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An Efficient RPL Protocol in Wireless Sensor Networks Based on Energy Balance

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Abstract

An efficient RPL protocol in wireless sensor networks based on energy balance (EBE-RPL) is proposed to solve the problems that the best parent node selected by the subsequent is unreasonable and the lifetime calculated by bottleneck node is longer than the actual lifetime in the EB-RPL protocol, EBE-RPL protocol proposes a new traffic accumulation mechanism to calculate expected lifetime of bottleneck on each path, so that the lifetime calculated of bottleneck is closer to the actual value and proposes a new bottleneck re-estimating mechanism to avoid the bottleneck's change after node's joining in the DODAG. EBE-RPL improves accuracy for selection the best parent node, and balances the energy of networks. Simulation results show that, EBE-RPL contributes to the balance of network energy, the extension of network lifetime and the decrease of network energy consumption.

Keywords*: RPL, Bottleneck node, Parent node, Energy balance*

1. Introduction

In recent years, with the development of technology and application, the wireless sensor networks(WSN) technology has become one of the main streams of in the world. In WSN, a large number of devices, called smart objects, such as sensors, actuators, and Radio Frequency Identification(RFID) tags perform the sensing or identifying task in the real world. However, these devices are constrained by computation capability, memory size, energy supply, and bandwidth. The links formed by these devices in the networks typically exhibit a high packet error rate, low data rate, and link outages due to environmental conditions. This network is 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 [1-5]. RPL has been widely used in many kinds of project about IoT, and has caused widely attention in the academia. Due to the energy limitation and link lossy characteristics in the network, the nodes are easily to energy depletion and failure so that the data cannot be transmitted to the destination on time, and what's worse is that the data may transmit to the destination failed. So energy balance is one of the key research directions of low power loss network. There are lots of literatures which pointed to node's energy equilibrium and efficiency improvement for low-power and lossy network, which use energy or other parameters such as hop count, ETX combined as the routing Parameter, can balance the energy and prolong the lifetime of network effectively. Hu.q.y et al [6] proposed an Energy Efficient RPL algorithm called EERPL, it takes hops and energy of nodes into account to select the best parent, so that the data can be transmitted to the destination through the nodes that with sufficient energy and achieve the result of energy balance and prolonging the network's lifetime. Both L.H. Chang et al [7] and Abreu et al [8] proposed

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a strategy that combine the ETX with residual energy to select the best parent, this enable the nodes to join DODAG by choosing the nodes with best conditions, and achieve the purpose of balancing the energy consumption of each node. Capon et al [9] propose a routing metric called L2AM which combine link quality and residual energy with transmission power of the nodes to select the prefer parent, it balanced energy and prolonged the lifetime of network. O. Iova et al [10] proposed an EBRPL algorithm which used a metric called ELT to select the best parent. Before joining DODAG, a node should calculate the expected lifetime of the bottleneck node and the one of itself, and compare these values to choose out the node with maximum ELT, then it selects the node on the path with the maximum ELT to be the best parent. This algorithm can balance the energy of bottleneck nodes on some extent, and also prolong the network survival time. The main problem of the EBRPL is that the nodes do not take the traffic generated by the children of the parent into account, by calculating the ELT of bottleneck with the traffic generated by itself only will result to a longer ELT value, so that affect the accuracy of selecting the best parent and cannot achieve the best effect of energy balance and prolong the lifetime of network. Point to the problem mentioned above, this paper proposed an EBE-RPL protocol. This protocol can make more accurate to join nodes choose the optimal parent node, effectively improves the network energy balance ability, reduces the network control overhead, extends the network survival time and so on.

The rest of the paper is organized as follows. Section 2 presents a brief introduction to the traditional RPL. Section 3 describes Network model and problem description. Section 4 describes the proposed EBE-RPL in detail. Section 5 shows the simulation and performance evaluation, while conclusions are provided in section 6.

2. RPL Overview

You may prepare your camera-ready manuscript with MS-Word using this typeset together with the template joc.dot (see Sect. 3) or any other text processing system. In the latter case, please follow these instructions closely in order to make the volume look as uniform as possible.

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2.1. Construction of DODAG

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 RPL stipulates that there must be a root node or boundary node which broadcast the DIO messages periodically to maintain the DODAG, and the DIO messages are used to find the RPL instance, understand the information about the network configuration information and select the parent node set. After receiving a DIO message, a node should decide whether to join the DODAG.

Each DIO message should contain three part of the base information: version number of DODAG, routing metric and the sender’s rank. The node which received the DIO messages should compute its rank value according to the object function (OF), and select the node to be its parent which can make it has the minimum rank value, and then, broadcast the DIO messages to its neighbor with the Trickle timer, after this step, the node joined the DODAG and realized the upward routing namely MP2P routing. Besides, after a node jointing in the DODAG, it will decide whether to construct the downward rout according to the MOP bit in DIO message, if the MOP bit is not 0, it means that the node can build a downward route, and then send a Destination Advertisement Object (DAO) to its parents or the root node to advertise them its destination address. The nodes receiving a DAO message will feedback a DAO-ACK message to the sender. Each node sends the

DAO messages upward, and then finished the downward route and realized the P2MP routing. Fig. 1 illustrates the example of the construction of a DODAG.

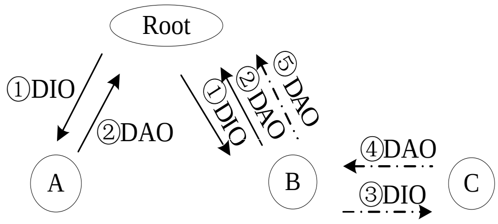

Figure 1. Example of the Construction of a DODAG

In Figure 1, the root broadcasts a DIO message to its neighbor A and B, then the two nodes decide to join in the DODAG, so they broadcast the new DIO messages with the Trickle mechanism to their neighbor, and also send a DAO message to their parent node namely the root node. There is a node C in Fig. 1, if C didn't receive a DIO message, then it will broadcast a DODAG Information Solicitation (DIS) to find a neighbor. At one moment, B received the DIS from C, then it send a DIO message to C， and will receive a DAO message of C.

2.2. Loop Detection and Avoidance

In RPL, loop detection and avoidance mechanism ruled that each node cannot select the node with higher rank value to be its parent, and the node must confirm the rank value is descending from itself to the root node so that it can assure there is no cycle in the DODAG. For detecting the cycle, every packet must add a mark bit in its head. if the packet is downward, then the mark bit is set as 'down'. The node receive the packet will search its route table, and if it finds the packet's destination node is above itself, it means that there must be a loop between itself and the destination node, and then discard the packet. Conversely, if the packet is send to the node upward, the mark bit will be set as 'up', and the node receive the packet will search its route table to judge whether the destination node is below itself, and then make the conclusion of whether there is a loop between itself and the destination and whether to discard the packet.

2.3. Repair Mechanism

RPL supports two complementary repair mechanisms: (i) global repair and (ii) local repair. When a node detects a network inconsistency (e.g. a link between two nodes fails or a local loop is detected), it triggers a local repair operation. It finds a backup path urgently without trying to repair the whole DODAG. This alternate recovery path may not be an optimal path. If local repairs are not efficient for network recovery due to several inconsistencies, the DODAG root may trigger a global repair operation and then it increments the DODAG version number and initiates a new DODAG version. The global repair operation leads to a fundamental reconstruction of the network topology.

2.4. Data Transmission

In the phase of data transmission, each node transmits packets to its optimal parent by default until the packets arrive the root, this way of data transmission from multiple nodes to a simple node is called MP2P routing.

The nodes can also transmit packets to its children. Before sending out the packets, a node knows the destination of these packets by searching its routing table, this way of data transmission from one point to multiple points is called P2MP routing. P2MP routing generally applies to home automation and industrial control and other fields. In RPL routing protocol, each node unicast DAO message to its parent node and then sent by the parent up until the DAO message reaches the root node.

In addition to the two routing modes mentioned above, there is another kind of routing mode, by which a node can send packet to a specific node, called P2P routing. When the source and destination nodes in the same communication range, the source node sends data directly to the destination node; when they are not in the same communication range, P2P routing can differ with different operation modes of nodes.

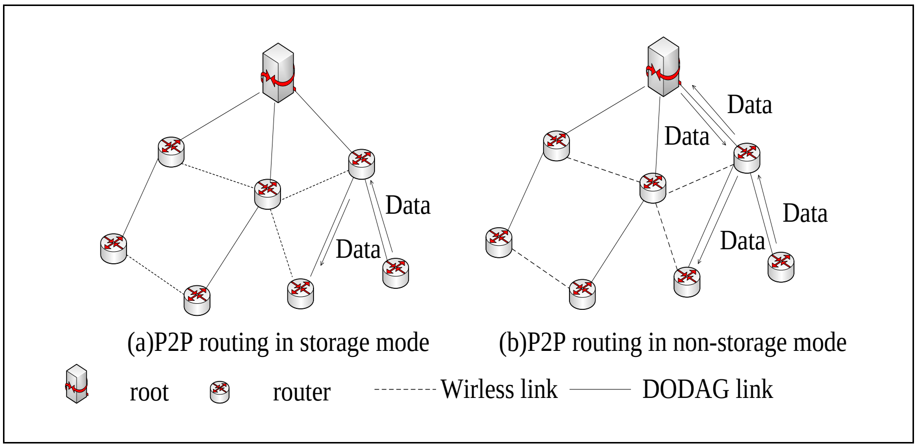

Figure 2. Data Transmission under Different Mode

As is shown in Figure 2, in the storage mode, a node must transmit the packets upward until the packets arrive the node which is the co-ancestor of the destination and itself, then the co-ancestor sends the packets to the destination by searching the right routing in its routing table. In the non-storage mode, the source node must transmit the packets to the root, and then send the packets to destination by root.

3. Network Model and Problem Description

3.1. Network Model

Assume there is a low power and lossy network with N wireless sensor nodes randomly deployed, the other conditions are as follows.

(1) In the EBE-RPL protocol, all nodes except the boundary node are randomly deployed in a 300*300m square monitoring area, and the boundary node is located at the edge of the sensor area. Once all the nodes are deployed, their position is fixed.

(2) Each node has a short sleep cycle, and can monitor the situation of each node's packet transmission.

(3) The nodes in the network contain a boundary node, routers and leaf node. The boundary node has infinite energy, and the energy of both routers and leaf nodes is supplied by battery which means a constrained energy.

(4) The routers can not only generate data but also transmit packets to other nodes, while the leaf nodes can generate data only which means the leaf nodes cannot role as a router. All nodes have the same transmission range.

Definition 1: The bottleneck, which represents the node that has the least residual energy in the path from node to root.

Definition 2: Network survival time, which means the period from the network's beginning to the merge of the first node that out of usage, it is similar to the working time of the bottleneck with the least residual energy.

Definition 3: The ELT. The expected survival time of node that obtained by estimation. Its calculation formula [10] is:

$$ELT(n) = \frac{E_{res}(n) \times DATA\_RATE}{T_{total}(n) \times ETX(n, P_n) \times P_{tx}(n)} \tag{1}$$

In Eq. (1), the $E_{res}(n)$ represents the residual energy of node, and the $DATA\_RATE$ represents data rate, the $ETX(n,P_n)$ represents expected times of transmission, the $P_{tx}(n)$ represents transmission power, the $T_{total}(n)$ represents the traffic forwarded to parent and its calculated by:

$$T_{total}(n) = T_{gen}(n) + \sum_{i \in Children(n)} T_{total}(i) \tag{2}$$

In Eq. (2), $T_{gen}(n)$ is the data traffic generated by the node n, and $T_{total}(i)$ is the total traffic go through node i in the same path.

3.2. Problem Description

The EB-RPL protocol [10] calculate the ELT of bottleneck in each path and then select the node which is in the path with the maximum ELT as the best parent to join DODAG. But there are three problems in the protocol:

(1) The joining nodes only considered the traffic generated by itself without the one generated by the other sub-nodes of the same parent node. This lead to the lifetime calculated for bottleneck node longer than the actual lifetime, and affected accuracy of judging the bottleneck.

(2) Because of no considering the diversification of bottleneck after the node's joining, the subsequent nodes cannot select the best parent accurately and cannot achieve a best result of both energy balance and prolonging network's lifetime.

(3) The protocol did not consider the circumstance that the ELT of bottleneck on different path is equal. If choose parent blindly, it may increase the burden of a certain node, and have no advance to energy balance.

4. EBE-RPL Protocol

In this paper, we propose an improved RPL protocol named EBE-RPL based on EB-RPL. The main contribution of EBE-RPL is designed three new mechanisms: (1) Traffic accumulation mechanism. (2) Control message accumulation mechanism. (3) Bottleneck re-estimating mechanism.

4.1. New Mechanism for EBE-RPL

(1) Traffic Accumulation Mechanism: Traffic accumulation mechanism means that before the node joining in the DODAG, the node should firstly accumulate the data traffic which generated by the nodes who have already joined the DODAG through the same parent node, then use the accumulated traffic to calculate the expected lifetime of the bottleneck node. For example, in Figure 3, in the process of selecting F as the optimal parent of G, another node H have already joined the DODAG through F, the traffic of H can also reduce the ELT value of the bottleneck C, so when node G is calculating the ELT of bottleneck, it must take into account the traffic of node H to avoid the calculated result more than the actual result.

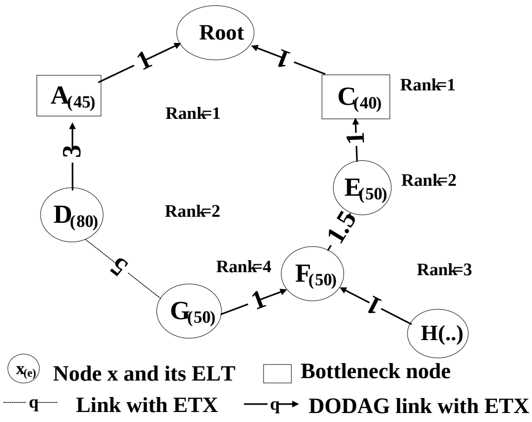

Figure 3. Example for Parent Node Have Other Children

The steps of traffic accumulation mechanism are as follows:

Step 1: The nodes monitor the packets sent by its neighbor by cross-layer listening, if the listened packet is a DAO-ACK, then record the number of DAO-ACK sent by each neighbor node in its neighbor table, we set the numbers of DAO-ACK packet as CDAO-ACK.

Step 2: When the nodes haven't joined the DODAG receive a DIO packet, it firstly calculates the Rank value, and then add the nodes which have lower Rank value into its parent set.

Step 3: Calculate the ELT for each bottleneck node in every path. The node uses each CDAO-ACK to present the traffic through each parent, then add itself traffic to calculate the ELT of each bottleneck in every path. The calculation formula is as follows:

$$T_{total}(B) = T_{gen}(B) + \sum_{i \in Children(B)} T_{total}(i) \tag{3}$$

In Eq. (3), the $T_{total}(B)$ present the traffic through bottleneck, the $T_{gen}(B)$ is the traffic generated by bottleneck, and the $T_{gen}(i)$ is the traffic of the child node i in the same path. The energy consumption of node to transmit 1bit data in unit time is:

$$ETX(B, P_B) \times P_{tx}(B) \tag{4}$$

In Eq. (4), P_B is the parent of node B, $P_{tx}(B)$ is the transmission power. We assume that the current residual energy of bottleneck B is $E_{res}(B)$, so the ELT of bottleneck after node joined in the DODAG through a parent node is:

$$ELT(\mathrm{B}) = \frac{E_{res}(\mathrm{B})}{T_{total}(\mathrm{B})' \times P_{tx}(\mathrm{B})} \times DATA\_RATE \tag{5}$$

In Eq. (5), $T_{total}(B)'$ is:

$$T_{total}(\mathrm{B})' = (C_{DAO-ACK} \times T_{gen}(\mathrm{n}) + T_{total}(\mathrm{B})) \times ETX(\mathrm{B}, \mathrm{P}_B) \tag{6}$$

The traffic accumulation mechanism of parent makes the joining node calculate the ELT of each bottleneck more accurate. It is beneficial for the joining node to judge and select out the best parent. In addition, the mechanism does not increase any network overhead.

(2) Control Message Accumulation Mechanism: Control message accumulation mechanism means that a node in survival time is expected when the calculation itself, not only to consider the influence of their own forwarding packets, but also consider the influence of sending many control messages such as DIO or DAO messages. Therefore, when it estimates on its own survival time, it should not only consider their own forwarding data traffic, but also compute the control message accumulation traffic. The steps of Control message accumulation mechanism are as follows:

Step 1: Node records the number of DIO and DAO message, and the sum of the number of two control messages was denoted $T_{control}(n)$;

Step 2: Node records the number of packets which were forwarded, and the number was denoted $T_{total}(n)$;

Step 3: When a node receives inconsistent DIO message stating that there is the node property changes, the nodes need to recalculate the value of their ELT, The calculation formula is as follows:

$$ELT(n) = \frac{E_{res}(n) \times DATA\_RATE}{T_{total}(n) \times ETX(n, P_n) \times P_{tx}(n)} - \frac{E_{res}(n)}{T_{control}(n) \times ETX(n, P_n) \times P_{tx}(n)} \tag{7}$$

In Eq. (7), the $E_{res}(n)$ represents the residual energy of node, and the $DATA\_RATE$ represents data rate, the $ETX(n,P_n)$ represents expected times of transmission, the $P_{tx}(n)$ represents transmission power, the $T_{control}(n)$ represents the number of control messages sent by its own node, the $T_{total}(n)$ represents the traffic forwarded to parent and its calculated by:

$$T_{total}(n) = T_{gen}(n) + \sum_{i \in Children(n)} T_{total}(i) \tag{8}$$

In Eq. (8), $T_{gen}(n)$ is the data traffic generated by the node n, and $T_{total}(i)$ is the total traffic go through node i in the same path.

Control message accumulation mechanism can accumulate the number of control messages which were sent to other node, it considers the influence of ELT value from the control message. Therefore, the node can calculate the ELT value more accurate, and it's advantageous to select path bottleneck node to balance the network energy.

(3) Bottleneck Re-estimating Mechanism: A joining node should calculate the ELT of bottleneck firstly. But the process is executed before the node joining in the DODAG. The bottleneck re-estimating mechanism is different from it. After the node joining in the DODAG, it will estimate whether there is a possible for itself to be the bottleneck if there exist one node at least will join the DODAG through it. We use the Fig.4 as an example.

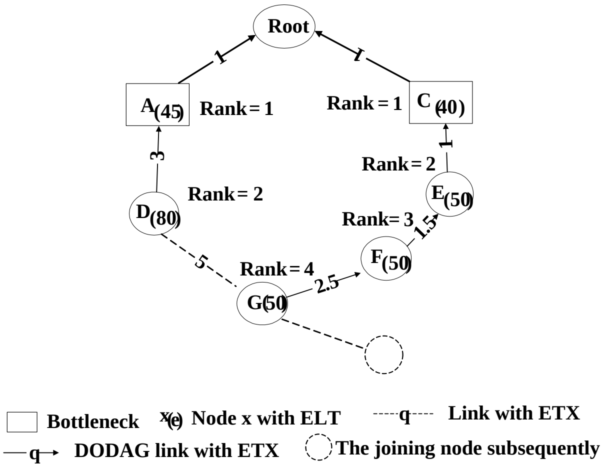

Figure 4. Example for Bottleneck Re-estimating Mechanism

In Figure 4, if G joined in the DODAG through F, the ELT of C is 35 units, the ELT of G is 37.5 units, so the bottleneck is still C, and the subsequent node of G will consider C as bottleneck. However, after the subsequent node of G joining in the DODAG through G, the ELT of C change to be 30 units, and the one of G is changed to be 25 units, G should be the real bottleneck of the path. And the subsequent nodes should use the ELT of G to compare with itself ELT. The operation steps of the Bottleneck re-estimating mechanism are as follows:

Step 1: The first step. After joining in the DODAG, the node first judges whether it is a leaf, if so, then give up the re- estimation process. Otherwise, proceed to step 2;

Step 2: The second step. If the joining node is the bottleneck node with the largest ELT, then broadcast DIO messages to its neighbor nodes directly, and give up the re-estimation process. Otherwise, proceed to step 3;

Step 3: The third step. Suppose that there is at least one node will join in the DODAG through itself, then estimate the $ELT(n)^{new}$ of itself and $ELT(B)^{new}$ of the bottleneck after forwarding another one packet to the root, if $ELT(n)^{new}<ELT(B)^{new}$, then the node be the new bottleneck and broadcast the DIO with its information to neighbors; If $ELT(n)^{new}>ELT(B)^{new}$, then the node cannot be the bottleneck, and the information in DIO messages is still belong to the current bottleneck.

According to the bottleneck re-estimating mechanism, the distribution of bottleneck nodes in the path can be considered more comprehensive, so that the subsequent nodes can choose the correct optimal parent node. So the mechanism is good to balance the energy and the load of the path bottleneck nodes, it prolongs the network survival time.

4.2. Operations of EBE-RPL Algorithm

The operation steps of EBE-RPL algorithm are as follows:

Step 1: The first step. After initializing the network, the root broadcast DIO messages with configure information;

Step 2: The second step. The node received DIO messages judge whether it is the first time to receive DIO, if it is the first time to receive DIO, then calculate the ELT of each bottleneck in every path according to traffic accumulation mechanism and proceed to step 4. If not, discard the DIO message;

Step 3: The third step. Confirm the bottleneck of each path. The joining node calculates its ELT according to control message accumulation mechanism, and compares its ELT with the bottleneck nodes' ELT, if $ELT\ (n) < ELT\ (B)$, then the joining node is the new bottleneck, otherwise, the current bottleneck is not changed;

Step 4: The fourth step. Select the best parent. Compare the ELT of each bottleneck, and select the parent node in the path with the largest $ELT\ (B)$ as the best parent. If there is a situation that the $ELT\ (B)$ in two paths or more than two paths are equal, the joining node should select the parent node which send the least DAO-ACK messages as the best parent to reduce the calculation and storage overhead, so that to balance the cost caused by sending control packet of each parent;

Step 5: The fifth step. After joining in the DODAG, the node process according to the bottleneck re-estimating mechanism and broadcast the new DIO message to its neighbors.

5. Simulation and Performance Evaluation

In this paper, we use the COOJA [11] platform of the Contiki [12] OS to build the simulation platform, and select the PRL protocol and EB-RPL algorithm as the comparison object. Through the comparison of simulation result, we can analysis the differences about the network survival time, the total number of event, the number of control packet and the energy consumption of node for the three protocols.

5.1. Network Scene and Parameter

In order to compare with the EB-RPL algorithm of [10], we also set the work mode of all nodes in the network as storage model. And the wireless channel model is based on the shadow fading model. In this experiment, we place 30 to 100 nodes in network respective, and each network scene simulate 20 times. Specific simulation parameters are shown in Table 1.

Table 1. The Specific Simulation Parameters

Parameter	Value
Simulation duration	1800s and 3600s
Number of nodes	30~100
Simulated area	200m×200m
Traffic type, rate	CBR, 0.5pkt/min
Data packet size	127 bytes
Min hop rank increase	256
MAC layer	802.15.4
Node mode	Storage mode
Shadowing, path loss	1.97
Standard deviation	2.0

We configure the parameters of all the three protocols as the parameters in Table 1, and all of them support the local and global repair strategy. We use ETX as the routing metric for RPL protocol, and consider both residual energy and ETX for EB-RPL protocol.

5.2. Simulation Results and Analysis of Each Performance Index

(1) Network Survival Time: The network survival time is a duration from the initial operation to the happened the first node death, it reflects the effective operation time for all nodes in the network and is an important indicator to measure the performance of network topology.

From Figure 5 we can see that both the EB-RPL protocol and the EBE-RPL protocol we proposed have a longer lifetime than the RPL protocol which use ETX as metric. Because using the ETX only as the metric for choosing the best parent node just considered the link quality between the node and parent node, although the total average number of packet transmission will be less, but it does not consider the minimum energy of node in one path, so that it cannot balance the energy and prolong the lifetime of network.

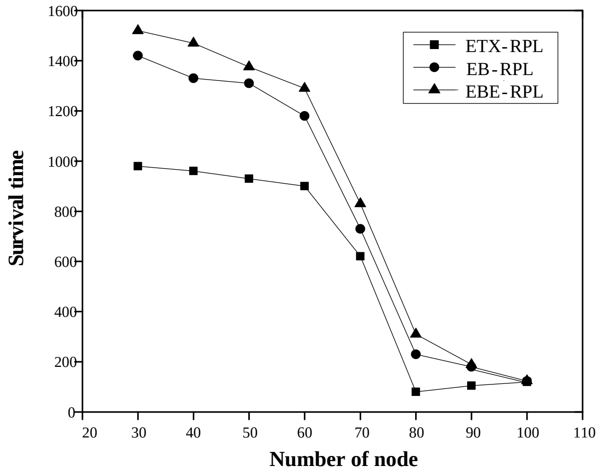

Figure 5. The Lifetime of Network with Each Number of Nodes

When the number of nodes in the network is less than 60, the EBE-RPL protocol we proposed in this paper is better with performance of about 10% than the EB-RPL protocol. The reason is that when calculating the ELT of bottleneck node, EBE-RPL protocol take into account the traffic of other children which belong to the same parent, so that the ELT calculated will be less than or equal to the value calculated in EB-RPL protocol, and a node can judge selecting which node as its best parent will achieve the load balance and prolong the lifetime of network more effectively.

(2) The Total Number of Events: The total number of events refers to the number of packets sent by all nodes in the network lifetime. The total number of events is counted by root node, and is proportional to the survival time of the network. The longer the survival time is, the greater the total events are.

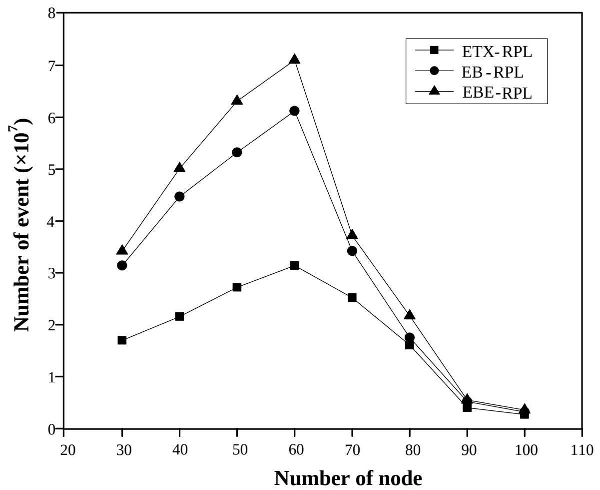

Figure 6. Network Event Number Correspond to Each Number of Node

From Figure 6, we can see that the number of event for the three algorithms is increased when the number of node increased. Especially after the number of node being 60, the network lifetime and the number of event are decreased sharply. The number of event for EBE-RPL protocol is bigger than the one of the other two protocols. Because the EBE-RPL protocol prolongs the network lifetime, so all node in network can send more packets to root.

(3) The Energy Consumption of Node: In this paper, we obtain the energy consumption of nodes through detecting the average energy consumption of 60 nodes which are of different distance from boundary node in one hour of simulation and two hour of simulation. The result of energy consumption for the 60 nodes is shown in Fig.7.

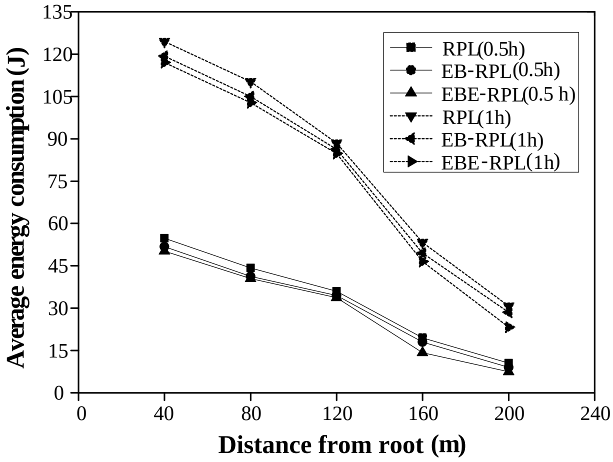

Figure 7. The Simulation Result after 0.5 Hours and 1 Hour

From Figure 7, it can be seen that the EBE-RPL algorithm is lower than the EB-RPL algorithm and the RPL protocol in terms of node energy consumption, because the EBE-RPL algorithm reduces the unnecessary DAO-ACK message sending process, it saves the control overhead. In addition, after 1 hour in the simulation, the energy consumption was significantly more than 1 times the one of 0.5 hours, which is because of the transmission energy consumption, as well as the CPU energy consumption and monitoring energy consumption.

6. Conclusion

This paper presents an energy balanced and high efficiency routing protocol in low power and lossy networks called EBE-RPL, it uses a traffic accumulation mechanism to calculate expected lifetime of bottleneck on each path, so that the lifetime calculated of bottleneck is closer to the actual value. Finally, it uses a bottleneck re-estimating mechanism to avoid the bottleneck's change after node's joining in the DODAG. EBE-RPL improved accuracy for selection the best parent, and balanced the energy of networks.

Acknowledgement

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