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An Energy-Efficient Routing Protocol for ZigBee Networks

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Abstract. ZigBee networks have known battery-life problems, so, in this paper, we propose an energy-efficient routing protocol for them named LCF-ZBR (Low Formation of cluster ZigBee Routing). If the energy of one particular cluster head node is not sufficient, an alternative cluster head is used to preserve the residual energy of the original node, thus avoiding cluster head node failure due to excessive use. This will help to prolong the service life of the entire network. LCF-ZBR and ZBR energy consumption problems were simulated using NS2， and the residual energy and the number of dead nodes were compared. The results showed that the proposed energy-efficient routing protocol was more effective.

1. Introduction

A ZigBee network is a low-power, low-rate and low-cost wireless communication technology that operates over short distances. Its bottom layer is based on IEEE 802.15.4 standard physical and MAC layers[1]. ZigBee networks are widely used for wireless communications in application areas as diverse as industrial control, communication services, home automation and medical device control[2]. ZigBee network nodes are powered by batteries, but a node battery's energy and lifespan are limited and they are not easy to replace[3]. Making ZigBee networks more energy-efficient is therefore an ongoing concern. In relation to this, the development of a routing protocol that would make ZigBee networks more durable and their route-addressing processes more energy-efficient would provide a significant contribution to dealing with the problem.

Work has already been undertaken on the routing algorithm for ZigBee networks, mainly in terms of improving the transmission path and transmission range of the control packets and reducing the network's energy consumption [4]. In [5] an improved version of a simplified Ad hoc On-demand Distance Vector (AODVjr) algorithm is proposed that uses energy thresholds to limit the broadcast range and broadcast direction of a route request control packet (RREQ). This reduces unnecessary overhead and extends the working life of the network. Another study [6] proposes a routing algorithm for ZigBee networks that mainly controls the transmission range and approximate direction of the RREQ by using a neighbor lookup table to avoid nodes with insufficient residual energy, thus prolonging network life. All of these methods achieve energy efficiency, but work exclusively by controlling the RREQ packets. Working on the basis of a standard ZigBee Routing (ZBR) algorithm, this paper proposes an energy-efficient routing protocol called Low Formation of cluster ZigBee Routing (LCF-ZBR). In this case, when the energy of a cluster head node is insufficient, the protocol uses an alternative cluster head node to avoid provoking total cluster head node failure.

2. ZigBee Routing Protocol

The ZigBee protocol divides communication devices into two class: a Full-Function Device (FFD) and a Reduced-Function Device (RFD)[7]. An FFD has routing ability, whilst an RFD does not. Within a ZigBee network, the coordinator (ZC) and the router (ZR) belong to the FFD and the terminal node (ZED) belongs to the RFD. The FFD can communicate with another FFD and an RFD, but an RFD can only communicate with the FFD that has established the network[8].

2.1. Routing Algorithms for ZigBee Networks

At present, ZigBee networks use a ZBR routing algorithm, which is a combination of AODVjr and Cluster-Tree algorithms. The Cluster-Tree algorithm is used within the clusters, whilst the AODVjr algorithm works between the clusters. Thus, the ZBR algorithm seeks to combine certain advantages from each of them.

2.1.1. The AODVjr Algorithm. The AODVjr algorithm searches for an optimal path according to whatever takes the shortest time[9]. First of all, it eliminates the destination node sequence number from a basic AODV algorithm and specifies that only the destination node can send route reply (RREP) packets, thus avoiding loops. Then, KEEPALIVE information is used in the AODVjr algorithm to replace the HELLO information found in the basic AODV algorithm to maintain the routing. The destination node sends the KEEPALIVE information periodically. If the source node does not receive the information within a certain period of time, the link is considered to be interrupted. The AODVjr algorithm uses a local repair mechanism to save time when re-discovering a route. If the repair fails, the link will be sent directly. A route error (RERR) packet is given to the source node, which differs from the AODV algorithm, where this has to be sent by the parent node.

2.1.2. The Cluster-Tree Algorithm. The Cluster-Tree provides a network layer and a logical link layer protocol that uses link state packets to establish a network[10]. If a routing node address is A and the network depth is d , Formula (1) can be used to decide whether the destination node is its child node. Formula (2) can then be used to determine whether the data frame with its received address D should be sent to the parent node or the child node.

$$A < D < A + Cskip(d-1) \tag{1}$$

$$N = \begin{cases} D, D > A + Rm * Cskip(d) \\ A + 1 + \left\lfloor \dfrac{D-(A+1)}{Cskip(d)} \right\rfloor * Cskip(d) \end{cases} \tag{2}$$

The Cluster-Tree algorithm performs routing and package forwarding according to the tree structure. As a result, the frequency with which data is forwarded to routing nodes closer to the coordinator is increased, leading to greater levels of energy consumption. An energy-efficient routing protocol is therefore needed to reduce the energy consumption and maintain battery power over longer periods of time.

3. Energy-efficient Routing Protocol LCF-ZBR

3.1. Concept

To solve the energy problem currently confronting ZigBee networks, we have developed an energy-efficient routing protocol named LCF-ZBR (Low Formation of cluster-ZBR). Our goal was to reduce energy loss while still ensuring normal communication. The protocol first of all sets the lowest energy value for all of the nodes. When a node value is lower than the lowest value, the node is preserved and only needs to have a pass-through effect, without data forwarding. After this, a clustering technique is used to divide the nodes into cluster heads, ordinary members and alternative cluster heads. When the cluster head nodes have insufficient energy or leave the network, an alternative cluster head can directly replace them, thereby preventing routing nodes from being exhausted.

3.2. Implementation

As noted above, in the LCF-ZBR protocol, the nodes in a cluster are divided across three roles: a cluster head, a normal member, and an alternative cluster head. The routing nodes with the most child nodes are directly connected to the coordinator and form a cluster. The selection of the cluster head is related to its residual energy. The formula for residual energy, E , is as follows in formula (3):

$$E = E_0 - \left[\frac{kt}{d+1} \right] \tag{3}$$

where E_0 represents the initial energy of the node, d represents the depth of the network, t represents temporal duration, and k is a fixed coefficient, the value of which can be self-established (wherein the k value of a cluster head node is slightly larger than that of an ordinary node).

3.2.1. Setting the Energy Threshold. The energy values are set according to three possible states: sufficient energy; low energy; and alert. The energy values relating to all ‘sufficient energy’ nodes and ‘low energy’ nodes are fixed. It is the energy setting of the alert nodes that changes dynamically, regardless of the degree to which the network energy changes overall. Every network has different energy requirements for its nodes. In a network where the nodes are frequently forwarding data, the energy of the alert node needs to be set higher. Otherwise, when a node reaches the alert value, there is a risk of it failing and exiting the entire network. Here, the minimum threshold of the node, $MinEnergy$, is set for small networks, as shown in Formula (4):

$$MinEnergy = \beta \times Energy \tag{4}$$

where Energy represents the initial energy value of the node and β is a fixed coefficient. By comparing the residual node energy E with the $MinEnergy$ value, when $E \le MinEnergy$, the node is protected. If the node is a routing node, the node will only be allowed to forward data, not receive it, thus ensuring that its life and the life of the entire network is extended.

3.2.2. Alternative Cluster Head Selection. In the LCF-ZBR protocol, the coordinator collects the residual energy values for the nodes in each cluster and assumes the role of cluster head node in its own cluster. The coordinator selects the routing node with the most residual energy as the cluster head and selects the node that is directly connected to the cluster head node with the second-most energy as the alternative cluster head. The other nodes are considered ordinary members. The structure of a LCF-ZBR cluster is shown in figure1.

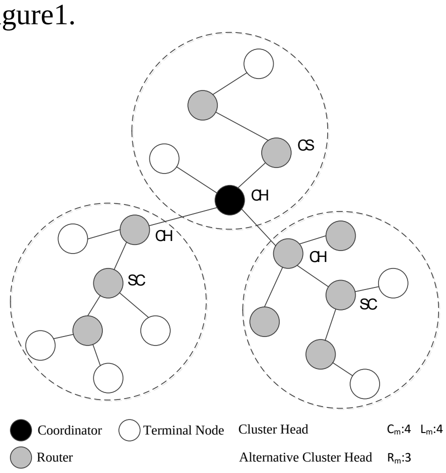

Figure 1. LCF-ZBR cluster structure.

As the energy requirements of the cluster head node are different from those of the ordinary node, the energy formula for the cluster head node is defined separately in the LCF-ZBdR protocol. The cluster head node energy E_h needs to satisfy the following in formula (5):

$$E_h = MinEnergy + E_0 \times (\frac{\alpha}{d}) \qquad (5)$$

where $MinEnergy$ represents the lowest value of the node, which is the lowest threshold given by Formula (4);$E_0 \times (ad^{-1})$ represents the energy required by the cluster head node; E_0 represents the initial energy of the node; d represents the depth of the network; and α indicates a fixed value. When the residual energy E of the cluster head node does not satisfy E_h, the cluster head node needs to be replaced by an alternative cluster head node. The cluster head replacement process is shown in figure 2.

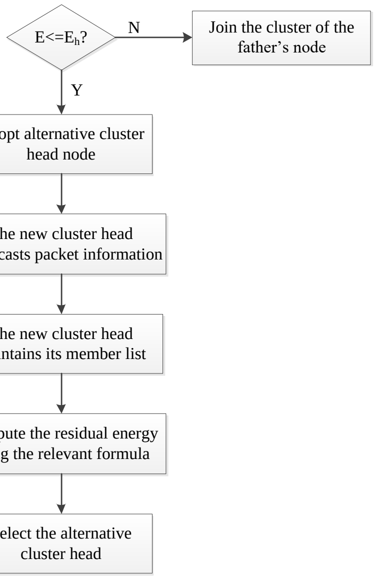

Figure 2. The cluster head replacement process.

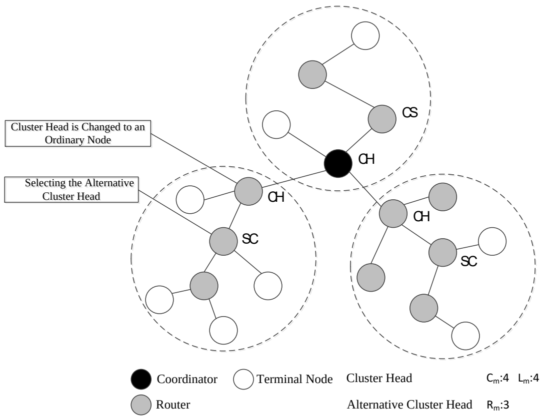

Figure 3. Cluster structure change process.

As can be seen from figure 2,

If (E≤Eh)

{

The cluster head is replaced with an alternative cluster head node and the replaced node becomes an ordinary node;

The new cluster head node broadcasts cluster header message information;

The new cluster head maintains its own member list;

The residual energy the other nodes is calculated using the energy formula to select a new alternative cluster head;

}

Failing this:

Join the cluster of the parent node.

In the LCF-ZBR protocol, when the residual energy of the cluster head node does not satisfy E_h, the process for changing the cluster structure and using an alternative cluster head node is shown in figure 3. In addition to the alternative cluster head replacement process, this process also shows the new alternative cluster head selection.

4. Simulation and Performance Comparison

4.1. Simulation Set-up

NS2 simulation software was used in Linux to analyze and compare the existing ZBR algorithm and the LCF-ZBR algorithm. The simulation area was 150m×150m, the number of nodes was set to 50, the simulation time was 200s, the number of data streams was 8, the data flow was constant bit rate (CBR), the initial energy of the node was defined as 50J, the network parameter Rm was 5, Lm was 4, Cm was 5, the next hop node transmission distance was 15m, and the fixed values for α, β, k were set at 0.5, 0.25, 0.3, respectively. The specific simulation parameters are shown in Table 1.

Table 1 . Simulation parameters.

Simulation area /m×m	150×150
Number of nodes	50
Simulation time / seconds	200
Initial energy of node / J	50
Transmission distance / m	15
Number of data flows	8
Type of data flow	CBR

4.2. Simulation Results

4.2.1. Network Delay. Figure 4 provides a comparison of the network delays when the concurrent CBR data stream is equal to 8. The LCF-ZBR adopts a clustering method to reduce the time taken for the node to find a path. This reduces the hop count but involves monitoring the energy of the cluster head node. As a result there is an increase in the overall network energy requirement, but a reduction in network delay. So, although the LCF-ZBR routing algorithm is only slightly different to the source algorithm, it reduces the network delay and improves the data stream transmission efficiency.

Figure 4. Network delay.

4.2.2. Residual Energy. Figure 5 reflects the relationship between the residual energy of the node and time. Comparing the residual energy of the nodes for the ZBR and the LCF-ZBR algorithms, the residual energy for the LCF-ZBR nodes is significantly better, which will have the effect of prolonging the life of the whole network. By reducing the network consumption over time, the LCF-ZBR algorithm provided 3.74% more residual energy than the ZBR algorithm.

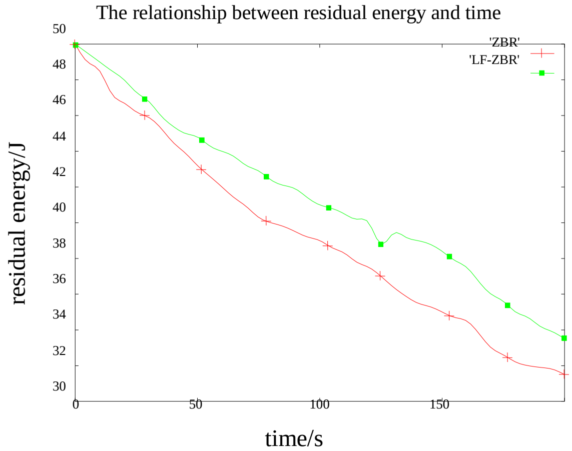

Figure 5. Relationship between residual energy and time.

4.2.3. Number of Dead Nodes. Figure 6 shows a comparison of the number of dead nodes for the two routing algorithms. Both algorithms reduced the node mortality over time, but the LCF-ZBR algorithm had a significantly lower node death rate than the ZBR algorithm. The LCF-ZBR algorithm sets a minimum energy threshold for each node, which avoids its premature failure. As discussed above, the increased number of alternative cluster heads in a cluster enables the premature death of a cluster head node through overuse to be evaded.

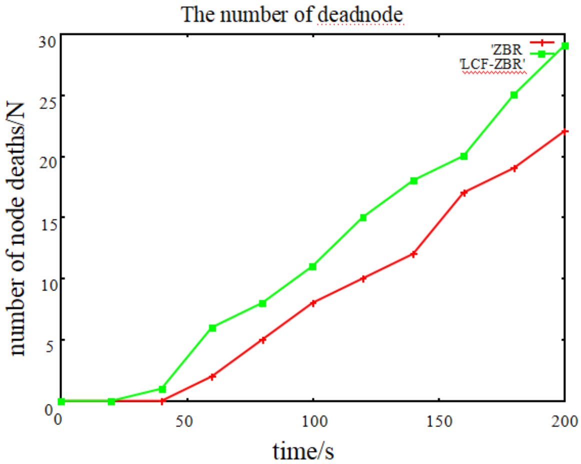

Figure 6. The number of dead nodes.

The simulation enabled us to analyze the impact of the proposed protocol upon network delay, residual node energy and the number of node deaths. Over time, the proposed LCF-ZBR routing algorithm reduces the energy consumption of a node, improving its durability and thus increasing the network's life.

5. Conclusion

As ZigBee network nodes use battery power, their available energy is limited and the batteries are not easy to replace. Studies regarding ways of improving node energy efficiency have become increasingly important in ZigBee network research because node life ultimately impacts the life of the whole network. An energy-efficient routing protocol called LCF-ZBR has been presented in this paper, which offers a way of replacing the energy of one cluster head node with the energy of an alternative cluster head node. Results from a NS2 simulation showed that the LCF-ZBR protocol reduced network energy consumption, reduced node mortality and effectively improved the lifespan of a node. However, the protocol has not yet been designed to accommodate the processing of link interruption. This will therefore form the basis of our next body of research regarding how to maximize node

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energy efficiency in networks.

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