly, hence we use the current consumption during each node state

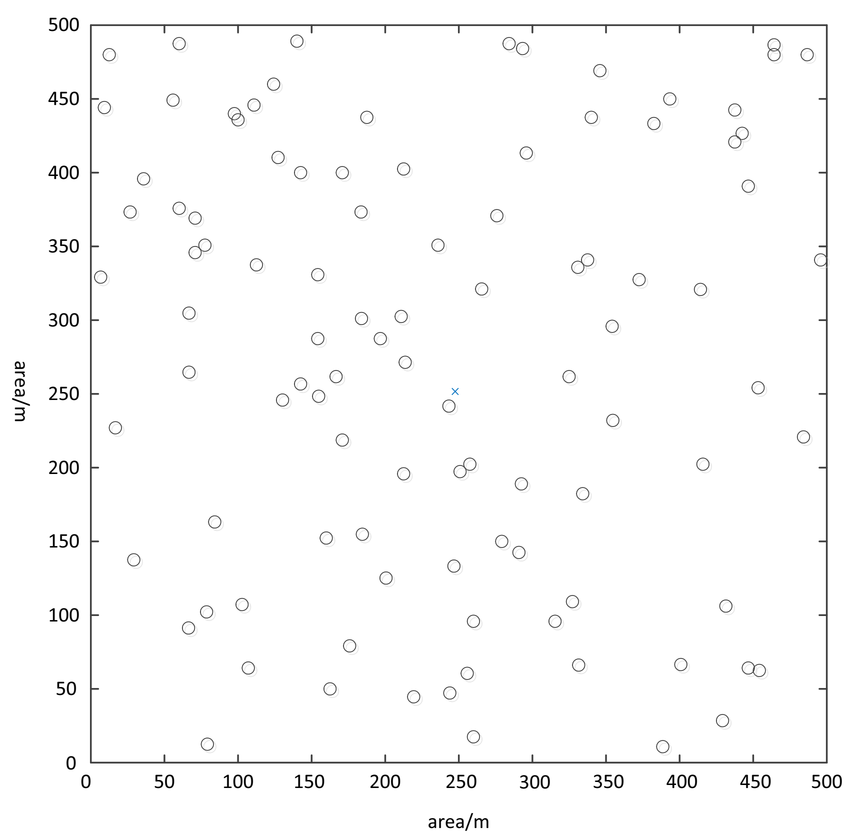

Fig. 7 The diagram of randomly distributed node

and its duration to estimate the battery remaining energy. The remaining energy can be expressed in formula (20): [20]

$$Remaining\ \ energy = Battery{-}Energy\ \ Consumption \qquad (20)$$

Battery:

The X-MAC which is the MAC layer of COOJA, has the battery as 3 voltages. The listening, transmission and CPU energy consumptions are 20 mA, 17.7 mA and 1.8 mA, respectively [31].

Energy Consumption: as shown in formula (21)

$$Energy\ consumption = T_{cpu}\bullet P_{cpu} + T_R\bullet P_R + T_S\bullet P_S \qquad (21)$$

where T_{cpu}represents the run time of CPU, P_{cpu} represents the power of CPU, T_R stands for the receiving time of packets, P_R stands for the power of packets, $T_S$denotes the sending time of packets, P_S denotes the power of packets.

- Network lifetime: time before the first node dies. We measured the network lifetime when varying the number of nodes while maintaining the simulation area constant.

Table 2 shows the simulation results of RPL and improved-RPL protocol. As you can see from Table 2, the RPL's load is higher than that of IRPL protocol by over 2.1%.The new calculation method of node's Rank considers the residual energy and link quality. This can avoid premature failure of some nodes' energy consumption [32] and make the network load more balanced. Due to multipath routing scheme, nodes can use other useful paths to forward data packet when congestion occurs. For this reason, the end-to-end delay of IRPL protocol is significantly less than the RPL's. The packet delivery ratio shows that the RPL's packet delivery has a big problem, and the gap is about 5% when comparing with the improved protocol. As RPL does not realize the load balance and the calculation of Rank only considers the hop, RPL can lead to some nodes early running out of resources and a decline in data delivery ratio. Taken together, these factors have led to lower packet delivery rate. All the above suggest IRPL is more applicable.

Fig. 8 shows the packet delivery ratio of different time. The scheme considering the residual energy has the lowest packet delivery rate at low sending rate. The scheme only considers the energy of nodes, and chooses the node with the largest residual energy as parent node, and almost every time selects new node as the next jump. This will have a significant impact on the network and lead to a lower packet delivery ratio. In the beginning, ETX's delivery rate is higher [33]. LCI scheme not only considers the link, but also considers the link bottleneck. This increases the amount of calculation. Because only the link with good quality can transport, with the increasing of sending rate of packets, other links cannot be used in their spare time, thus link congestion is caused. But congestion detection factor CF(N) can detect congestion, and the multi-path routing can be triggered. Therefore, the improved protocol packet delivery rate could be improved by more than 12%.

Fig. 9 shows the end-to-end delay of different schemes. We can clearly see the scheme with consideration of node energy's end-to-end delay is small, because most of the data packets with no better link are abandoned. The more the data packets are abandoned, the smaller the time delay is. But at the same time the number of times that needs to pass will increase. So it will consume more energy. Although the time needed is less every time,

Table 2 Experiment Results Comparison

Parameters	Load(%)	Delay(s^{-3})	Packet Delivery Ratio(%)
RPL	39.69	97.11	73.36
IRPL	37.53	87.31	78.54

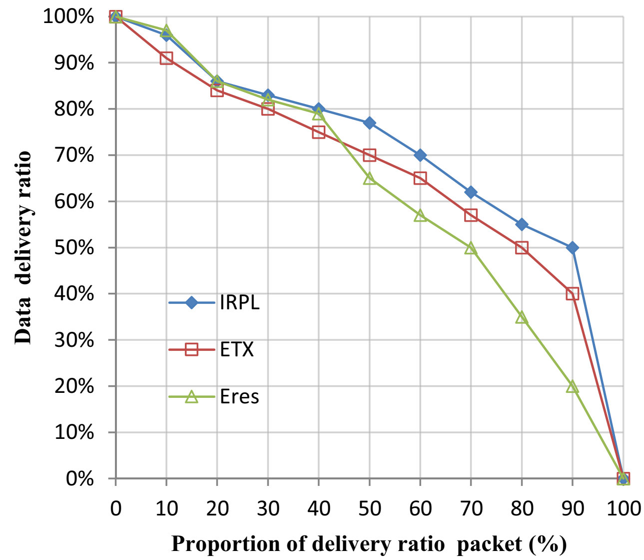

Fig. 8 Packet delivery ratio

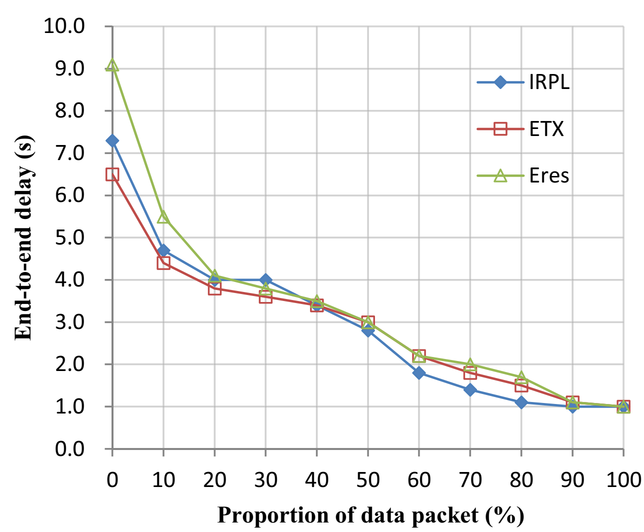

Fig. 9 Average end-to-end delay

more energy will be wasted due to the low delivery rate. Because of choosing the good quality links every time, ETX and LCI schemes' end-to-end delay is almost the same initially. But later on LCI scheme's end-to-end delay is less than ETX's because of the introduction of multi-path routing scheme. The LCI scheme considers node energy, the data packets with no better link is abandoned, but the multi-path can re-select another path for the abandoned. The retransmission delay is practically much shorter than the buffering delay. And the protocol that we proposed is more suitable for low energy network.

Fig. 10 shows change number of optimal parent node. From Fig. 10, we can see that more than 50% of the node that their optimal parent change in the improved scheme is less than 5 times during the simulation, but the changing time in traditional routing schemes is around 10 times. Therefore, we can choose more stable parent nodes by using the network LCI to make the network more stable and reduce the change of network topology, at the same time decrease the consumption of network energy. The nodes' survival time is different in fixed area through observation. We can see that the nodes will die firstly in those schemes which only consider the link quality. Those schemes which only consider the node energy will need to be resent frequently due to too much invalid routing and will also run out of energy quickly. The LCI scheme has the longest network survival time with comprehensive consideration, thus LCI scheme can improve the network survival time.

Fig. 11 indicates the data delivery ratio with different number of data packets per second. As we can see from Fig. 11, the variation of data delivery ratio of improved scheme (LCT scheme) and ETX scheme is stable. And the stability of LCT scheme is higher than that of ETX in general, about 6%. Meanwhile, the stability of LCT scheme has more than 50% higher than the scheme considering the residual energy. When sending rate is bigger, the scheme considering the link quality is very effective.

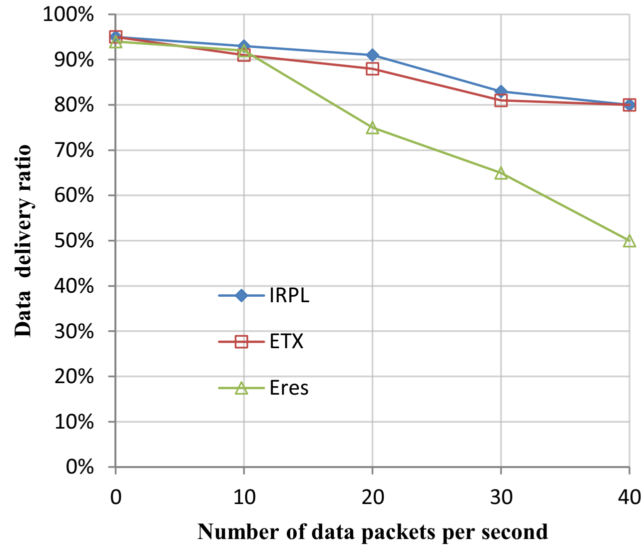

Fig. 11 PDRwith different number of data packets per second

Fig. 12 indicates the network energy consumption. We can see that the improved protocol consumes balanced energy, the energy consumption of each stage is all less than the other two protocols, and the network survival time also has prolonged. The analysis shows that the protocol with residual energy element can effectively avoid premature failure of most nodes. However, some links with bad quality may be selected all the time due to their nodes have more energy. Although the scheme could balance energy consumption locally, the network work efficiency will be affected. If ETX which considers the quality of the link is used, only those nodes with higher

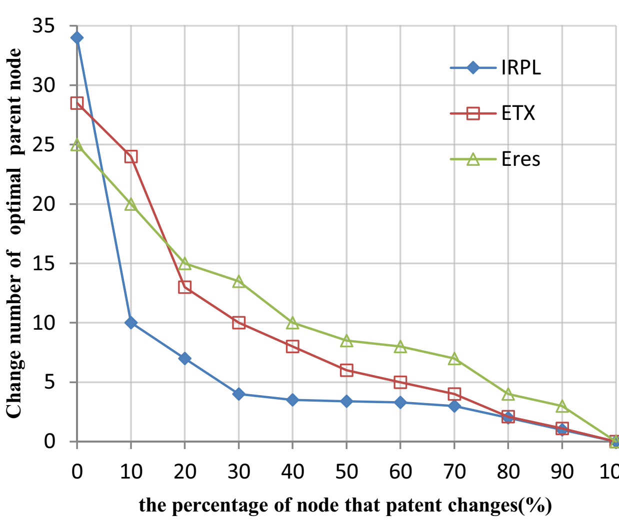

Fig. 10 Change number of optimal parent node

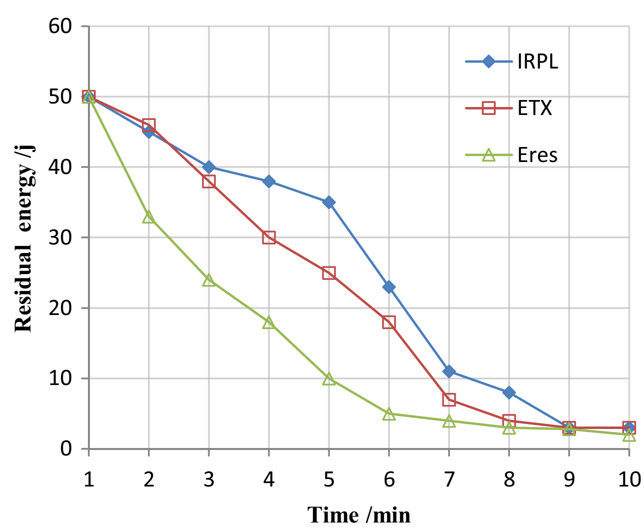

Fig. 12 Network residual energy

quality can transmit data, the energy consumption is the smallest, but at the same time some nodes' energy may run out quickly because of the high-quality link. Using the improved LCI, we redefine the Rank value and select the optimal parent node with consideration of some factors, such as link quality and sending rate. The improved scheme can meet the demand better by choosing the link with larger residual energy and node link with better ETX to transmit data. Despite the fact that LCI creates more than one path by splitting traffic flows as congested node, it has lower energy consumption than other schemes.

We also evaluated the lifetime of the network (time until the first node will run out of energy) in function of the number of nodes. We kept the same simulation area and increased the number of nodes. As we can observe from Fig. 13, LCI scheme manages to double network lifetime when compared to ETX. The lifetime decreases when the network becomes denser. This is due to the bottlenecks will have to relay more packets. Despite all this, LCI has an obvious comparative advantage in network lifetime compared to the ETX scheme and the residual energy scheme. Because of ETX scheme chooses good quality links that do not require many retransmissions, the ETX scheme has better lifetime than the residual energy scheme. When the network has 50 nodes and 70 nodes, a significant difference can be observed between the LCI. This is because a lot of packets are dropped, and too much time must be spent in the buffer.

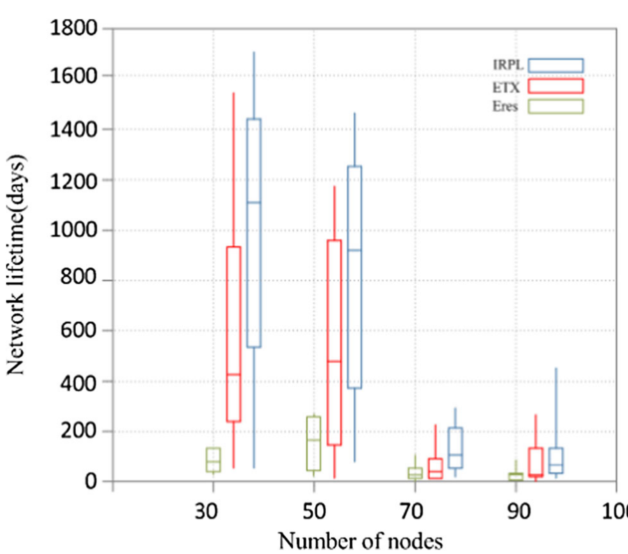

Fig. 13 Network lifetime (time until the first node will run out of energy) in function of the number of nodes

5 Summary and outlook

With the popularization of intelligent device, the rapid development of Internet of Things pushes the society forward continuously and the research of WSN network becomes increasingly popular. We analyzed the existing problems of RPL protocol in this article, and proposed the improvement scheme and made the improved protocol better meet the needs of WSN network. We proposed a new routing measurement mode—lifecycle index LCI with consideration of link quality, node energy, energy consumption rate, throughput, data transmission speed, congestion detection factor CF(N) and so on. The index can find the bottleneck of candidate path in advance. The bottleneck indicates the transferring bottleneck value of one link. According to the LCI index, our method designs a new node grade calculating formula to improve the calculating method of Rank and the selection method of optimal parent node. When selecting the next-hop, we choose the node whose LCI index is larger, and at the same time store a spare parent node to realize the multi-path function. Meanwhile, we use the multi-path scheme to solve the congestion problem.

The experiment results show that the improved scheme can reach a better load balance, reduce the end-to-end delay, improve the packet delivery, and prolong the network lifetime. The subsequent studies will improve the parent node selection, and calculate the LCI value in advance; further optimize the parent node selection scheme; set the reasonable threshold to reduce the sending of control information in the local repair algorithm using social welfare function; enhance the protocol support for mobility and others.

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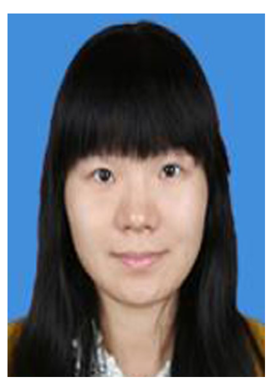

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